1-1-2006

The behaviour of a gaseous transient jet in a direct injection turbulence chamber.

Chunyi Xia
University of Windsor

Follow this and additional works at: https://scholar.uwindsor.ca/etd

Recommended Citation
https://scholar.uwindsor.ca/etd/7225

This online database contains the full-text of PhD dissertations and Masters' theses of University of Windsor students from 1954 forward. These documents are made available for personal study and research purposes only, in accordance with the Canadian Copyright Act and the Creative Commons license—CC BY-NC-ND (Attribution, Non-Commercial, No Derivative Works). Under this license, works must always be attributed to the copyright holder (original author), cannot be used for any commercial purposes, and may not be altered. Any other use would require the permission of the copyright holder. Students may inquire about withdrawing their dissertation and/or thesis from this database. For additional inquiries, please contact the repository administrator via email (scholarship@uwindsor.ca) or by telephone at 519-253-3000ext. 3208.
NOTICE:
The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Canada

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
ABSTRACT

In order to advance the understanding of interaction and mixing between a turbulent transient gaseous jet and ambient turbulent flow of zero-mean velocity in a confined space, both experimental investigation and numerical modeling were employed. In experimental modeling, a cubic chamber of 1 liter (10 cm × 10cm × 10 cm) was selected to house the turbulent transient jet and the ambient turbulent flow. The turbulent jet was produced by an injector mounted at the center of the chamber top wall. Inside the chamber, a pair of oscillating perforated plates was used to generate the ambient turbulent flow. With carefully selected stroke, oscillation frequency and diameter of holes in the plates, this apparatus can produce a semi-homogeneous turbulence field in the central region of the chamber. The turbulence length scales and intensity were controlled by the choice of plate stroke and oscillation frequency.

The resulting flow field was characterized using a two-component Laser Doppler Velocimetry system. The injection process was visualized by fast Schlieren motion pictures. The recorded images were processed to extract injection characteristics such as the jet penetration depths and spread angles.

A numerical model of the injection and mixing process was also created using a commercial CFD code, KIVA3V. This model was based on the experimental configuration, with the perforated plates and their oscillating movement closely modeled. With the numerical model, the turbulence generation process by oscillation of perforated plates, the development of the transient gaseous jet and the interactions and mixing between the jet and the ambient flow could be thoroughly investigated in a three-dimensional time-dependant computational domain.
Both the experimental and numerical results show that the turbulent intensity in the centre of the cubic chamber follows correlation similar to that governs the turbulence generated by a pair of oscillating grids in a water tank. That is, the power law of decay of the turbulent intensity in the chamber centre follows,

$$q = 0.328 f_{osc} S^{1.5} M^{0.5} H^{-1}.$$  

The turbulence length scale at the chamber center increase slightly with an increase in the oscillation frequency.

Results from both the experiments and numerical simulations show that the penetration depth of the transient jet, with Re between 7,600 ~ 19,000, has a strong dependency on the square root of time and the momentum rate of the jet, beyond 10 injector nozzle diameters away from the exit. No significant influence was observed on the penetration depth and the spread angle based on the ambient turbulent flows generated with the parameters used in this work.
DEDICATION

To my parents, for their everlasting love
ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. A. Sobiesiak, for his support, patience, and encouragement throughout my graduate studies. His guidance and financial assistance made the completion of this dissertation possible.

I would also like to thank the rest of my internal committee members, Dr. G. Rankin, Dr. D. Ting and Dr. R. Carriveau, who provided many valuable comments which improved the contents of this dissertation. Special thanks also go to Dr. Weckman, my external examiner, for her detailed correction and insightful comments.

A number of people have contributed to the completion of this research and their assistance must be gratefully acknowledged. They are: Dr. Rafal Jarnicki and Dr. Biao Zhou, who helped considerably with my understanding of the KIVA code; Mr. Andy Jenner, who dedicated his professional expertise in fabricating the state-of-art experimental apparatus; Mr. Pat Seguin and Mr. Gangyong Zhang, who helped to build and debug the power unit to the control circuit; Mr. Galus Chelaidite, who contributed his private time in helping me with the LabView programming; and in particular, Mr. Bruce Durfy, who worked in an ingenious way in solving my seemingly small but head-cracking problems around the laboratory.

The financial support of University of Windsor Faculty of Graduate Studies and Research and Department of Mechanical Engineering is gratefully acknowledged.

I would like express my special thankfulness to my ‘greater family’ in Windsor, which was formed around the ‘magic papa’ Smiley and with which I shared the happiness and
sadness over the seven-year journey. The 'greater family' includes: Jing and Daniel's family, Karen and Jerry's family, Tina and Joe's family, Lian and Ben's family, Joe and Crystal and their loving daughters Stefani and Samantha, etc.

I am very grateful to my many friends who made my life much more enjoyable. They are: Hannah and Rick Zhang, Gang Wang, David Quan and Jenny Li, Yi Zong, Rui Liu, Ligong Yang, Lihong Han, Jun Zuo, Sabrina Ji, Xiaoguang Mu. My thanks also go to my colleagues at University of Windsor, with who I had many interesting and good-spirited discussions related and non-related to this research. They are Dr. Chunhua Zhang, Phil Zoldak, Shengmei Zhang, Michael Johnson, Clarence Melanga, Prakash Gnanam, Mehash Babu, Mohsen Battoei, Anthony Lam, etc.

Last, but not least, I would like to express my deepest gratitude to my family: my parents, Youbin Xia and Arong Liu, and my elder brother, John Fengxu Xia, for their unconditional love through my life. Their encouragement and confidence in me was in the end what made the completion of this dissertation possible.
Table of Contents

ABSTRACT...................................................................................................................... iii
DEDICATION................................................................................................................... v
ACKNOWLEDGEMENTS ............................................................................................. vi
List of Tables ................................................................................................................... xii
List of Figures................................................................................................................. xiv
Nomenclature ............................................................................................................... xxiii

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Introduction</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.1 Background</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1.2 Physical Model under Study</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1.3 Objectives</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1.4 Methodology</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>Literature Review</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Experimental Modeling</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>3.1 Introduction</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>Experimental Techniques</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>4.1 Introduction</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>4.2 Velocity Measurement with LDV</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>4.2.1 Basic Principle and Configuration of LDV</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>4.2.2 Frequency Shift and Effective Frequency Shift</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>4.2.3 Seed Generation and Seeding</td>
<td>72</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>Results from Numerical Simulations ...................................................... 156</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>---------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>7.1</td>
<td>Introduction........................................................................................ 156</td>
<td></td>
</tr>
<tr>
<td>7.2</td>
<td>DI Chamber Turbulent Flow Field ...................................................... 160</td>
<td></td>
</tr>
<tr>
<td>7.2.1</td>
<td>Velocity Field.................................................................................... 161</td>
<td></td>
</tr>
<tr>
<td>7.2.2</td>
<td>Turbulent Kinetic Energy $k$............................................................ 175</td>
<td></td>
</tr>
<tr>
<td>7.2.3</td>
<td>Turbulence Length Scales.................................................................... 187</td>
<td></td>
</tr>
<tr>
<td>7.2.4</td>
<td>Discussion........................................................................................ 194</td>
<td></td>
</tr>
<tr>
<td>7.3</td>
<td>Turbulent Transient Jet ..................................................................... 196</td>
<td></td>
</tr>
<tr>
<td>7.3.1</td>
<td>Penetration Depth............................................................................... 198</td>
<td></td>
</tr>
<tr>
<td>7.3.2</td>
<td>Axial Velocity..................................................................................... 213</td>
<td></td>
</tr>
<tr>
<td>7.3.3</td>
<td>Methane Concentration along the Centerline...................................... 220</td>
<td></td>
</tr>
<tr>
<td>7.3.4</td>
<td>Radial Concentration.......................................................................... 221</td>
<td></td>
</tr>
<tr>
<td>7.3.5</td>
<td>Spreading Angle.................................................................................. 224</td>
<td></td>
</tr>
<tr>
<td>7.3.6</td>
<td>Flammable Mixture............................................................................. 232</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 8</th>
<th>Comparison of Experimental and Numerical Results .......................... 241</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1</td>
<td>Turbulent Intensity and its Power Decay Law..................................... 241</td>
</tr>
<tr>
<td>8.2</td>
<td>Turbulence Length Scales.................................................................... 242</td>
</tr>
<tr>
<td>8.3</td>
<td>Penetration Depths of Turbulent Transient Jets................................... 246</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 9</th>
<th>Conclusions and Recommendations................................................... 248</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1</td>
<td>Overview of the Unique Aspects of the Work....................................... 248</td>
</tr>
<tr>
<td>9.1.1</td>
<td>Turbulence Generation in a Gaseous Media....................................... 248</td>
</tr>
<tr>
<td>9.1.2</td>
<td>Use of the DI Chamber in Study of Transient Gaseous Injection........... 248</td>
</tr>
<tr>
<td>9.1.3</td>
<td>Numerical Modeling of the DI Chamber.............................................. 249</td>
</tr>
<tr>
<td>9.2</td>
<td>Conclusions Made Regarding Research Objectives.............................. 249</td>
</tr>
<tr>
<td>9.2.1</td>
<td>Physical Model Creation..................................................................... 249</td>
</tr>
<tr>
<td>9.2.2</td>
<td>Measurement Techniques...................................................................... 250</td>
</tr>
<tr>
<td>9.2.3</td>
<td>Numerical Model Creation.................................................................. 250</td>
</tr>
<tr>
<td>9.2.4</td>
<td>Turbulence Generated by the Oscillation of the Perforated Plates........ 251</td>
</tr>
<tr>
<td>9.2.5</td>
<td>Behavior of the Turbulent Transient Gaseous Jet.............................. 252</td>
</tr>
</tbody>
</table>
### List of Tables

3.1 Parameters for generating intended motion ............................................................ 45
3.2 Input parameters for output motion with frequency of 8 Hz and stroke of 2.5 cm ............................................................................................................................. 46
3.3 Frequencies and Strokes that had been carefully tuned ......................................... 48
3.4 Estimation of turbulence intensity (cm/s) from selected oscillation frequencies and strokes ........................................................................................... 49
3.5 Specifications of the injector .................................................................................... 53
4.1 Main Components of the LDV system .................................................................... 63
4.2 Dimensions of the transmitting geometry ............................................................... 65
4.3 Dimensions of the measuring volume ..................................................................... 66
4.4 Effective frequency shift commonly used in this research .................................... 72
4.5 LDV signal processor operating parameters ........................................................... 75
4.6 Record rates over 250 fps and available display size ............................................. 82
4.7 Display size and the corresponding number of frames one can record ................. 82
4.8 The weighting numbers for the $5 \times 5$ filtering scheme. The pixel of interest takes the weighting number of 36, which is in the center of the table and marked with hatched lines ...................................................................................... 89
4.9 Uncertainty in the image processing ................................................................. 92
5.1 Boundary and initial conditions of the chamber walls and fluid ......................... 123
5.2 Boundary conditions for the injected gas (Reference temperature and pressure are required to calculate the reference density, which is used in Eq. 5.19) .......................................................................................................................... 124
6.1 Experimental matrix for LDV measurements ....................................................... 127
6.2 Mean velocities and rms velocities at different frequencies with stroke $S = 1.4 \text{ cm}$ ............................................................................................................. 128
6.3 Mean velocities and rms velocities at different frequencies with stroke $S = 2.5 \text{ cm}$ ............................................................................................................. 128
6.4 Kolmogorov scales at the DI chamber center at different oscillation frequencies ............................................................................................................. 136
6.5 Injection Matrix ................................................................. 144
6.6 Experimental matrix .......................................................... 145
6.7 Spread angles of transient jets for selected cases ................ 155
7.1 Simulation matrix .............................................................. 158
7.2 Turbulent kinetic energy and turbulent intensity at the DI chamber center for different oscillation frequency .................................................. 186
7.3 The $L_e$ at the chamber center at different oscillation frequency ................ 188
7.4 Equations of the best fit straight lines of the $W_0/W_0(z)$ curves at the linear region ................................................................. 216
7.5 The spreading rate SR for turbulent round jets (from Panchapakesan and Lumley, 1993) .............................................................. 224
7.6 Half angle and the intermediate quantities during the calculation for the case 'W0=40 m/s; 20 Hz, stopped while injecting' ........................................ 226
7.7 The spread angles and the intermediate quantities for the case with the transient methane injection into the quiescent chamber air at W0 = 40 m/s 229
List of Figures

1.1 Transient gaseous jet spreading into homogeneous isotropic turbulent flow. ..... 3
1.2 Schematic of a HPDI NG engine (Ouellette and Hill, 1997). ..................... 5
2.1 Illustration of Turner’s assumption on the transient jet. ............................... 9
2.2 Schematic of an oscillating grid mixing box (a) and the grid (b). ................. 12
2.3 Schematic diagram of the experimental apparatus used by Srdic et al. (1996) .......................................................................................................................... 16
2.4 Plot of the non-dimensional r.m.s. velocities \( \left( \frac{u'^2}{f_{osc}} \right)^{1/2} \), \( \left( \frac{w'^2}{f_{osc}} \right)^{1/2} \) vs. normalized distance \( x/D \): \( f_{osc} = 3 \) Hz, \( S = 2 \) cm, \( M = 5 \) cm, (●) \( \left( \frac{u'^2}{f_{osc}} \right)^{1/2} \), (□) \( \left( \frac{w'^2}{f_{osc}} \right)^{1/2} \); \( f_{osc} = 4 \) Hz, \( S = 2 \) cm, \( M = 5 \) cm, (○) \( \left( \frac{u'^2}{f_{osc}} \right)^{1/2} \), (△) \( \left( \frac{w'^2}{f_{osc}} \right)^{1/2} \).
(Measurements were made along the x axis) (Srdic et al., 1996) ...................... 17
2.5 Measurements were made along the z axis, which show approximated vertical homogeneity in the central region of the tank. (△) \( f_{osc} = 4 \) Hz, \( x/D = 0.2 \); (●) \( f_{osc} = 3 \) Hz, \( x/D = 0.0 \); (□) \( f_{osc} = 4 \) Hz, \( x/D = 0.0 \); (○) \( f_{osc} = 3 \) Hz, \( x/D = 0.2 \). (Srdic et al., 1996) ...................................................................................... 17
2.6 Schematic experimental apparatus used by Shy et al. (1997). ....................... 19
2.7 Schematics of the experimental set-up used by Law et al. (2001). Imaged location was shown with dashed line................................................................. 22
2.8 Jet spread as a function of downstream distance (Law et al. 2001). .......... 22
2.9 Schematics of experimental set-up by Guo et al. (2005).............................. 23
3.1 Experimental setup for transient gaseous jet study. ........................................ 28
3.2 An exploded view of the cubic chamber. ................................................... 29
3.3 Two sectional views of the cubic chamber.................................................. 31
3.4 Picture of components on top of the chamber......................................... 32
3.5 Schematic of a drive system commonly used in previous oscillating grid turbulence research. ................................................................. 35

xiv

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
3.6 Design of the 1.0 cm plate. (a) Sketch drawing; (b) Geometry for calculation of solidity; (c) modified central hole; (d) A solid design image of the plate with ribs clearly shown .......................................................... 37
3.7 Photo of the 0.3 cm perforated plate ........................................................................ 38
3.8 Schematic of the pneumatic drive system ............................................................... 39
3.9 Principle of proportional valves and pneumatic cylinders ...................................... 41
3.10 Proportional valve working positions and air flow rate as a function of set-point voltage ................................................................. 42
3.11 Schematic of the closed loop control circuit ......................................................... 43
3.12 Visual interface of LabView control program ....................................................... 44
3.13 Illustration of plates’ position for stroke of 2.5 cm .............................................. 47
3.14 Schematic of the pneumatic cylinder mount .......................................................... 50
3.15 Potentiometer and the guiding rails to prevent rotation of the shaft ..................... 50
3.16 Schematic of the gas injection system .................................................................. 51
3.17 A photo of gas injection system .......................................................................... 52
3.18 A photo of the commercial gaseous fuel injector ................................................ 53
3.19 Illustration of the mounting of the injector and its connection with flexible tube through adaptor ................................................................. 55
3.20 A photograph of combined power supply box ..................................................... 56
3.21 Cubic chamber traverse system .......................................................................... 57
3.22 The ruler and knife-edge indicator ....................................................................... 57
4.1 The penetration depth and spread angle from a processed Schlieren image .... 60
4.2 Two component Laser Doppler Velocimetry and basic principle ....................... 62
4.3 Schematic of the transmitting geometry ............................................................... 64
4.4 Schematic of the measuring volume ..................................................................... 65
4.5 Illustration of how frequency shifting eliminates directional ambiguity ............. 67
4.6 A particle moving across the LDV measuring volume ........................................ 68
4.7 Frequency shifting and mixing in the ColorLink Plus .......................................... 72
4.8 Seeding device and solution used for seed particle generation ............................. 73
4.9 Mean velocity values against different sample number ....................................... 76
4.10 Principle of a basic Schlieren imaging system .................................................... 78

xv

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
(a) inner limit positions; (b) outer limit positions

5.12 Mesh of side wall with the injector in the center and mesh for injector nozzle exit area.

5.13 Geometry of the injection cells.

6.1 (a) Cartesian coordinate system for presentation of the experimental results; and (b) notation for the velocity components (Letters in brackets are means).

6.2 LDV measurement location and velocity components.

6.3 The effect of oscillation frequency on turbulent velocity at the chamber center.

6.4 Turbulent kinetic energy at the chamber center at different oscillation frequencies.

6.5 Illustration of the calculation of the integral time scale from the $R_e(t)$ curve.

6.6 Autocorrelation coefficient curves at different frequencies (calculation of coefficients was based on y-direction fluctuation component $v'$).

6.7 Variation of Eulerian integral time scale as a function of oscillation frequency.

6.8 Variation of calculated integral length scale with oscillation frequency.

6.9 Frequency spectrum for the case with $f_{osci} = 8$ Hz and $S = 2.5$ cm. (a) spectrum is calculated based on $u'$; (b) spectrum is calculated based on $v'$.

6.10 Frequency spectra for the cases with $S = 2.5$ cm. (spectra are calculated based on $v'$).

6.11 Frequency spectra for cases with stroke $S = 1.4$ cm (spectra are calculated based on $v'$).

6.12 Frequency spectra for cases with $f_{osci} = 4$ Hz and $S = 2.5$ cm (spectra are calculated based on $v'$). The measurement point is (a) at the DI chamber center, i.e., (0, 0, 5); (b) 1.0 cm to the left of the DI chamber center, i.e., (0, -1, 5).

6.13 The calculated coefficient $C$ versus the oscillation frequency.

6.14 The effect of grid oscillation frequency on turbulent intensity for two grid
turbulence in the mid-plane between the grids \((z = 0)\) at a hole and node
(cross) position........................................................................................................ 143

6.15 Effect of injection pressure on penetration depth. Methane at 0.069, 0.138,
0.276 MPa injected into chamber air; \(d = 0.3\) cm; \(f_{osc}\) = 8 Hz ....................... 146

6.16 Data of jet penetration depth for cases with different injection pressures...... 147

6.17 Data of jet penetration depth for cases with different injection pressures...... 148

6.18 Penetration depth curves for cases with different injected gases, \(p_0 = 0.069\)
MPa; \(f_{osc} = 0\) Hz. ............................................................................................. 150

6.19 Relationship between K coefficient and \(y\). ..................................................... 151

6.20 Penetration depth for cases with different ambient gases, \(p_0 = 0.069\) MPa;
\(f_{osc} = 0\) Hz. ........................................................................................................ 151

6.21 Penetration depth for cases with different oscillation frequencies. Methane
at 0.069 MPa injected into chamber air; \(d = 0.3\) cm........................................... 152

6.22 Penetration depth for cases with different sets of perforated plates. Helium
at 0.069 MPa injected into chamber air, \(f_{osc} = 8\) Hz........................................... 154

7.1 The Coordinate system and terminology.......................................................... 159

7.2 The field of the magnitude of the velocity V-component across the C-plane
at the 18th cycle with the plates 4.46 cm, in; \(f_{osc} = 12\) Hz, \(S = 2.5\) cm.......... 163

7.3 Visualization of the velocity vector field across the C-plane at the 18th
cycle with the plates 4.46 cm, in; \(f_{osc} = 12\) Hz, \(S = 2.5\) cm......................... 164

7.4 The field of the magnitude of the velocity V-component across the C-plane
at the 18th cycle with the plates 2.93 cm, in; \(f_{osc} = 12\) Hz, \(S = 2.5\) cm........ 165

7.5 Visualization of the velocity vector field across the C-plane at the 18th
cycle with the plates 2.93 cm, in; \(f_{osc} = 12\) Hz, \(S = 2.5\) cm......................... 166

7.6 The field of the magnitude of the velocity V-component across the C-plane
at the 18th cycle with the plates 2.04 cm, out; \(f_{osc} = 12\) Hz, \(S = 2.5\) cm........ 167

7.7 Visualization of the velocity vector field across the C-plane at the 18th
cycle with the plates 2.04 cm, out; \(f_{osc} = 12\) Hz, \(S = 2.5\) cm......................... 168

7.8 The field of the magnitude of the velocity V-component across the C-plane
at the 18th cycle with the plates 3.57 cm, out; \(f_{osc} = 12\) Hz, \(S = 2.5\) cm........ 169

7.9 Visualization of the velocity vector field across the C-plane at the 18th
cycle with the plates 3.57 cm, out; $f_{osci} = 12$ Hz, $S = 2.5$ cm. .................. 170

7.10 The field of the magnitude of the velocity V-component across the C-plane at the 18th cycle with the plates 4.46 cm, in; $f_{osci} = 12$ Hz, $S = 2.5$ cm. .......... 171

7.11 Visualization of the velocity vector field across the C-plane at the 18th cycle with the plates 4.46 cm, in; $f_{osci} = 12$ Hz, $S = 2.5$ cm. ......................... 172

7.12 The magnitude of the y-direction velocity component V along the C-line. .... 173

7.13 The magnitude of the x-direction velocity component U along the C-line. .... 174

7.14 The magnitude of the z-direction velocity component W along the C-line. .... 175

7.15 Visualization of turbulent kinetic energy field on the C-plane at cycle 15 with $f_{osci} = 12$ Hz, $S = 2.5$ cm; the plate state '3.57, out'. ...................... 179

7.16 Visualization of turbulent kinetic energy field on the C-plane at cycle 15 with $f_{osci} = 12$ Hz, $S = 2.5$ cm; the plate state (a) '4.46 cm, in'; (b) '2.93 cm, in.' ................................................................. 180

7.17 Visualization of turbulent kinetic energy field on the C-plane at cycle 15 with $f_{osci} = 12$ Hz, $S = 2.5$ cm; the plate state (a) '2.04 cm, out' (b) '3.57 cm, out'. .............................................................................. 181

7.18 Turbulent kinetic energy along the C-line at four instants within cycle 15. $f_{osci} = 12$ Hz; $S = 2.5$ cm; in the central region. .............................................. 182

7.19 Turbulent characteristic velocity along the C-line between $y = -1$ cm and $y = 1$ cm at four instants within cycle 15. $f_{osci} = 12$ Hz; $S = 2.5$ cm; in the central region. ................................................................. 182

7.20 Cyclic turbulent kinetic energy along the C-line for the case with oscillation frequency of 20 Hz. ................................................................. 183

7.21 Cyclic turbulent kinetic energy along the C-line for the case with oscillation frequency of 12 Hz. ................................................................. 184

7.22 Turbulent kinetic energy at the DI chamber center versus cycle number. ...... 185

7.23 Turbulent kinetic energy at the DI chamber center versus time. .................. 185

7.24 Turbulent kinetic energy and the turbulent intensity at the DI chamber center ........................................................................................................ 186

7.25 Visualization of $L_e$ field on the C-plane at the 18th cycle with plates 4.46 cm, in; $f_{osci} = 12$ Hz, $S = 2.5$ cm. ................................................................. 189

xix

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
7.26 Visualization of $L_e$ field on the C-plane at the 18th cycle with plates (a) 2.93 cm, in; $f_{osci} = 12$ Hz, $S = 2.5$ cm; (b) 2.04 cm, out; $f_{osci} = 12$ Hz, $S = 2.5$ cm. 190

7.27 Visualization of $L_e$ field on the C-plane at the 18th cycle with plates 3.57 cm, out; $f_{osci} = 12$ Hz, $S = 2.5$ cm. 191

7.28 Visualization of $L_e$ field on the C-plane at the 18th cycle with plates 2.93 cm, in; $f_{osci} = 12$ Hz, $S = 2.5$ cm. 191

7.29 The turbulence macro-length scale along the C-line at four instant during the 18th cycle. 192

7.30 The turbulence macro-length scale along the segment of C-line (between the inner limit planes) at different cycles at the instant with plates '2.04 cm, out'. 192

7.31 The turbulence macro-length scale at the chamber center versus the cycle number. 193

7.32 The turbulence macro-length scale at the chamber center for different oscillation frequency. 193

7.33 The values of coefficient $C$ from numerical simulations versus the oscillation frequency. 195

7.34 Definition of radial lines. 198

7.35 Visualization of the development of the transient jet. $D_{inj} = 30$ ms, $W_0 = 40$ m/s. 204

7.36 (a) Visualization of a methane transient jet in a DI chamber cross C-plane at 18 ms after injection. (b) Mesh and methane mass fraction contour for study of definition of penetration. 205

7.37 Methane mass fraction along the jet axis at 18 ms during injection. 206

7.38 Details of axial methane mass fraction at the jet front shown in Fig. 7.37. 206

7.39 Methane mass fraction along the centerline at different instants during injection. 207

7.40 Comparison of jet penetration at different conditions. 208

7.41 The chamber velocity field across the C-plane by the transient injection into the quiescent chamber air with $W_0 = 40$ m/s; at 20 ms during injection. 209

7.42 The chamber velocity field across the C-plane by the transient injection into
the chamber air with \( W_0 = 40 \) m/s; 20 Hz, stopped while injecting; at 20 ms during injection.

7.43 The chamber velocity field across the C-plane by the transient injection into the chamber air with \( W_0 = 40 \) m/s; 20 Hz, running while injecting; at 20 ms during injection.

7.44 Comparison of jet penetration for different oscillation frequency.

7.45 Comparison of jet penetration for different injection velocity.

7.46 Axial velocity along the centerline at different instants.

7.47 Axial velocity along the centerline when the transient jets approach the chamber bottom.

7.48 The variation with axial distance of inversed axial velocity along the centerline.

7.49 The linear range of the inversed axial velocity along the centerline.

7.50 Radial profiles of axial velocity at different distance from the nozzle.

7.51 Illustration of the definition of half-width.

7.52 Axial velocity against radial distance in a turbulent jet with injection velocity of 80 m/s.

7.53 Axial velocity along radial distance in a turbulent jet with injection velocity of 40 m/s.

7.54 Axial velocity along radial distance at different conditions.

7.55 Methane mass fraction along the centerline for different conditions.

7.56 Radial profile of methane mass fraction in a turbulent jet with injection velocity of 80 m/s.

7.57 Non-dimensional radial profile of methane mass fraction in the same turbulent jet in Fig. 7.56.

7.58 Non-dimensional radial profile of methane mass fraction.

7.59 Change of the half-widths on both side of the jet with the distance from the nozzle exit.

7.60 Change of spread angles of a turbulent jet at different instants since the start of injection. Spread angles are calculated based on the half radius.

7.61 2% mass fraction contours at different instants during injection. \( W_0 = 40 \)
m/s; 0 Hz; D_{inj} = 30 ms. .................................................................................................................. 227

7.62 Illustration of the calculation of the cross-angle based on the mass fraction contour line. ............................................................................................................ 228

7.63 Variation of spread angles of a turbulent jet at different instants since the start of injection. Spread angles are calculated based on the 2% mass fraction contour. ........................................................................................................... 230

7.64 Density gradient field and 0.0002 g/cm$^4$ ................................................................................ 231

7.65 Variation of spread angles of a turbulent jet at different instants since the start of injection. Spread angles are calculated based on the contour of density gradient .................................................................................................................. 232

7.66 Visualization of the flammable methane mixture across the C-plane for the transient methane injection into the quiescent chamber air with W_0 = 40 m/s; D_{inj} = 30 ms. ........................................................................................................ 236

7.67 Mass of the total injected methane and mass of the methane in flammable mixture ................................................................................................................................. 237

7.68 Changes of percentage of flammable methane with time ........................................................ 238

7.69 Changes of percentage of flammable methane with penetration depth ................................. 239

7.70 The boost of percentage of flammable methane from the impingement of jet ............................. 240

8.1 Turbulent intensity in the DI chamber center versus the oscillation frequency ....................... 241

8.2 Calculated values of C from versus the oscillation frequency .................................................. 242

8.3 Turbulence length scales from experimental measurements and numerical simulations ............ 243

8.4 Variation of turbulence micro-length scales along the C-line .................................................. 245

8.5 Variation of integral length scales with the distance between the grids at points e (node) and c (hole) for both horizontal and vertical components (extracted from Shy et al., 1997) .................................................................................. 245

8.6 Penetration depths of transient methane jets from the numerical simulations. 247

xxii

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Nomenclature

\[ A_{\text{inj}} \] Area of the injector nozzle exit [cm\(^2\)]

\[ c_p \] Specific heat at constant pressure [J/kg \cdot K]

\[ c_{\mu}, c_{\epsilon_1}, c_{\epsilon_2}, c_{\epsilon_3} \] Constant of STANDARD \( k-\epsilon \) model constant

\[ C \] Constant in turbulent intensity power decay law

\[ C_1, C_2, C_3 \] Constants in spatial evolution law of turbulence in the monoplanar mixing box experiments.

\[ d \] Diameter of the perforation hole on the perforated plate [cm]

\[ d_B \] Beam spacing [mm]

\[ D \] Injector nozzle exit [cm]

\[ D_h \] Jet maximum width [cm]

\[ D_{\text{inj}} \] Injection duration [ms]

\[ D_L \] The diameter of the beams before the pass through the lens [mm]

\[ D' \] Half distance between the grids [cm]

\[ E \] Expansion ratio

\[ f \] Signal frequency [Hz]

\[ f_0 \] Doppler frequency [Hz]

\[ f_{\text{osci}} \] (Plate or Grid) oscillation frequency [Hz]

\[ F \] Focal length [mm]

\[ H \] Distance between the grids [cm]

\[ I \] Internal energy [kJ/kg]

\[ J \] The heat flux vector
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Coefficient</td>
</tr>
<tr>
<td>$L_a$</td>
<td>Turbulence macro-length scale [cm]</td>
</tr>
<tr>
<td>$L_i$</td>
<td>Turbulence integral length scale [cm]</td>
</tr>
<tr>
<td>$k$</td>
<td>Turbulent kinetic energy [cm$^2$/s$^2$]</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass [kg]</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>Mass flow rate [kg/s]</td>
</tr>
<tr>
<td>$M$</td>
<td>Grid mesh size [cm]</td>
</tr>
<tr>
<td>$\dot{M}_n$</td>
<td>Momentum injection rate [kg-m/s$^2$]</td>
</tr>
<tr>
<td>$n$</td>
<td>The power for the turbulent decay law in oscillating grid turbulence</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of fringes</td>
</tr>
<tr>
<td>$p_0$</td>
<td>Injection pressure [MPa]</td>
</tr>
<tr>
<td>$p_a$</td>
<td>Chamber (ambient) pressure [MPa]</td>
</tr>
<tr>
<td>$P_{k_0}$, $P_{\varepsilon}$</td>
<td>Constants of STANDARD $k$-$\varepsilon$ model constant</td>
</tr>
<tr>
<td>$q$</td>
<td>Turbulent characteristic velocity (or turbulent intensity) [cm/s]</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number [-]</td>
</tr>
<tr>
<td>$R_0$</td>
<td>Universe gas constant, $R_0 = 8.314$kJ/(kmol·K)</td>
</tr>
<tr>
<td>$S$</td>
<td>(Plate or grid oscillation) stroke [cm]</td>
</tr>
<tr>
<td>$t$</td>
<td>Time [ms]</td>
</tr>
<tr>
<td>$U$</td>
<td>Velocity vector</td>
</tr>
<tr>
<td>$u$, $v$, $w$</td>
<td>Instantaneous velocity components, in x, y and z direction, respectively [cm/s]</td>
</tr>
<tr>
<td>$u'$, $v'$, $w'$</td>
<td>Fluctuation velocity components, in x, y and z direction, respectively [cm/s]</td>
</tr>
</tbody>
</table>
WO Injection velocity [m/s]
W_0(z) Velocity on the injector centerline [m/s]
W_m Molecular weight of species m [kg/mol]
y Distance from the injector nozzle centerline [cm]
z Distance from the nozzle [cm]
z_t Penetration depth of a transient jet [cm]

Greek Symbols
\( \delta_f \) Fringe spacing [\( \mu m \)]
\( \delta_m \) Mean diameter of the measuring volume [mm]
\( \alpha_{0.5} \) Spread angle based on half distance [degree]
\( \alpha_{dg} \) Spread angle based on density gradient [degree]
\( \beta \) model constant (Schulz and Chaudhry) [-]
\( \gamma \) Specific heat ratio
\( \varepsilon \) Dissipation rate [cm\(^2\)/s\(^3\)]
\( \theta \) Angle between the two laser beams of same color [degree]
\( \lambda \) Wave length [nm]
\( \nu \) Kinematic viscosity of fluid [m\(^2\)/s]
\( \rho \) Density [kg/m\(^3\)]
\( \sigma_x, \sigma_y, \sigma_z \) The dimensions of the measuring volume [mm]

Superscripts
* At choked position
+ Calculation is based on the values at \( y > 0 \)
- Calculation is based on the values at \( y < 0 \)
### Subscripts

<table>
<thead>
<tr>
<th>Subscript</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Injection reference; or Centerline</td>
</tr>
<tr>
<td>0.5</td>
<td>Point where velocity (or concentration) equals half of centerline velocity (or concentration); or based on the half distance (or radius)</td>
</tr>
<tr>
<td>1</td>
<td>Beginning of gaseous injection</td>
</tr>
<tr>
<td>3</td>
<td>End of injection</td>
</tr>
<tr>
<td>a</td>
<td>Ambient (or chamber)</td>
</tr>
<tr>
<td>i</td>
<td>Integral</td>
</tr>
<tr>
<td>ic</td>
<td>Injection cell</td>
</tr>
<tr>
<td>in</td>
<td>Incoming flow (inflow)</td>
</tr>
<tr>
<td>inj</td>
<td>Injection</td>
</tr>
<tr>
<td>int</td>
<td>Internal</td>
</tr>
<tr>
<td>m</td>
<td>Relative to species</td>
</tr>
<tr>
<td>n, n+1</td>
<td>Indication of time step;</td>
</tr>
<tr>
<td>osci</td>
<td>Oscillation</td>
</tr>
<tr>
<td>rms</td>
<td>Root-mean-square</td>
</tr>
<tr>
<td>stoic</td>
<td>At stoichiometric chemistry</td>
</tr>
<tr>
<td>S</td>
<td>With frequency shift</td>
</tr>
</tbody>
</table>
Chapter 1  Introduction

1.1  Background

Natural gas (NG) and air mixing has become a focus of many investigations (Xu and Furuyama, 1997; McDonnell and Samuelsen, 2000; Fleck et al., 2000, etc.) over the last decade. With global environmental problems being increasingly of concern, natural gas has emerged as the most promising alternative fuel for being economically viable, environmentally friendly, and compatible with existing distribution infrastructure (Weaver, 1989). At present, combustion is still the primary mode to extract energy from NG and injection is a common and effective way to bring the NG into combustion devices to initiate the mixing with combustion air and to realize different combustion modes (premixed or non-premixed). Even though NG injection has been utilized in NG-fuelled industrial furnaces and combustion engines for many years, the mixing process of NG and air streams is far from being optimized in these engineering applications (Fleck et al., 2000).

Turbulence (in both the fuel jet and combustion air flow), has been identified as a primary factor that affects mixing, even though many questions remain to be answered. For instance, in engines, the injected gaseous fuel is in the form of a transient, short-duration and relatively high momentum jet. At a very early stage of injection, high levels of the turbulence are generated near the nozzle exit by the jet shear layer. After this stage, the turbulence energy balance becomes fixed in time and the turbulent field near the nozzle remains statistically frozen. Also, during the initial stages of injection, the fuel-rich core of the natural gas plume forms along the jet axis. The formation of the core is...
driven by the initial penetration and spreading of the completely unmixed NG fuel issuing from the nozzle exit. The development of the fuel rich core is responsible for the rapid increase in the jet’s early mixing. At the same time, the outer layer of the fuel rich core is significantly influenced by the surrounding turbulent air flow. These two flows, in addition to a range of turbulent eddies, might be characterized by macro-scale organized motions, like the swirl, tumble and squish motions in combustion engines, which may distort the jet, depending on their relative movement. Turbulence length scales in such complex flow fields cover a wide range from the smallest (Kolmogorov) scale to the largest one, which in engines, for example, could vary from a fraction of the clearance height (at top dead center) to a size on the order of cylinder diameter or stroke (at bottom dead center). Turbulence intensity may also change dramatically, depending on the engine operating conditions, such as engine speed and load. The mixing between the fuel jet and the combustion air is a combined result of turbulent motions at both large and small scales. Even though many questions involving mixing in engineering devices have been addressed, a number of fundamental questions still remain unanswered. For instance: (a) how does a turbulent gaseous jet interact with ambient air turbulence that possesses different characteristics, such as turbulence intensity and length scale? (b) does ambient turbulence of different characteristics interact differently with the jet and does this make a difference in the mixture preparation? (c) are there optimal characteristics of ambient flow turbulence that promote faster mixing? Clearly, the answers to these questions will not only lead to better understanding of the interactions and mixing process between the two flows, but could also lead to changes and improvements in the design of combustion devices.
1.2 Physical Model under Study

A simple and idealized physical model was created to facilitate the analysis of the interaction between a transient gaseous jet and its surrounding (or ambient) air flow. It is illustrated in Fig. 1.1. The model consists of a transient turbulent gaseous jet of constant exit velocity spreading into a confined space that contains a zero mean velocity air flow that has uniform turbulence characteristics.

This model is a simplification of situations encountered in reality. Macro-scale organized motions are eliminated in this model and turbulent flow is simplified as being zero-mean velocity and both isotropic and homogeneous. Isotropic homogeneous turbulence is the simplest turbulence that can be characterized with only two parameters, turbulence length scale and turbulence intensity (Batchelor, 1956 and Pope, 1987). Therefore, under the present setting, the behavior of the turbulent transient jet is to be probed as it responds only to the turbulence length scale and intensity of the ambient flow.

Fig. 1.1 Transient gaseous jet spreading into isotropic homogeneous turbulent flow.
This idealized flow situation may not be directly found in real devices, but many flow situations may be close to it. For example, in compression ignition engines fuelled with gaseous fuel, the macro-scale motions decay rapidly and eventually break up into small-scale turbulence prior to and after the fuel injection (close to TDC), and the fuel-and-air mixing is more dependent on the jet and micro-scale turbulence in the air flow field.

By studying this model, the goal is to find the answers to the questions listed above. A hypothesis for this proposed work is that there is a set of optimal turbulence characteristics in a gaseous jet and its ambient flow that speed the mixing. The results could serve as building blocks to the understanding of the behavior of a transient jet in more complex flow situations like in engines, and could also help the design of engineering applications involving mixing using transient jets.

Many ongoing research projects could benefit from the study. For example, high-pressure direct injection (HPDI) natural gas technology, which is still being developed in Westport Inc., uses direct-injected natural gas as primary fuel and uses a pilot diesel fuel to promote the ignition (see Fig. 1.2). Understanding of the behavior of the transient gaseous jet under the influence of the chamber flow would help the design of the injector and the chamber.

Another example is for natural gas direct injection (NGDI) spark-ignition (SI) engines, a concept under development (Xia and Sobiesiak, 2002). In such an engine, natural gas is directly injected as fuel into the combustion chamber on the intake stroke. To fully exploit the potential benefits of such an engine, it is necessary for a NGDI engine to be operated in two distinct modes: (a) homogeneous stoichiometric operation at full load conditions, and (b) stratified lean operation for idle and low load conditions. In addition
to changes in ignition timing, both modes require much more precise control of mixture formation, which is in essence a result of interaction between a transient gaseous fuel jet, ambient turbulent flow and combustion chamber geometry.

Fig. 1.2 Schematic of a HPDI NG engine (Ouellette and Hill, 1997).

1.3 Objectives

The general objective of present work is to advance, by means of studying the idealized physical model, understanding of the interactions and mixing between a turbulent transient gaseous jet and ambient turbulent flow of zero-mean velocity in a confined space.

Even though this is an idealized scenario involving isotropic homogeneous turbulence and relatively simple geometry, the complexity of turbulence and the transient nature of the phenomena under study preclude a complete theoretical analysis. Therefore, both
experimental modeling and numerical modeling were employed in order to accomplish the objective, with a strategy that includes the following steps:

- To develop the experimental apparatus and employ diagnostic techniques.
- To experimentally characterize the ambient turbulent flow field.
- To experimentally examine the development of the turbulent transient jet in a stagnant ambient.
- To experimentally examine the development of the turbulent transient jet in the presence of the ambient flow.
- To develop a mathematical model and examine the development of the turbulence transient jet with/without the presence of the ambient flow.

1.4 Methodology

In experimental modeling, a cubic chamber of 1 liter (10 cm × 10cm × 10 cm) was selected to house the turbulent transient jet and the ambient turbulent flow. The turbulent jet was produced by an injector mounted at the center of the chamber top wall. Inside the chamber, a pair of oscillating perforated plates was used to generate the ambient turbulent flow. With carefully selected stroke, oscillation frequency and diameter of holes in the plates, this apparatus can produce a semi-homogeneous turbulence field in the central region of the chamber. The turbulence length scales and intensity were controlled by the choice of stroke and oscillation frequency.

The resulting flow field was characterized using two-component Laser Doppler Velocimetry system. The injection process was visualized by fast Schlieren motion pictures. The recorded images were processed to extract the injection characteristics such as the penetration depths and spread angles.
A numerical model of the injection and mixing was also created using a commercial CFD code, KIVA3V. This model was based on the experimental configuration, with the perforated plates and their oscillating movement closely modeled. With the numerical model, the turbulence generation process by oscillation of perforated plates, the development of the transient gaseous jet and the interactions and mixing between the jet and the ambient flow can be thoroughly investigated in a three-dimensional time-depdendant computational domain.
Chapter 2  Literature Review

The following literature review is focused on three topics that are relevant to this study. The first is on the transient turbulent jet; the second is on isotropic turbulence generated by oscillating grids; and the third is on the interaction between a turbulent jet and oscillating-grid turbulence.

2.1 Transient Turbulent Jet

Even though the structure of the steady turbulent gas jet has been studied and documented in several monographs (Pai, 1954; Abramovich, 1963; Schlichting, 1976; Rajaratnam, 1976), understanding of transient turbulent jets is much less developed. An early study conducted by Garside (1943) has captured in Schlieren photos the beginning of an impulsively started round jet issuing into a stationary fluid of the same density (see also Batchelor (1967) and List (1982)). Before the jet has moved one diameter into the fluid a head vortex appears, followed by symmetrical wave-like disturbances in the transition toward turbulence. Rizk (1958) and Lahbabi et al. (1993) have provided informative flow visualization of the subsequent transient turbulent jet behavior. Miyake et al. (1983), Chepakovich (1993), and Ouellette (1996) have measured the penetration rates of transient gaseous jets under conditions similar to those prevailing in diesel engines. Their experimental observations showed that the penetration of the fuel jets with Reynolds number of magnitude $5 \times 10^5$ is proportional to the square root of time. Turner (1959) proposed (for buoyant plumes) that the transient turbulent jet is comprised of two parts—a quasi-steady-state jet region and a vortex ball that precedes that region (refer to Fig. 2.1). Turner pictured the head vortex as being spherical, having modest
rotational momentum, and being subject to viscous and inertial retarding forces but not as entraining ambient fluid to any significant extent. The vortex ball is continuously supplied with mass and momentum by the jet which displays steady-state behavior within its region as long as the nozzle exit flow is steady. These ideas and associated force estimates have been used successfully in estimating the development of transient jets. Abramovich and Sloan (1973) applied such concepts to calculate the penetration rate of non-buoyant transient laminar jets and Witze (1980) extended the application to turbulent jets, both using momentum integral methods coupled with steady-state jet growth rate information. Ouellette and Hill (1992) applied the integral method to a turbulent conical jet sheet.

![Diagram of Turner's assumption on the transient jet.](image)

**Fig. 2.1 Illustration of Turner’s assumption on the transient jet.**

Rizk (1961) measured the penetration rate of incompressible jets. His photographs reveal that the jets reach a self-similarity expressed by a constant ratio of the jet maximum width ($D_h$) to the jet penetration length ($z_t$). This ratio was found to be $D_h/z_t = 0.25\pm0.05$. This observation was corroborated by the compressible jet data of Miyake et al. (1983). In Hill and Ouellette (1999), this self-similarity observation was used in conjunction with a momentum conservation argument to establish that the penetration of jets can be
expressed by

\[ z_t = \Gamma \left( \frac{\dot{M}_n}{\rho_a} \right)^{1/4} t^{1/2} \] (2.1)

where \( z_t \) is the jet penetration, \( \dot{M}_n \) is the momentum injection rate at the nozzle, \( \rho_a \) is the density in the chamber, \( t \) is the time from the beginning of injection, and \( \Gamma \) a constant whose value is 3.0±0.1 for turbulent jets issuing from round nozzles. For a constant nozzle exit velocity \( U_n \), \( \dot{M}_n \) can be calculated as

\[ \dot{M}_n = \rho_n \frac{\pi}{4} D^2 U_n^2, \] (2.2)

where, \( D \) and \( \rho_n \) are the nozzle diameter and exit flow density. To derive Eq. 2.1, the mass entrainment rate correlation of Ricou and Spalding (1961) was used. The jet penetration measurements of Rizk, Witze, Miyake et al., Chepakovich, and Ouellette all have the same slope of 3.0 ± 0.1 when scaled with the above ratio of momentum injection rate to chamber density. As the above-cited experimental data cover incompressible and compressible jets, including underexpanded, sonic and subsonic cases, the above expression has a wide range of applicability. The limitations are that the expression is valid only for distances greater than about 20 nozzle diameters, for free jets (no wall contact) with jet Reynolds number greater than 3×10^4 and for times shorter than the injection duration. The expression states that the penetration is not directly dependent on the injection pressure, velocity or nozzle diameter, but strictly on the momentum injection rate \( \dot{M}_n \). Eq. 2.1 can be transformed into the following form, which is often cited (for example, in Abraham et al., 1994), showing the similarity length and time scales employed:
\[
\frac{z_r}{D_{eq}} = \Gamma \left( \frac{\pi}{4} \right)^{\frac{1}{4}} \left( \frac{t U_n}{D_{eq}} \right)^{\frac{1}{2}}
\]  
(2.3)

where, \( D_{eq} \) is the equivalence diameter and is equal to \( D \sqrt{\frac{\rho_g}{\rho_a}} \).

Eqs. 2.2 and 2.3 provide a good basis for understanding the influence of many operating parameters in engineering devices on the penetration of a gaseous fuel jet. In engines, for example, the effect of cylinder pressure and temperature, injection pressure and nozzle diameter can easily be derived from Eq. 2.3. The effect of surrounding turbulence, however, has not been incorporated into the relationships above, even though turbulence has been identified as one factor affecting the behavior of a transient jet (Ouellette and Hill, 2000). This poses quite a limitation on the application of these relationships, particularly, in the engineering design process. In fact, very few attempts have been made to look specifically into the effect of ambient turbulence on the behavior of a transient gaseous jet. The present study is designed to shed more light on this question.

### 2.2 Turbulence generation by oscillating grids

Most experimental studies on isotropic turbulence have been conducted in wind and water tunnels where, either a uniform mean flow is passed through a stationary grid (Mohamed and LaRue, 1990) or a perforated plate (Liu et al., 2004), or a grid is moved through a stagnant fluid layer (Dickey and Mellor, 1980). An enclosed chamber with a single-passing perforated plate has been also adopted in efforts to investigate the effect of isotropic turbulence on combustion (Checkel, 1985; Ting and Checkel 2001). When properly designed, these configurations provide nearly isotropic decaying flow, the turbulent statistics of which can be measured using suitable techniques. Because of the
rapid decay of the turbulence generated, however, these are not suitable configurations when steady or sustainable turbulence characteristics are required in order to study the effect of turbulence on a specific flow configuration, as in this research.

**Turbulence Generated by a Single Oscillating Grid**

An alternative to water- or wind-tunnel turbulence is the oscillating-grid turbulence that is generated in a water tank by a monoplanar grid vibrating perpendicularly to its plane, as shown in Fig. 2.2.

![Figure 2.2 Schematic of an oscillating-grid mixing box (a) and the grid (b).](image)

Since Rouse and Dodu (1955) proposed the use of oscillating-grid turbulent flow to study turbulent mixing between two fluid layers in 1955, and the set-up has been commonly employed in laboratory settings to investigate the interfacial mixing in stratified fluids that widely exists in the ocean, the atmosphere, and lakes. Pioneering work in this area was conducted by Thompson and Turner (1975) and Hopfinger and Toly (1976), who explored the spatial decay of turbulence and entrainment across salinity interfaces.
Similar experiments have also been performed to study the free-surface affected turbulence and the gas transfer processes at the gas/water interface (Brumley and Jirka, 1987; Jirka, 1991). In addition, Brunk et al. (1996) considered that grid-generated turbulence, as a self-contained system, is particularly suitable for studies in environmental engineering because it provides an ideal environment for the investigations of physical and chemical processes of pollutant dispersion over long time spans, which would otherwise require an unacceptably long channel in a conventional flume-type system.

Compared with turbulence in boundary layers and open channels, the turbulence generated by an oscillating grid is considered to be theoretically simpler, since it is characterized by zero mean velocity and can be assumed to be homogeneous. However, such grid-induced turbulence is also complex through obvious influences by the shape and size of the grid, and the stroke and oscillation frequency of the grid oscillation. Many attempts have been made to characterize such a turbulent field. The early measurements of grid-induced turbulence were performed with a hot-film probe mounted on a spindle, which rotated in a plane parallel to the grid (Thompson and Turner, 1975; Hopfinger and Toly, 1976). Laser-based techniques such as Laser Doppler Velocimetry (McDougal, 1979; De Silva and Fernando, 1992), ADV (Brunk et al., 1996), Particle Image Velocimetry (PIV) (Lyn, 1997) and Digital Particle Image Velocimetry (DPIV) (Cheng and Law, 2001) have also been employed. In general, it has been found that at sufficiently large distances from the grid, the spatial evolution laws of turbulence for the configuration shown in Fig. 2.2(a) and the grid shown in Fig. 2.2 (b) are given by (Hopfinger and Toly, 1976; De Silva and Fernando, 1993)
\[
\left( \overline{u'^2} \right)^{1/2} = C_1 M^{1/2} S^{3/2} f_{osci} z^{-n} \quad (2.4)
\]
\[
\left( \overline{w'^2} \right)^{1/2} = C_2 \left( \overline{u'^2} \right)^{1/2} \quad (2.5)
\]
\[
L_i = C_3 z, \quad \text{and} \quad (2.6)
\]
\[
\overline{u'v'} \approx \overline{u'w'} \quad (2.7)
\]

where, \(u', v', w'\) are the fluctuation velocity in x, y and z direction, respectively; \(M\) is mesh size defined as the distance between the centers of two neighboring openings, \(f_{osci}\) is the grid oscillating frequency (in Hz), \(S\) is stroke, \(L_i\) is integral length scale of the turbulence, \(z\) is distance measured from a virtual origin near the mid-position of the grid, and \(n\) is equal to 1; \(\overline{u'v'}\) and \(\overline{u'w'}\) are the Reynolds stresses and \(C_1\), \(C_2\), and \(C_3\) are constants that may depend on the geometric parameters of the grid. The measurements of Atkinson et al. (1987) indicate that Eqs. 2.4 and 2.5 are valid beyond about two mesh sizes away from the grid, whereas De Silva and Fernando (1992) found that, for smaller strokes, these relationships are valid beyond about four stroke lengths. McDougal (1979) found that the turbulence generated with a 1-cm stroke was far from homogeneous in the horizontal plane. His results also showed that the upper limit of the oscillating frequency was approximately 7 Hz, above which a large circulating motion occurred and the \(\left( \overline{u'^2} \right)^{1/2}\) values were no longer linearly related to the oscillation frequency. To reduce the possibility of induction of a mean secondary circulation, Fernando and Silva (1993) demonstrated that the solidity of the grid in the mixing box experiments should be less than 40% and proper end conditions of the grid are also required.

Hopfinger and Toly (1976) concluded that the turbulent kinetic energy \(k\) decays approximately with \(z\) according to a power law \(k \propto z^{-2}\) and that the turbulent Reynolds
number, defined as \((u'^2)^{1/2} \cdot L_i / \nu\), where, \(\nu\) = kinematic viscosity of fluid, remains approximately constant during the decay.

To maximize the agreement of the measurements with the proposed power law, both Thompson and Turner (1975) and Hopfinger and Toly (1976) adopted a virtual origin instead of the mid position of the grid when measuring the distance \(z\). Thompson and Turner reported that the virtual origin should be generally below the grids, with 1 and 2 cm for the square-barred and round-barred grids, respectively. In comparison, Hopfinger and Toly defined the virtual origin as the height in the fluid where the integral length scale became zero, which was computed to be slightly below the mid position. Generally, the power \(n\) in Eq. 2.4 is very sensitive to the position of the virtual origin. In fact, various values of the power \(n\) have been reported in the literature (Cheng and Law, 2001).

Brunk et al. (1996) used five horizontally oscillating grids to simulate the hydro-dynamic and chemical processes associated with pollutant dispersion in aquatic environments. Despite the very different grid arrangement, their results on the turbulence kinetic energy are close to those obtained earlier by Hopfinger and Toly (1976). Lyn (1997) measured the oscillating-grid turbulence using the PIV technique and reported that the spatially averaged characteristics agreed with previous work, while the time-averaged results at a single section implied strong and persistent large-scale motion.

In summary, for a given value of \(z\) that was at least two mesh sizes away from the single grid, turbulence was homogeneous in the vertical plane (for the configuration similar to Fig. 2.2), in that the ratio of turbulent intensity of the vertical component to that of the horizontal component was typically in the range of 1.1-1.3 and mean velocities were
approximately zero. However, such a flow is only roughly isotropic in the horizontal plane and turbulent intensities decay rapidly as the distance away from the grid increases \((u'^2)^{1/2} \sim z^{-1}\).

**Turbulence Generated by a Pair of Oscillating Grids**

To amend the spatial decay of \((u'^2)^{1/2}\), Srdic et al. (1996) and Shy et al. (1997) applied a pair of monoplanar grids oscillating in homogeneous fluid to generate a nearly isotropic stationary turbulence in the core domain. Srdic et al. used a configuration shown in Fig. 2.3 and measured the velocity field between the two grids up to \(x/D' = 0.4\). The results are shown in Fig. 2.4 and Fig. 2.5. In Fig. 2.4 the normalized root mean square velocity \((u'^2)^{1/2}\) and \((w'^2)^{1/2}\) measurements along x axis for two different frequencies are presented, with the distance normalized by the half distance between the grids \(D' (=22\text{cm})\) and the velocity scaled by \(f_\text{osc}^2S\). The data from the single grid oscillations are also shown in the graph, with the dashed line for \(u\) component and the solid line for \(w\) component.

![Schematic diagram of the experimental apparatus used by Srdic et al. (1996)](image-url)

Fig. 2.3 Schematic diagram of the experimental apparatus used by Srdic et al. (1996)
Fig. 2.4 Plot of the non-dimensional rms velocities $\left( \frac{u'^2}{f_{osc}} \right)^{1/2}$ and $\left( \frac{w'^2}{f_{osc}} \right)^{1/2}$ vs. normalized distance $x/D$: $f_{osc}=3$ Hz, $S=2$ cm, $M=5$ cm, $\bigcirc$; $f_{osc}=4$ Hz, $S=2$ cm, $M=5$ cm, $\bigcirc$; $f_{osc}=4$ Hz, $S=2$ cm, $M=5$ cm, $\square$; $f_{osc}=3$ Hz, $S=2$ cm, $M=5$ cm, $\triangle$. (Measurements were made along the x axis) (Srdic et al., 1996)

Fig. 2.5 Measurements were made along the z axis, which show approximated vertical homogeneity in the central region of the tank. $\bigtriangleup$ $f_{osc}=4$ Hz, $x/D=0.2$; $\bigcirc$ $f_{osc}=3$ Hz, $x/D=0.0$; $\square$ $f_{osc}=4$ Hz, $x/D=0.0$; $\bigcirc$ $f_{osc}=3$ Hz, $x/D=0.2$. (Srdic et al., 1996)
The two spatially decaying velocity fields of individual grids interacted to yield a nearly homogeneous field in the middle part of the tank. An unusual amplification in $\langle w'^2 \rangle^{1/2}$ was noticed when both grids were in motion (see Fig. 2.4). The possible explanation for this is the "stagnation effect" of the flow. Each grid produces a bias effect in the $u$ direction (the direction of oscillation) and these effects are compensated when both grids are in use. During this interaction, stagnation-point type flow could be generated, enhancing the $w$ component. Vertical $z$ distribution of the $\langle w'^2 \rangle^{1/2}$ component at $x/D'=0$ and $x/D'=0.2$ was shown in Fig. 2.5, which demonstrated the vertical homogeneity surrounding the middle region between the grids.

In their experiments, the integral length scales were not measured. But they reported that the length scale $l$, which was calculated by $\langle u'^2 \rangle^{1/2} \cdot \tau$, is uniform in the central region of the tank, with $l=0.1D'$, where $\tau$ is the integral time scale.

Through extensive LDV measurements, Shy et al. (1997) studied the nearly isotropic turbulence field formed in the region between a pair of vertically oscillating grids. The configuration of the set-up is shown in Fig. 2.6. Shy et al. (1997) concluded that the turbulence flow field generated by a pair of vertically oscillating grids could be distinguished as having two distinct flow regions. The first is the highly turbulent flow region near each grid in the form of turbulent wakes with flow characteristics similar to that of the one-grid turbulence. At $1 < z/M < 2$, the power constant of the velocity decay law had two different modes, $n = 2$ at the grid bar intersections (node) and $n = 1$ at the center of the grid mesh (hole). Shy et al. argued that this also might be the reason for the discrepancy between the velocity decay laws found by different researchers. As $z/M > 2$,
the difference between nodes and holes tends to vanish, and values of the effective turbulent intensity could be fitted into a form

\[ q \approx 0.25 f_{osc} S^{1.5} M^{0.5} z^{-n}, \tag{2.8} \]

with \( n = 1.5 \) rather than 1, where, \( q \) is overall energy-weighted (effective) turbulence intensity at a fixed horizontal plane and is defined as

\[
q = \left( \frac{1}{N} \sum_{i=1}^{N} \left( \frac{u_i'^2 + u_j'^2 + w_i'^2}{3} \right) \right)^{1/2}, \tag{2.9}
\]

where, \( N \) is the number of measurement points in one horizontal plane. The second flow region is a nearly isotropic stationary turbulent flow field located in the core between the two grids. It was also found that there is a linear relationship between the height of
second flow region and $H$, the distance between grids, thus another form of velocity
decay law in the region of nearly isotropic stationary turbulence was proposed as

$$q = 0.89 f_{osci} S^{1.3} M^{0.3} H^{-1.5}.$$  \hspace{1cm} (2.10)

According to Shy et al., Eq. (2.10) is most valid in the range of $4 < H/M < 6$, which
reveals an optimum arrangement for obtaining a high degree of isotropy in the flow with
conditions $f_{osci} = 1 \sim 8$ Hz and $S/M = 2/3$. From these velocity measurements, it was
cailed that the energy released in the system per unit time by each grid can be
directly additive, in support of the Villermaux et al. (1995) prediction, i.e.

$$u'_{eff} = 2^{1/3} u_{rms},$$ \hfill (2.11)

where, $u'_{eff}$ was the effective turbulent velocity for two grids, and $u_{rms}$ was the
characteristic turbulent intensity for one grid such as the one given by Eq. 2.4.

For turbulence length scale, Shy et al. calculated the integral length scale $L_i$ by

$$L_i = \sqrt{8 \tau / \pi \cdot u'_{eff}},$$ \hspace{1cm} (2.12)

where, $\tau$ was the integral time scale. It was found that, $L_i$ is independent of $f_{osci}$ for $H = 10$ cm. This is because the integral time scale was found to be inversely proportional to
the grid oscillation velocity $f_{osci} \cdot S$, whereas the overall turbulent intensity proportional
to $f_{osci} \cdot S$. Also it was found that values of $L_i$ increase linearly with $H$, but there was no
definite relationship given, and it was not clear why $L_i$ for single grid is larger than that
for two grids.

In summary, the turbulence in the central region for the two-grid configuration displays
the characteristics of nearly isotropic and homogenous turbulence. The turbulent velocity
decay law has been identified, as given in Eq. 2.10. However, all these results were
obtained in the set-ups with water as working fluid. In this study, the transient jet and its ambient fluid are gaseous, and re-evaluation of the turbulent velocity decay law (Eq. 2.10) has to be carried out.

2.3 Interaction between Turbulent Jet and Grid Turbulence

While many investigations have been carried out either on turbulent transient jets or grid turbulence, there has been no research, to the author’s knowledge, about the influence of oscillating-grid turbulence on behavior of a transient jet. In fact, only a few attempts have been made to study the interaction between a steady turbulent jet and the turbulent flow generated by a single oscillating grid.

Ching et al. (1995) considered the effect of background turbulence on the breakdown of a buoyant line plume, which is usually detected by the abrupt change of the spread angle. Law et al. (2001) reported the preliminary experimental data on spreading of a round jet in oscillating grid turbulence. Their set-up is reproduced in Fig. 2.7. A vertical jet was produced through the nozzle with its exit 50 cm away from an oscillating grid. PIV was adopted as the measurement technique and a square of 10cm x 10 cm was taken as the recorded area, which was about three mesh sizes away from the grid.

The jet spread along the nozzle centerline is shown in Fig. 2.8. In the graph, z denotes the distance measured from the jet virtual origin and b is the spread of the jet, which is defined as the radial distance where the velocity drops to $e^{-1}$ of the centerline value. A reference line based on a classical linear expansion of a jet in a still ambient fluid is shown for comparison. The figure shows that initially, the jet spreads at a rate similar to that of a jet in a still ambient fluid, and the influence of the ambient turbulence becomes notable further downstream where the spreading rate increases significantly. This occurs
Fig. 2.7 Schematics of the experimental set-up used by Law et al. (2001). Imaged location was shown with dashed line.

Fig. 2.8 Jet spread as a function of downstream distance. (Law et al., 2001)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
at approximately 50 nozzle diameters downstream from the source, although the data indicates that the behavior of the 1.27 m/s (nozzle exit velocity) jet changes before that of the 1.41 m/s jet. Additional results show that with ambient turbulence fluctuations about 10-20% of those expected at the jet centerline with a quiescent ambient fluid, the axial mean velocity profile of the jet was found to remain essentially Gaussian, even as the jet approached the grid.

With a similar set-up (shown in Fig. 2.9) to the one used by Law et al., Guo et al. (2005) further attempts to relate the position at which this disruption of the spreading of the turbulent jet occurs to (i) the jet flow parameters and (ii) characteristics of the grid turbulence. They suggested that the evolution of a free turbulent jet is destroyed when the local rms velocity of the background turbulence exceeds about 0.44 times of that of the

---

**Fig. 2.9** Schematics of the experimental set-up by Guo et al. (2005).
incident jet and this is valid for a wide range of source Reynolds number, including
values for which the jet is not fully turbulent.

The investigations above provide some good references on studying the interaction of a
turbulent jet and oscillating-grid turbulence. However, their focus was on the breakdown
process of the evolution of the turbulent jets, which were all steady-state, and they did not
provide any information about the behavior of a transient jet, such as its penetration depth
or spread angle.
Chapter 3  Experimental Modeling

3.1 Introduction

Experimental modeling is a primary tool for scientific research. By examining, under controlled conditions, the processes or phenomena with similar physics to those in reality, one can advance the knowledge of those processes in real world applications.

For this research, an experimental model is needed through which the behavior of a transient turbulent gaseous jet and its interaction with ambient flow of zero mean velocity, turbulent or non-turbulent, in a confined chamber could be carefully examined with available scientific instruments. In order to achieve this, the following features should be implemented in this model:

- the model should be housed in a confined space designed to accommodate the following physical phenomena;
- a transient gaseous jet of controlled duration;
- a background ambient turbulent flow with zero mean velocity and variable turbulence characteristics;
- optical accessibility.

An easy option for the design of confined space was a cylindrical chamber. Because of its geometric resemblance to an engine cylinder, the results obtained from such a chamber also had potential for immediate application in engines. However, the curved cylindrical perimeter acts as a lens and distorts the pathway of beams of light such as laser beams, preventing the use of laser-based measurement technique. For this reason, a cubic chamber was chosen. A chamber of cubic shape is also easy to be fabricated.
In order to realize transient gaseous injection, a commercially available gaseous fuel (natural gas) injector was adopted in this research. It was rugged, robust and easy to control. The gas intended for injection was stored in a gas tank at a certain pressure and introduced to the injector through flexible tubing. The injector’s electric terminals were connected to a power supply, which was integrated with a computer-based timing control circuit. At each experimental trial, a controlled short-duration digital signal was generated by the timing control circuit and amplified by the power supply; it then triggered the injector to open its nozzle for the specified length of time, during which the gas, driven by the pressure difference across the injector, was forced through it, forming a transient gaseous jet. By adjusting the pressure in the gas storage tank, the injection velocity was changed.

The turbulent flow of zero-mean velocity with controlled turbulence characteristics inside the chamber was generated by a pair of perforated plates oscillating against each other. The change of turbulence intensities was achieved by running the perforated plates at different frequencies. The change of turbulence length scales was done by use of separate plates with different sizes of perforation holes. Obviously, a driving mechanism was needed for running the plates. For this research, pneumatically operated cylinders were chosen for this purpose. Like the injector, the pneumatic cylinders were also controlled by a computer-based control circuit. These computer-controlled pneumatic cylinders deliver precise motion in terms of oscillation frequencies and strokes. In addition, pneumatic cylinders could be stopped quickly without use of external forces, a crucial advantage over other mechanically operated mechanisms in injection sequence control.

To control both the movement of the pneumatic cylinders and the injection duration and
timing, LabView programs were written and used. The diagnostics approaches for the study of transient jet injection and the interaction of the transient jet with the surrounding turbulent flow included both a Laser Doppler Velocimetry (LDV) system and a Schlieren imaging system. A two-color, two-component LDV system was utilized to characterize the turbulent flow field in the chamber before injection; Schlieren, an optical visualization technique, was employed together with a fast CCD camera for imaging and recording the injection process. A Windows®-based image-processing software package was used for extraction of information from the recorded movies about the penetration rate and spread characteristics of the transient gaseous jets.

To facilitate the LDV measurement of turbulent flow inside the 3-D domain of the cubic chamber, a traverse system was utilized that allowed positioning of the chamber. The LDV transmitting probe was kept at a fixed position. By moving the cubic chamber through the traverse system, most of the 3-D cubic space inside the chamber was accessible to the LDV measuring volume.

A photograph of this integrated setup for experimental modeling is shown in Fig. 3.1. With its position occupied by Schlieren Imaging System, the LDV system is not shown in the picture. This chapter is focused on description of the design and operation of the experimental set-up. Items described in this chapter include:

- Constant volume chamber
- Perforated plates and pneumatic drive system
- Gas injection system and injection timing control
- Traverse system
3.2 Constant Volume Cubic Chamber

The constant volume cubic chamber (or the cubic chamber, or the chamber, hereinafter) was the main component of the experimental setup. It provided a confined space in which the physical phenomena under study were accommodated. This space defined both the physical domain for the measurements and the geometrical configuration to be modeled in numerical simulations.

The original design of the chamber can be traced to Iskender and Lock (1999). It was fabricated in Mechanical Engineering Department of University of Windsor as final year project. The original design was heavily modified to fit our research purposes, with in
particular components for transient injection and motion control added, and an improved sealing mechanism employed. An exploded view of the chamber is shown in Fig. 3.2.

The chamber is comprised of three blocks: the center block is 17.2 cm $\times$ 17.2 cm $\times$ 10 cm, and two side blocks of 17.2 cm $\times$ 17.2 cm $\times$ 4 cm hold two quartz windows of 12.4 cm $\times$ 12.4 cm $\times$ 2 cm. An opening of 10 cm $\times$ 10 cm was cut through both the center block and side blocks, so when bolted onto the center block, the two side blocks clamp the quartz windows onto the center block, enclosing an inner cubic volume of 10 cm $\times$ 10 cm $\times$ 10.0 cm. These two quartz windows allow for optical access to the chamber interior.

As mentioned above, the thickness of the walls is 3.6 cm and the thickness of the quartz windows is 2.0 cm. These dimensions were determined so that the chamber was able sustain a maximum pressure of 2.8 MPa and temperature of 3000K during combustion. A
design factor of 6.0 based on yielding was included in Iskender and Lock's calculation. Combustion was their primary research objective for this device. Even though study of combustion was not part of this research, it can be a direct follow-up in view of the fact that investigation into transient jets is, in fact, about mixing processes similar to those in preparation for combustion. Therefore, combustion was always under consideration when components were added, with sealing examined with the thought that pressure measurement was crucial in combustion analysis.

Fig. 3.3 illustrates two sectional views of the cubic chamber. Some functional elements are also shown in the figure. There are two perforated plates inside the chamber, each of them attached to a shaft of a pneumatic cylinder, which is in turn mounted on the chamber sidewall. The pneumatic cylinders and their control circuit are the so-called motion drive system and details of this system are presented in Section 3.3.

On the same walls that the pneumatic cylinders are installed, two ignition electrodes are mounted as well. They could be used for the ignition of flammable mixture inside the chamber if combustion were to be investigated. The electrodes were sealed in the insulation blocks, which were made of high temperature resistant polymer. The ends of the electrodes were threaded, thus by turning the electrodes, the gap between the electrodes could be adjusted. Since combustion was not involved in this work, the distance between electrodes was set to 4.0 cm. This distance was large enough to prevent the interference of the electrodes with the oncoming jets.

On top of the chamber, the injector, a venting valve and a four-way valve are shown in Fig. 3.3. A pressure transducer is another component installed on the chamber top wall but not depicted in the sectional views. The position of its mounting hole is shown in the
Fig. 3.3 Two sectional views of the cubic chamber.
picture in Fig. 3.4. This was again in preparation for the future combustion research.
Details of the design for the mounting hole, which was prepared for a pressure transducer
of Model Kistler 6051B1, are included in Appendix A. During this research, the
mounting hole was filled with a stopper identical in dimensions to the real pressure
transducer.

The injector is located in the center of the top wall of the center block (see Fig. 3.3a and
3.4). Details of the injector and its installation are reviewed in Section 3.4, together with
other components of the gas injection system. In the following, the venting valve and the
four-way valve are described in detail. They are grouped together as “aspirating valves”
for serving the same function: to prepare the chamber for a fresh charge in each
realization of the injection experiment.

![Fig. 3.4 Picture of components on top of the chamber.](image)

**Aspirating valves**

In this work, different injected gases and chamber gases were used. When a different
chamber gas was to be used for the next injection trial, the chamber gases from the
previous trial had to be purged. In addition, during the trials with the same chamber gas (or chamber charge), fluctuations in operating conditions such as injection pressure or injected gas temperature may occur. These fluctuations affect the behavior of the transient gaseous jet and therefore the measurement results. In order to reduce the uncertainties from these fluctuations, experiments under the same nominal conditions were repeated, allowing for averaging of the measurement results. To repeat the experiments at the same conditions for the next injection sequence, the content of the chamber after each trial were purged and then fresh charge was admitted.

The venting valve acted like an exhaust valve in an engine, providing a passage for the chamber gases after injection or the flushing gas to vent out of the chamber. It directed these gases through plastic tubing to a venting fan installed on the laboratory ceiling. Whenever flammable or toxic gases were used, the venting fan was kept running throughout the experiment periods for safety. The venting valve was simply an industrial quarter-inch ball valve. Details of the design of the mounting hole are included in Appendix A.

The four-way valve was mounted above another corner of the cubic space, with its three ports connected, respectively, with a compressed air supply line, a storage bottle for intended chamber charge other than air, and a vacuum pump.

Air was the most frequently used fluid in this research, both as the chamber charge and flushing gas, and it was supplied from a compressed air line, which runs through the laboratory at rated pressure of 6 bars, and is regulated through a ball valve.

A number of other gases were also used in this study, including helium, carbon dioxide, propane, methane and hydrogen. These gases were stored in separate bottles at very high
pressure. When used as chamber charge, the gases were first regulated to a lower pressure of 0.5 bars (gauge pressure) through the regulator installed on the bottle and then connected to the four-way valve.

To prepare a fresh charge to the chamber, the venting valve was kept open while the intended chamber gas was flowing in. This operation usually lasted for about 30 seconds. To further reduce the residual gases from the last experimental trial, continuing operation included alternate closing and opening of the venting valve 10 times over, thus the chamber underwent reciprocal buildup and release of pressure from the intended chamber charge. This procedure was followed consistently through the research whenever the fresh charge was needed.

A vacuum pump was connected to the four-way valve to partially remove the combustion exhaust in the scenario that combustion was to be studied. If combustion were studied, it could be required that only part of combustion products be removed from the chamber, in situations such as research into Exhaust Gas Recirculation (EGR) in engines.

The fourth port of the four-way valve was blocked by a plug and it was switched to shut off the chamber’s connection to the other three ports after the chamber was filled with fresh charge.

3.3 Perforated Plates and Pneumatic Drive System

In order to generate an isotropic homogeneous turbulent flow of zero mean velocity in the chamber, a pair of oscillating perforated plates was used. The function of the pneumatic drive system was to provide a controlled motion, oscillation frequency and stroke of choice, to the perforated plates.
The initial design option was based on a motor (see Fig. 3.5), similar to the system used in research in water tank (Shy et al., 1997). Through a disk and a connecting rod, the rotational motion from the motor was converted to linear reciprocal motion. The oscillation stroke could be varied by adjusting $r$ and the oscillation frequency by the rotational speed of the motor. Such a configuration, however, would present some problem if combustion were involved.

In order to have accurate measurements of pressure for study of combustion processes, the chamber would need to be sealed properly. With the sealing materials properly implemented, large friction forces would be exerted on the reciprocal shafts and a large motor of high torque would be required to drive the system. It would be extremely difficult, however, for the large motor to stop quickly (within a fraction of second) as the plates reached their required positions (at the walls), which was crucial for the determination of elapse times of decaying turbulence. To achieve this quick stopping, a mechanical braking system would have to be implemented on the system. This would dramatically increase the complexity of the whole system, considering the extra need for

---

Fig. 3.5 Schematic of a drive system commonly used in previous oscillating grid turbulence research.
controlling the braking system in addition to the motor.

A pneumatic drive system based on pneumatic cylinders provided unparalleled advantages over the above system and its inherent limitation. First, one needed only to consider the design of sealing between the pneumatic cylinders and the chamber walls, which was much easier than that for the reciprocating shaft, due to the industrially proven sealing design between the shaft and cylinder body. In addition, with the pressurization of the cylinders there would be fewer tendencies to leak during combustion due to the smaller pressure difference across the cylinder sealing. Second, the pneumatic cylinders were able to be stopped quickly without external forces, even when running at high speed.

**Perforated plates**

Two sets of perforated plates were designed and fabricated for this research. One set had perforation holes of 1.0 cm diameter and the other set had perforation holes of 0.3 cm diameter. They are referred to as the ‘1.0 cm plates’ and the ‘0.3 cm plates’, hereinafter. Both sets of plates were made of aluminum, with width × length of 9.8 cm × 9.8 cm. A sketch and a picture of the 1.0 cm plate are included in Fig. 3.6. The detailed drawings of both plates are appended in Appendix A.

The distance between two adjacent holes on the 1.0 cm plate is 1.2 cm. This gives a nominal solidity of 37%. The nominal solidity is defined as the shaded area within the triangle divided by areas of the triangle (see Fig. 3.6 (b)), which in this case, is equal to

\[
\text{The area of the triangle } - 3 \times \text{area of the sector} \\
\frac{\text{Area of the triangle}}{\text{Area of the triangle}} = 37\%
\]
Fig. 3.6 Design of the 1.0 cm plate. (a) Sketch drawing; (b) Geometry for calculation of solidity; (c) modified central hole; (d) A solid design image of the plate with ribs clearly shown.
The above calculation does not account for incomplete triangles at the edges of the plates. Thus the solidity with all the edges considered is somewhat different from the nominal one. For the 1.0 cm plate, the solidity for the whole plate is 38.2%. This is in agreement with one of the design criteria for oscillating grids, that is, the solidity of a grid should be less than 40 % (De Silva and Fernando, 1993). The same design criteria were applied to the 0.3 cm plates. This leads to a distance between two adjacent centers of holes of 0.37 cm. A picture of the 0.3 cm plate is shown in Fig. 3.7.

![Fig. 3.7 Photo of the 0.3 cm perforated plate.](image)

The mesh size, \( M \), of a grid is an important parameter in oscillating-grid mixing-box experiments. For perforated plates, \( M \) is referred to as ‘plate mesh size’ and is defined here as the distance between the centers of two solid parts located between three aligned holes (refer to Fig. 3.6 (a)). It can be easily derived that \( M \) is also equal to the distance of two adjacent centers of holes for the perforated plates used in this work, i.e., \( M \) is equal to 1.2 cm for the 1.0 cm plates and 0.37 cm for the 0.3 cm plates.

The thickness of the 1.0 cm plates is 0.2 cm. In order to fortify their rigidity, ribs of 0.2 cm high were added along the edges and across the middle during fabrication. The
thickness of the 0.3 cm plates was kept 0.4 cm (see Fig. 3.7). The center area of the plate was modified to provide junction points to the pneumatic cylinder shaft (Fig. 3.6(c)). When assembled together with the cylinder, the plates were able to move close to the walls with a 0.1 cm clearance.

**Pneumatic drive system**

A schematic of the pneumatic drive system is shown in Fig. 3.9. The system is composed
of the components linked by the compressed air line, a computer-integrated control circuit and the related LabView control program. The components linked by the compressed air line include a pressure regulator, a compressed air reservoir, two proportional valves and two pneumatic cylinders. The compressed air from the laboratory pipeline first goes through a pressure regulator, where, it is filtered and regulated to 4 bars. The compressed air then enters the compressed air reservoir, a cylinder of 76 cm in length and 6 cm in diameter. The reservoir reduces the pressure fluctuations when the air flow rate passing the reservoir is high at high oscillation frequency (above 12Hz). From the reservoir, the compressed air is directed to two proportional valves, and from there it is delivered to the pneumatic cylinders, with its direction and flow rate regulated by the proportional valves, which are controlled by the LabView control program.

Double-ended pneumatic cylinders, of type FESTO DSNU-25-41-P-A-S2-SA, and two 5-way 3-position directional proportional valves, of type FESTO MPYE-5/3-1/8-HF-010B, were selected and they were the key components in delivering the desired motion. Their working principle is illustrated in Fig. 3.9. The proportional valve has 5 ports. Port 2 and 4 are connected at all times to the left (L) and right (R) ports on the pneumatic cylinder, respectively. Port 1 is connected with the compressed air reservoir and ports 3 and 5 are exhaust ports, which are directly connected with the atmosphere. At working position (a) (see Fig. 3.9 (a)) of proportional valve, ports 1 and 2 are linked together and so are ports 3 and 4. Thus the compressed air enters the left side compartment of the pneumatic cylinder and pushes the piston to the right; At work position (b) (see Fig. 3.9 (b)) of the proportional valve, ports 1 and 4 are linked together and so are ports 2 and 5, thus the compressed air enters the right side compartment of the cylinder, moving the piston.
Fig. 3.9 Principle of proportional valves and pneumatic cylinders.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
and the shaft to the left; At working position (c), all the ports of the proportional valve are disconnected from one another, thus the cylinder shaft is kept still. By switching the proportional valve working positions between (a) and (b), the pneumatic cylinder shaft oscillates.

Switching between the three working positions of the proportional valves is controlled by an input analog voltage signal, between 0 ~ 10 V, to the proportional valves. The voltage of this signal is called the set-point voltage. Fig. 3.10 shows the positions and air flow rate as a function of set-point voltage.

![Diagram of proportional valve working positions and air flow rate as a function of set-point voltage.](image)

Fig. 3.10 Proportional valve working positions and air flow rate as a function of set-point voltage.

For precise motion control of the pneumatic cylinder shafts, a linear potentiometer was mounted at the end of each pneumatic cylinder (see Fig. 3.8). The potentiometer, proportional valves, a properly configured power supply and a computer constituted a closed-loop control circuit, which is illustrated in Fig. 3.11. A multifunctional data acquisition card (NI-DAQ PCI-6036E) and the terminal box shown in Fig. 3.8 were used.
as the interface between the computer and the power supply, and they were treated as the computer peripheries and are not shown in this schematic.

![Diagram of the closed loop control circuit](image)

**Fig. 3.11 Schematic of the closed loop control circuit.**

The computer with its periphery devices was the central element in this control circuit. It read, at very short intervals (between 2 ~ 10 ms, depending on the setting on sampling rate in the control program), the position signals of the cylinder shafts from the potentiometers, and fed them into the LabView control program for processing. The set-point signals were calculated by the program based on a PID algorithm, and then fed to the proportional valves after amplification by the power supply. This closed-loop circuit ensured a steady output motion from the pneumatic cylinders according to the pre-set parameters in the LabView control program.

**Control program**

The LabView control program was the heart of the motion drive system. A great deal of effort was devoted to the programming, with a number of control schemes tested. The completed program incorporates a PID real-time control scheme. Fig. 3.12 shows the
LabView program visual interface (front panel). The block diagrams (a graphical source code) of this program are documented in Appendix B. The parameters that were often changed for different intended motions are listed in Table 3.1, together with their functions. A real-time display of PID outputs from both channels (i.e., the set-point signals sent to the power supply for controlling both proportional valves) was incorporated in the visual interface, together with a real-time display of 'process variables', which were the displacement signals read from the potentiometers and reflects the movement of the pneumatic cylinder shafts. From the display of the process variables, the stroke of oscillation could be calculated by subtracting the minimum value from the maximum value on the graph, which was quite stable once the appropriate values in Table 3.1 were reached. For example, the readings displayed in Fig. 3.12 show the

![Visual interface of the LabView control program.](image)

Fig. 3.12 Visual interface of the LabView control program.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Entry in the Visual interface of the LabView program  | Function
---|---
Frequency (Hz)  | Sets the intended output oscillation frequency ($f_{osc}$) of the perforated plates.
Sampling rate (Samples/s)  | Determines the execution speed of the control loop and needs to keep up with the oscillation frequency to ensure precise motion outputs.
Set Point Max. and Min.  | Control the stroke of the oscillating plates.
P. I. D. tuning parameters  | Control the shape of the profiles of the oscillation motion (the intended shape is sinusoidal). Two tuning parameter columns (left and right) to control two pneumatic cylinders separately.
Number of cycle to stop  | Sets the number of oscillation cycles for the perforated plates before stopping.

Table 3.1 Parameters for generating intended motion.

stroke of 2.694 cm, which is equal to 3.107 minus 0.413.

As pointed out in Table 3.1, the desired oscillation frequency was set through the value of ‘Frequency’ ($f_{osc}$) in the LabView program front panel. However, at the same oscillation frequency, in order to have a different stroke, the P, I, and D parameters and the Set Point Max. and Min. values on the front panel had to be determined through a trial and error method. As an example, Table 3.2 lists the input parameters for output motion with a frequency of 8 Hz and stroke of 2.5 cm.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>2.40</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.4250</td>
<td>-0.379</td>
</tr>
<tr>
<td>I</td>
<td>-0.88007</td>
<td>-0.72774</td>
</tr>
<tr>
<td>D</td>
<td>-0.00020</td>
<td>-0.00040</td>
</tr>
</tbody>
</table>

Table 3.2 Input parameters for output motion with frequency of 8 Hz and stroke of 2.5 cm.

As listed in Table 3.2, ‘Number of cycles to stop’ was incorporated as an input parameter in the LabView program. This is a good feature, particularly during the design stage, when the minimum number of oscillation cycles of the plates is not determined.

During determination of the PID parameters for a certain stroke, efforts were taken to keep a space of 0.4 cm in width between a plate and its closest wall during oscillating of the perforated plates. Fig. 3.13 illustrates the plate positions when stroke of 2.5 cm is intended. This space acted like a cushion and helped smooth the running of the pneumatic cylinders by preventing collisions between the plates and the chamber walls when, if any, fluctuations of the oscillating motion occurred. In addition, it helped reduce the secondary flows inside the chamber (De Silva and Fernando, 1993).

From now on, the positions where the plates are closest to the chamber center are referred to as ‘inner limit positions’ and the positions where the plates are closest to the chamber walls are referred to as ‘outer limit positions’. These positions are shown in Fig. 3.13. As one can see from the discussion above, the inner limit positions do change for different
values of stroke, whereas, the outer limit positions do not change for any value of the stroke.

![Diagram of plate positions](image)

**Fig. 3.13 Illustration of the plate positions for stroke S = 2.5 cm.**

Limited by the maximum running speed of the computer and the data acquisition card, the motion drive system was able to deliver oscillations to the perforated plates at any stroke between 1.0 cm and 4.0 cm and any frequency less than 25 Hz. Table 3.3 lists the oscillation frequencies and strokes that were carefully tuned. The input parameters for all these cases are documented in Appendix B.

In Fig. 3.13, the plate neutral planes are also shown. These are the planes that are right in the middle between the inner and outer limit positions. As illustrated in the figure, H, the distance between the neutral planes, can be calculated by

\[ H = 100 - 2 \times 5 - 2 \times \frac{S}{2}. \]

This leads to H equal to 6.5 cm at S = 2.5 cm and H equal to 7.6 cm at S = 1.4 cm.
<table>
<thead>
<tr>
<th>Frequency</th>
<th>Stroke for 1.0 cm plate</th>
<th>Stroke for 0.3 cm plates</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1.4cm, 2.5cm</td>
<td>2.5cm</td>
</tr>
<tr>
<td>6</td>
<td>1.4cm, 2.5cm</td>
<td>2.5cm</td>
</tr>
<tr>
<td>8</td>
<td>1.4cm, 2.5cm</td>
<td>2.5cm</td>
</tr>
<tr>
<td>12</td>
<td>1.4cm, 2.5cm</td>
<td>2.5cm</td>
</tr>
<tr>
<td>16</td>
<td>1.4cm, 2.5cm</td>
<td>2.5cm</td>
</tr>
<tr>
<td>20</td>
<td>1.4cm, 2.5cm</td>
<td>2.5cm</td>
</tr>
<tr>
<td>25</td>
<td>2.5 cm</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.3  The oscillation frequency and stroke that were carefully tuned.

**Estimation of turbulence characteristics**

To estimate the turbulence intensity in the chamber that was induced by the oscillation of the plates, the correlation from Shy et al. (1997) is used. That is

\[ q = CM^{1/2} S^{3/2} f H^{-1.5}, \]  

where, \( q \) is the effective turbulent intensity and \( C \) is a constant equal to 0.89 according to Shy’s experiment. As mentioned in Chapter 2, this correlation was obtained in experiments carried out in a water tank. At the design stage, there was no information available for determination of the \( C \) value for gaseous working fluids such as air. Therefore, \( C \) was retained as a fixed value variable in the calculation using Eq. 3.1. Table 3.4 lists the calculated turbulent intensity at selected frequencies and strokes for both plate sets.

In the calculation above, \( H \) is equal to 6.5 cm for a stroke of 2.5 cm and 7.6 cm for a stroke of 1.4 cm. \( M \), the plate mesh size is taken to be 1.2 cm for the 1.0 cm plates and 0.37 cm for 0.3 cm plates. The ratio of the maximum turbulence intensity to the minimum
Table 3.4 Estimation of turbulence intensity (cm/s) from selected oscillation frequencies and strokes.

<table>
<thead>
<tr>
<th>Stroke</th>
<th>1.0 cm plates</th>
<th>0.3 cm plates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14 cm</td>
<td>25 cm</td>
</tr>
<tr>
<td>4</td>
<td>3.487C</td>
<td>10.45C</td>
</tr>
<tr>
<td>8</td>
<td>6.974C</td>
<td>20.90C</td>
</tr>
<tr>
<td>16</td>
<td>13.94C</td>
<td>41.77C</td>
</tr>
<tr>
<td>25</td>
<td>21.78C</td>
<td>65.27C</td>
</tr>
</tbody>
</table>

Turbulence intensity is 33.7 (=652.7·C / 19.35·C).

Shy et al. (1997) concluded that the turbulence integral length scale $L_i$ linearly increases with $H$, that is, $L_i = C_2 \cdot H$, but did not give a definitive value for coefficient $C_2$. According to Srdic (1996), $L_i = 0.1 \cdot D'$, where $D'$ is the half of the grid distance $H$. This leads to $C_2$ equal to 0.05. However, for the same reason as above, $C_2$ is kept as an unknown in the calculation of turbulence integral length scale. As known from previous discussion, $H$ is equal to 6.5 cm for a stroke of 2.5 and 7.4 cm for a stroke of 1.4 cm. This leads to a possible variation of turbulence integral length scale of 1.14 (= 7.4·C_2 / 6.5·C_2).

### Wiring and Installation

In order to attach the pneumatic cylinders to the chamber side walls, customized cylinder mounts were fabricated. Fig. 3.14 shows the schematic drawing of the pneumatic cylinder and the cylinder mount. The use of cylinder mounts allowed for selection of pneumatic cylinders of different diameters without modification of the cubic chamber. This was an important time saving measure at the design stage.
The pneumatic cylinder shaft had two degrees of freedom: linearly moving along the cylinder axis and rotating around the cylinder axis. The rotation of the shaft would have resulted in disorientation of the perforated plates, causing an asymmetric flow pattern inside the chamber and interruption of the oscillation if the plates touched the chamber inner surfaces and increased the friction. In order to prevent disorientation of plates, the other end of the cylinder shaft was attached to a slider, which slid smoothly on two guide rails through linear bearings. A photograph of this assembly is shown in Fig. 3.15.
As seen in this figure, the potentiometer is connected to the slider to track the positions of the corresponding cylinder shaft with the synchronized movement. A spacer block was employed to keep the alignment of the potentiometer and the connected cylinder shaft. To reduce the rigidity of motion due to misalignment of the components in the motion drive system, the guild rails were designed as being suspended-beam type, with one ends fastened on the spacer block and the other ends suspended.

3.4 Gas Injection System and Injection Timing Control

The function of the gas injection system is to realize controlled and short duration, gaseous injection into the cubic chamber. A schematic of the system is shown in Fig. 3.16.
It is comprised of the injector, the components on the injected gas line, a computer-integrated timing control circuit and the related LabView control program. As shown in Fig. 3.16, the components on the injected gas-line include a gas tank, a one-stage pressure regulator and a holding cylinder. The intended injection gas was stored in a gas tank at very high pressure, which was initially about 20 MPa, but the injector requires less than 0.6 MPa. To achieve this, a one stage regulator was mounted on the gas tank, reducing the pressure to about 0.69 MPa (100 psi). The reduced pressure gas was then introduced into a holding cylinder with a pressure gauge of resolution of 0.00345 MPa (0.5 PSI). There were two independent outlet needle valves. One was directly linked to the injector by a flexible metal tube. The other one was connected to the atmosphere through a releasing valve, which provided an easy means to adjust the injection pressure to the desired level. Fig. 3.17 shows a photograph of the gas injection system.

Fig. 3.17 A photo of gas injection system.
Injector

In the center of the top wall of the chamber, a commercial (IMPCO) gaseous fuel injector was mounted, as shown in Fig. 3.4. A photo of this injector is shown in Fig. 3.18. The injector is literally a solenoid valve, the specifications for which are listed in Table 3.5.

![Injector Image](image)

**Fig. 3.18 A photo of the commercial gaseous fuel injector.**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum length</td>
<td>7.20 cm</td>
</tr>
<tr>
<td>Maximum diameter</td>
<td>2.45 cm</td>
</tr>
<tr>
<td>Nozzle exit diameter (D)</td>
<td>0.325 cm</td>
</tr>
<tr>
<td>Activation voltage</td>
<td>12.0 V</td>
</tr>
<tr>
<td>Static resistance of coil</td>
<td>4.0 Ω</td>
</tr>
<tr>
<td>Maximum working pressure</td>
<td>0.6 MPa (90 PSI)</td>
</tr>
</tbody>
</table>

**Table 3.5 Specifications of the injector.**

Experimental measurements of injection velocity were conducted with the aid of Schlieren movies (the Schlieren Imaging System is presented in Chapter 4). The injected gas was methane and the chamber gas was air. Initial results showed that at an injection pressure of 0.069 MPa (10 PSI), the estimated injection velocity was about 45 m/s; at an
injection pressure of 0.414 MPa (60 PSI), the estimated injection velocity was about 100 m/s. This corresponded to the range of Reynolds number \( Re = \frac{W_0 \cdot D}{v} \) between 7,600 and 19,000, where \( W_0 \) denoted the injection velocity, \( D \) denoted the injector nozzle exit diameter, and \( v \) was the kinematic viscosity of methane and was taken to be \( 1.7 \times 10^{-5} \) m\(^2\)/s. The jet flow, with Reynolds numbers within this range, was deemed to be fully turbulent.

**Injection Timing Control**

The function of injection timing control was to determine how long and when to inject. As indicated in Fig. 3.16, the injection timing control circuit is composed of the computer and its periphery devices (the DAQ card and the terminal box), a power supply and the injector.

To produce an injection of specified duration, a digital TTL signal was generated by the computer and its periphery device. After amplification, the TTL signal was converted to a 12 volt pulse with sufficient current capacity to lift up the needle of the injector. This TTL pulse was generated as a counter-based TTL digital output, which had a resolution of 0.01 milliseconds and was controlled by a pulse generation program.

In order to control the injection timing relative to the motion of plates, the pulse generation program was incorporated into the same LabView program that controlled the pneumatic drive system (shown at the lower right corner of the front panel of the LabView program in Fig. 3.12). This program allowed triggering the injection at any time before or after the plates came to rest.

With the LabView program and the timing control circuit, transient injections with durations between 5 millisecond and 1.0 second were easily generated.
**Installation and Wiring**

To mount the injector on the cubic chamber, an injector housing was designed and used. The design of the injector housing allows for changes of injector model without modifying the chamber. The installation of the injector is illustrated in Fig. 3.19.

In order to connect the injector and the flexible metal tube delivering the injected gas, an adaptor was designed. Its installation is also illustrated in Fig. 3.19 (b). The details of the injector housing and injector clamps, adaptor and adaptor clamp are documented in Appendix A.

![Diagram of injector and flexible tube connection](image)

**Fig. 3.19** Illustration of the mounting of the injector and its connection with flexible tube through adaptor.

To amplify the digital TTL signal to meet the required current capacity, a special circuit was designed based on MOSFET. The circuit and a power supply were installed in the
same case with the power supply for the proportional valves. A photo of this power supply unit is shown in Fig. 3.20.

![Fig. 3.20 A photograph of combined power supply box.](image)

### 3.5 Traverse system

In order to measure three dimensional velocity fields inside the chamber by means of LDV, the chamber was mounted on a base plate assembly, which was bolted on a 3-D traverse system. In this way the chamber was moved with the LDV probe held fixed. This design was a convenient alternative to mounting LDV probe on the traverse system.

This traverse system is composed of one base table and three traverse plates providing the movement along three orthogonal directions (see Fig. 3.21). Each traverse plate was moved along its base through a trail and linear bearing assembly, and the distance it travels was controlled through turning the handle connected to a threaded shaft.

The plates could be moved about 15.0 cm in each direction. To help in accurate positioning, a ruler of resolution of 0.05 cm and a knife-edge indicator were attached on each rail and traverse plate, respectively, as shown in Fig. 3.22. A magnifying glass was also attached in front of each knife-edge indicator to facilitate reading.
3.6 Summary

In this chapter, the experimental apparatus for modeling a short-duration transient gaseous turbulent jet is described. The apparatus is capable of producing turbulent flow fields characterized by a near zero mean velocity field and a transient gaseous turbulent jet. The experimental system is comprised of:
1. a cubic chamber of 1 liter in volume with optical access windows and aspirating valves;
2. a pneumatic motion drive system based on pneumatic cylinders for delivering oscillation of controlled frequencies and strokes to the perforated plates;
3. a gas injection system built on a commercial gas injector for producing transient gas injection.

With the computer-integrated motion control circuit, the pneumatic cylinder provided oscillating motion to the perforated plates of frequency up to 25 Hz and stroke up to 2.5 cm, which, when both sets of plates (1.0 cm plates and 0.3 cm plates) are used, can generate turbulent flows in the chamber with a wide range of turbulent characteristics.

With the computer-integrated timing control circuit, the gas injection system can realize a transient gas injection at 0.414 MPa with duration up to 1000 milliseconds. The range of Reynolds number of the transient jets is between 7,600 and 19,000.

An ancillary traverse system was constructed to move the cubic chamber in 3 dimensions to facilitate velocity measurements using an LDV system.

From now on, the term ‘direct injection turbulence chamber’ (or ‘the DI turbulence chamber’ or ‘the DI chamber’) is used to refer to the cubic chamber equipped with perforated plates, motion drive system and gas injection system.
Chapter 4 Experimental Techniques

4.1 Introduction

The direct injection turbulence chamber for experimental modeling is described in Chapter 3. Estimates summarized in Table 3.4 showed that turbulent flows of a wide range of turbulence characteristics could be produced in this setup. The correlations used for the calculations, however, needed to be consolidated to determine constants, C, in the experimental setting in this work since there was little available data about the turbulence generated by oscillating perforated plates in gaseous media. In addition, the specific values of turbulent characteristics from this setup are required for verification of the numerical modeling conducted in this work. In order to characterize the turbulent flow field within the chamber space, a Laser Doppler Velocimetry (LDV) system was purchased and set up.

LDV is a non-intrusive technique. If one neglects the impact of seeding particles on the flow there is no other flow disturbance produced by this method. LDV can be used in highly unsteady and reversing flows. From this point of view, LDV has obvious advantages when compared with hot wire anemometry and pitot-probe measurements.

A few disadvantages can be identified with the use of LDV. The major one is that the system measures the velocity of the seed particles or droplets rather than the fluid velocity. This requires, or assumes, that the seed particles follow the fluid flow of interest. It is often a challenge to find appropriate seed particles. In some applications, seeding itself presents a problem. In addition, appropriate optical access is necessary. Comparing with hot wire and pitot-probe measurements, this system is complex,
expensive and involves relatively tedious and long alignment processes. Details of the LDV system configuration used in this research and its operation are given in Section 4.2. As discussed in Chapter 3, the DI chamber was capable of producing a transient gaseous jet of 10 ms to 30 ms in duration, with Reynolds number, $Re$, ranging from 8,000 to 20,000. Due to the transient nature of the jet (therefore, ensemble averaging would be required), it was impractical to use the LDV system for quantitative investigation of the behavior of the gaseous jet based on a set of point-by-point measurements, especially when coupled with the huge difficulty in seeding the jet material.

In this research, a Schlieren imaging system was set up and coupled with a fast video acquisition system to capture and record the transient injection process. The recorded Schlieren images were processed to extract the integral information — the penetration depth and spread angle — which are illustrated in Fig. 4.1. The method is referred as to 'integral measurement of a transient jet based on Schlieren imaging'. A Visual Basic program had been written to automate the image processing for the extraction of the integral information. The Schlieren imaging system, the video acquisition system and the processing program are described in Section 4.3.

![Penetration depth and spread angle from a processed Schlieren image.](image_url)

Fig. 4.1 The penetration depth and spread angle from a processed Schlieren image.
4.2 Velocity Measurement with LDV

4.2.1 Basic Principle and Configuration of LDV

In this research, a two component LDV system (TSI Incorporated) was employed for characterization of turbulence fields inside the cubic chamber. The system, set up to operate in backscatter, is sketched in Fig. 4.2. In the same figure the basic principle of the LDV system is also depicted. The main components of this system and their functions are summarized in Table 4.1.

As shown in Fig. 4.2, a multicolor laser beam from the Argon-Ion laser enters ColorBurst, a multicolor beam separator. It is split into two green (514.5 nm) and two blue (488.0 nm) beams of equal intensity and then transmitted through fiber optic cable to the probe in front of the cubic chamber. Two equal intensity laser beams of the same color exit the fiber optic probe and cross in the measuring volume, forming an interference pattern that is a set of planar fringes. A particle passing through the measuring volume scatters light with an intensity (I) modulated by the fringe pattern at the frequency ($f_0 = 1/t$, see Fig. 4.2(b)) of fringe crossing. This frequency $f_0$, the so-called Doppler frequency, is proportional to the velocity component perpendicular to the fringes and inversely proportional to the fringe spacing ($\delta$). The scattered light is retrieved by the detection probe and sent to ColorLink, where the light is again separated into different colors and converted into electrical signals. The signal processor, IFA 755, identifies the signal bursts by certain pre-set criteria such as threshold voltage and Signal-to-Noise ratio, and extracts the Doppler frequency. This information is then collected by a computer and the fluid velocity ($V$) is calculated in the FIND software (version 1.4) through the equation,
\[ V = \delta \times f_0. \] (4.1)

Velocity = \( f_0 \times \delta \)

Fig. 4.2 Two component Laser Doppler Velocimetry and basic principle.
### LDV System

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>Water-Cooled Argon-Ion Laser (Coherent INNOVA 75)</td>
</tr>
<tr>
<td></td>
<td>Output Power 5.00 W (multiline)</td>
</tr>
<tr>
<td></td>
<td>Wavelength 457.9 — 514.5 nm</td>
</tr>
<tr>
<td></td>
<td>Beam Diameter 1.5 mm</td>
</tr>
<tr>
<td></td>
<td>Beam Divergence 0.5 mrad</td>
</tr>
<tr>
<td>TSI 9201 (ColorBurst)</td>
<td>Multicolor Beam Separator. Splits the incoming beam of the multicolor Argon-ion laser into two (Green and Blue)</td>
</tr>
<tr>
<td>TSI 9721</td>
<td>Coupler (Units: 4) that launch light from the ColorBurst to the Fiber optic probe through the transmitting fibers.</td>
</tr>
<tr>
<td>TSI 9832-3</td>
<td>Transmitting probe with beam spacing of 50 mm. Features both focusing and receiving optics.</td>
</tr>
<tr>
<td>TSI 9230 (ColorLink)</td>
<td>Multicolor Receiver. Separates scattered light, converts light energy to electrical signals and provides frequency mixing capability.</td>
</tr>
<tr>
<td>IFA 755</td>
<td>Digital Burst Correlator. Identifies a signal burst and extracts the frequency information.</td>
</tr>
<tr>
<td>FIND for Window</td>
<td>Window based data acquisition and analysis software. Helps in establishing and setting the system, acquiring and analyzing the data.</td>
</tr>
</tbody>
</table>

Table 4.1 Main Components of the LDV system.
Through the FIND software, this velocity information is stored on hard disk for later analysis or displayed on the monitor in real-time mode, depending on the settings. This FIND software is also used for setting up hardware parameters in both the multicolor receiver (ColorLink) and the IFA755 processor, and helping with the data analysis with its built-in statistical functions.

The transmitting geometry of this system is sketched in Fig. 4.3 with specific values listed in Table 4.2. The schematic of the measuring volume is shown in Fig. 4.4. The dimensions of the measurement volume are tabulated in Table 4.3.

In order to carry out velocity measurements in the 3-d domain of the cubic chamber, the fiber-optic probe was mounted on a base table, which was kept stationary, and the traverse system carrying the chamber allowed the relative movement of the measuring volume within the chamber in horizontal and vertical directions.

For clear presentation of the working principle of the LDV method, a basic two-component LDV system without frequency shifting is described above. In this research, frequency shifting is crucial in the velocity measurements and is addressed separately in next section.

![Transmitting System](image)

*Fig. 4.3 Schematic of the transmitting geometry.*
<table>
<thead>
<tr>
<th>Symbol, Unit</th>
<th>Green beam</th>
<th>Blue beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>F, mm</td>
<td>350.0</td>
</tr>
<tr>
<td>Beam spacing</td>
<td>d_B, mm</td>
<td>50.0</td>
</tr>
<tr>
<td>Half angle</td>
<td>θ/2, degree</td>
<td>4.096044</td>
</tr>
<tr>
<td>The diameter of the</td>
<td>D_1, mm</td>
<td>2.20</td>
</tr>
<tr>
<td>beams before the pass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>through the lens</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expansion ratio</td>
<td>E</td>
<td>1.0</td>
</tr>
<tr>
<td>Wave length</td>
<td>λ, nm</td>
<td>514.5</td>
</tr>
</tbody>
</table>

Table 4.2 Dimensions of the transmitting geometry.

Fig. 4.4 Schematic of the measuring volume.
### Table 4.3 Dimensions of the measuring volume.

<table>
<thead>
<tr>
<th>MEASURING VOLUME</th>
<th>Symbol, Unit</th>
<th>Green beam* for measuring the vertical component</th>
<th>Blue beam* for measuring the horizontal component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave length</td>
<td>( \lambda ), nm</td>
<td>514.5</td>
<td>488</td>
</tr>
<tr>
<td>The length of the measuring volume</td>
<td>( \delta_x ), mm</td>
<td>( \frac{4 \cdot F \cdot \lambda}{\pi \cdot E \cdot D_L \cdot \sin \left( \frac{\theta}{2} \right)} )</td>
<td>( \frac{4 \cdot F \cdot \lambda}{\pi \cdot E \cdot D_L} )</td>
</tr>
<tr>
<td>The width of the measuring volume</td>
<td>( \delta_y ), mm</td>
<td>( \frac{4 \cdot F \cdot \lambda}{\pi \cdot E \cdot D_L} )</td>
<td>0.098850</td>
</tr>
<tr>
<td>The length of the measuring volume</td>
<td>( \delta_z ), mm</td>
<td>( \frac{4 \cdot F \cdot \lambda}{\pi \cdot E \cdot D_L \cdot \cos \left( \frac{\theta}{2} \right)} )</td>
<td>0.099102</td>
</tr>
<tr>
<td>Number of fringes (no shift)</td>
<td>N</td>
<td>( \frac{F \cdot \tan \left( \frac{\theta}{2} \right)}{8 \cdot \pi \cdot E \cdot D_L} )</td>
<td>29.011367</td>
</tr>
<tr>
<td>The spacing between the fringes,</td>
<td>( \delta_f ), ( \mu )m</td>
<td>( \frac{\lambda}{2 \cdot \sin \left( \frac{\theta}{2} \right)} )</td>
<td>3.601500</td>
</tr>
</tbody>
</table>

4.2.2 **Frequency Shift and Effective Frequency Shift**

The LDV system described in last section is a basic LDV system without frequency shifting. That is, the fringes in the measurement volume are stationary. Such a system cannot distinguish between forward or reverse flow. If particles were traveling at the same speed, the Doppler frequency of the particles traveling in the forward direction is equivalent to the Doppler frequency of particle traveling in the reverse direction through the measurement volume. Also the frequency of the signal would go to zero at zero velocity. This ambiguity can be eliminated by frequency shifting.
When frequency shifting is applied, one laser beam of the same color pair is shifted in frequency while the other beam is not. This causes the optical fringes in the measurement volume to move in the direction from the shifted beam (at a higher frequency) to the unshifted beam (at a lower frequency) at a frequency equal to the shift. Thus, a particle passing through this measurement volume, and moving in a direction against the fringes (referred as 'positive' direction), generates a signal with frequency that is equal to the frequency shift plus its own Doppler frequency. On the other hand the signal from a particle passing through the measurement volume but moving in the same direction as the fringes (referred as 'negative' direction) has a frequency that is equal to the difference of frequency shift and its Doppler frequency. For example, with a frequency shift of 2 MHz, the frequency output is 2 MHz at zero velocity. The frequency increases from 2 MHz in the positive flow direction and decrease from 2 MHz in the negative flow direction. This is illustrated in Fig. 4.5. As one can see, the directional ambiguity is eliminated within the range of negative velocity. The frequency shift is later subtracted from the frequency measured in order to get the Doppler frequency.

![Diagram showing frequency shifting and Doppler effect](image)

*Fig. 4.5 Illustration of how frequency shifting eliminates directional ambiguity.*
The magnitude of the frequency shift in this TSI system is 40 MHz. This gives a negative velocity range under this LDV configuration up to 144 m/s, which is large enough to cover the reverse flows in the DI chamber. This also means the frequency detected by the photomultiplier (inside ColorLink Plus) is always 40 MHz plus or minus the particle Doppler frequency. However, it is not always appropriate to send this photomultiplier signal with the full 40-MHz shift directly to the signal processor for extraction of the Doppler frequency because the resolution of the Doppler frequency measurement could be significantly impaired. The following provides a basis for understanding the matter.

![Diagram of a particle moving across the LDV measuring volume.](image)

**Fig. 4.6 A particle moving across the LDV measuring volume.**

Consider a particle (see Fig. 4.6) that is moving at velocity \( V_0 \) across the measurement volume, which has a mean diameter of \( \delta_m \) and fringe spacing of \( \delta_f \). Velocity \( V_0 \) forms an angle of \( \theta \) with direction opposite to that of the optical fringe movement. The number of fringes in the measurement volume with no frequency shifting \( (N_F) \) is given as

\[
N_F = \frac{\delta_m}{\delta_f}; \tag{4.2}
\]

Transit time \( (T) \) is the time it takes a particle to cross the measurement volume, thus
Without frequency shifting, the number of fringes \((N_1)\) a particle crosses depends on its trajectory, that is,

\[
N_1 = N_F \cdot \cos \theta ,
\]

(4.4)

where, \(N_1 = N_F\) when \(\theta = 0\) (particles are traveling normal to the fringes); \(N_1 = 0\) when \(\theta = 90^\circ\) (particles are moving parallel to the fringes).

With frequency shifting, the number of fringes \((N_S)\) crossing a stationary particle is given as, \(N_S = T \times f_s\) or

\[
N_S = \frac{\delta_m}{|V_0|} \times f_s
\]

(4.5)

where, \(f_s\) is the frequency shift magnitude. The Doppler frequency of the particle \((f_0)\) is

\[
f_0 = \frac{|V_0|}{\delta_f} \text{ or } |V_0| = f_0 \times \delta_f .
\]

(4.6)

The total number of fringes \((N)\) that a particle crosses with frequency shift is

\[
N = N_1 + N_S
\]

\[
= (N_F \cdot \cos \theta) + \left( \frac{\delta_m}{|V_0|} \times f_s \right) = (N_F \cdot \cos \theta) + \left( \frac{\delta_m}{\delta_f \times f_0} \times f_s \right)
\]

\[
= (N_F \cdot \cos \theta) + \left( N_F \times \frac{f_s}{f_0} \right)
\]

Thus,

\[
N = N_F \left( \cos \theta + \frac{f_s}{f_0} \right).
\]

(4.7)
In order to extract the frequency of an incoming burst (Doppler frequency plus shift), an average of 15 cycles from the central portion of the burst are sampled using a record of 256 samples. A double-clipped autocorrelation is performed on these samples to extract the number of valid cycles of the sampled signal (TSI, 2000). With the sampling rate known, the frequency of the sampled signal is calculated as follows

\[
\text{Frequency} = \frac{\text{the number of the valid cycles}}{\text{the time span of the valid cycles}}
\]

However, among the sampled cycles, only \( \frac{N_i}{N} = \frac{\cos \theta}{\cos \theta + \frac{f_s}{f_0}} \), or about \( \frac{\cos \theta \cdot f_0}{f_s} \) if \( f_s/f_0 \gg 0 \) cycles are from the Doppler signal. With an increase in \( f_s \), it is easy for the Doppler signal to be submerged below the resolution of measurement of the sampled signal, which is rated at 0.05% for this signal processor with an 11-bit output reading. For example, under certain conditions the velocity inside the cubic chamber has a magnitude of 1.0 m/s in vertical direction. Given the fringe spacing of 3.6015 μm (see Table 4.3) for the green beam, a particle at a velocity of such magnitude generates a Doppler frequency of about 0.3 MHz (\( \frac{1.0 \text{ m/s}}{3.6015 \times 10^{-6} \text{ m}} \)) in the vertical direction. If the full 40-MHz shift is used, the signal processor receives a burst signal with 40.3 MHz (assuming ‘positive’ direction), and resolution of the frequency measurement of this signal is about 0.02 MHz (\( = 40.3 \times 0.05\% \)), which is acceptable for the Doppler frequency measured. But, as the particle velocity drops to 0.1 m/s, the resolution of the burst signal of 0.02 MHz, which also dictates the resolution of Doppler frequency measurement, reaches an unacceptable level for a Doppler frequency of 0.03 MHz.
In order to optimize the Doppler frequency resolution and yield the measurement cycles required by the signal processor, an 'effective frequency shift' was implemented to replace the full 40-MHz shift in the measurement of the sampled signal. Thus, with this effective frequency shift ($f_{\text{eff}}$), the total number of fringes (N) a particle crosses is given by

$$N = N_p \left( \cos \theta + \frac{f_{\text{eff}}}{f_0} \right)$$

(4.8)

The effective frequency shift is set through the FIND for Windows software in the system. Its magnitude should be determined for optimal resolution of the Doppler frequency with the number of measurement cycles required. The general rule for measuring flow reversals is to select a magnitude that is twice the Doppler frequency corresponding to the maximum negative velocity. A simple proof of this is shown as follows; for reverse flow with $\theta = 180^\circ$,

$$N = N_p \left( -1 + \frac{f_{\text{eff}}}{f_0} \right) \Rightarrow \frac{N}{N_p} = -1 + \frac{f_{\text{eff}}}{f_0}$$

For $\frac{N}{N_p} = 1$

$$\frac{f_{\text{eff}}}{f_0} = 2 \Rightarrow f_{\text{eff}} = 2 \times f_0$$

Therefore, to ensure no loss of fringes, the frequency shift should be at least twice the Doppler frequency corresponding to the maximum negative velocity.

Implementation of an effective frequency shift involves electronic mixing in the ColorLink Plus. Fig. 4.7 illustrates the mixing process.

Appendix C lists the mix-frequency values corresponding to the various frequency shift
magnitude selections that can be made through the FIND program. Based on the general rule for selecting the effective frequency shift, the effective frequency shifts used, corresponding to the estimated reversal velocities in this research, are listed in Table 4.4.

<table>
<thead>
<tr>
<th>Incoming Signal</th>
<th>Mixing Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Doppler Frequency) ± (40 MHz from Bragg Cell)</td>
<td>(40 MHz Source Frequency) ± (Effective Frequency Shift)</td>
</tr>
<tr>
<td>( + ) = When flow is moving against the fringes</td>
<td>( + ) = When flow is moving with the fringes</td>
</tr>
<tr>
<td>( - ) = When flow is moving with the fringes</td>
<td>( - ) = When flow is moving against the fringes</td>
</tr>
</tbody>
</table>

The effective frequency shift is subtracted in the FIND software program to get the Doppler frequency.

**Fig. 4.7 Frequency shifting and mixing in the ColorLink Plus.**

<table>
<thead>
<tr>
<th>Estimation of maximum velocity of reversal flow</th>
<th>Doppler frequency</th>
<th>Effective frequency shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01 m/s</td>
<td>3 kHz</td>
<td>10 kHz</td>
</tr>
<tr>
<td>0.05 m/s</td>
<td>15 kHz</td>
<td>50 kHz</td>
</tr>
<tr>
<td>0.1 m/s</td>
<td>30 kHz</td>
<td>100 kHz</td>
</tr>
<tr>
<td>1 m/s</td>
<td>300 kHz</td>
<td>1 MHz</td>
</tr>
</tbody>
</table>

Table 4.4 Effective frequency shift commonly used in this research.

### 4.2.3 Seed Generation and Seeding

Successful application of an LDV system pretty much depends on the selection of the seed particles. The seed particles have to be small enough to follow the flow and also
have sufficient refractive index to generate strong back scattering signals. To serve the purpose of seed generation, a RadioShack® fogger model number 42-3085 was purchased, together with the fog liquid, which was a solution of food grade glycols and water (see Fig. 4.8). Very fine smoke could be produced continuously or on short intervals. A fogger of the same model had previously been characterized and the arithmetic mean diameter of smoke was measured as 2.84 micrometer over a sample size of 7579 particles (Mike Brown, 2001).

![Seeding device and solution used for seed particle generation.](image)

Fig. 4.8 Seeding device and solution used for seed particle generation.

To produce lasting smoke from this type of fogger machine, a relatively large space was needed to quickly condense the vaporized fog liquid to form small particles (smoke). Therefore it was not possible to feed the output vapor directly into the chamber. A large plastic bag was used to collect the smoke first, and then the smoke was fed into the chamber through aspirating valves.

During the LDV measurements, the concentration of smoke gradually dropped due to condensation on the chamber walls or evaporation. Therefore, every ten minutes, the chamber was flushed out with air and new seed was added. After a number of refills, the optical windows needed to be cleaned.
The above seeding method was successful in generating seed particles in the chamber for the characterization of turbulent flows generated by the oscillation of the perforated plates. However, it was extremely hard to apply the method for seeding the gas injection system when the measurement of the jet velocity was intended. First, the jet material injected was bottled gas that was impossible to seed with smoke before injection. The gas holding cylinder initially seemed to be an option as a point at which to bring smoke in, but that turned out to be no easy task because of the large flow resistance across the needle valves on the holding cylinder. Many attempts to feed smoke from the plastic garbage bag into the holding tank were made, but with no success.

An attempt to use alternate seed particles was made for velocity measurement in the transient turbulent jet. Microspheres from 3M™ (type W-210 with 50% under 4 micrometers) were used and added in the inlet of the injector. When injection was initiated, the seed particles were blown into the chamber. However, these solid seed particles soon formed deposits on the injector, preventing the needle from completely shutting off the flow and leading to injector leakage.

4.2.4 Processor Settings and the Sampling Scheme
Data rate is very important in LDV measurement, particularly in measurement of turbulence quantities, such as the turbulent time scales. Data rate can be affected by the density of seeding particles in the flow field and the processor operating parameters. Table 4.5 lists the processor operating mode and a number of settings used to validate the burst signals. As seen from the table, the signal processor operates at coincidence mode. In this mode, two active channels of the signal processor acquire and validate the signals within the specified coincident window. If both signals are not validated, all channels are
released and the coincidence data point is not acquired. In this work, the coincidence window was taken to be 1000 μs during data sampling. Under these parameters, the data rate was typically in the range of 1200 ~ 1500 samples per second.

<table>
<thead>
<tr>
<th>PROCESSOR/ColorLink</th>
<th>Green beam</th>
<th>Blue beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode: Random / Coincidence</td>
<td>Coincidence</td>
<td>Coincidence (coincidence window = 1000 μs)</td>
</tr>
<tr>
<td>Minimum Cycle per Burst:</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>SNR:</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>PMT Voltage:</td>
<td>1200 mV</td>
<td>1200 mV</td>
</tr>
</tbody>
</table>

Table 4.5 LDV signal processor operating parameters.

Two sampling methods are available using the LDV system: random sampling, for which the signal processor transmits every validated point, or equal interval sampling, for which the signal processor transmits only the last valid point that occurs during each sample period. In order to eliminate the bias in velocity measurement (Durao et al., 1980) and to avoid the need for corrections to the mean and fluctuating velocities (McLaughlin and Tielderman, 1973), the equal interval sampling scheme was used throughout the LDV measurements. To ensure the accuracy of the measurements using this scheme, the data sampling frequency has to be much lower than the data rate of signal processor. In this work, the data sampling frequency was kept at 50 Hz (i.e., 50 samples per second). It was well below 5% of the data rate of the signal processor (1200~1500 samples per second).

To determine the minimum number of measurements needed to measure the mean velocity, experimental trials in search of the optimal sample number were carried out. The results are shown in Fig. 4.9. As can be seen, the fluctuations in the calculated mean velocity...
velocities die out for both velocity components after the sample number reaches 5000. In this research, the velocity records for each case considered consisted of 7500 samples, which took 150 seconds to finish recording at 50 Hz sampling rate. The duration of sampling was much longer than the integral time scale of turbulence and hence can be considered sufficient for calculation of turbulent quantities.

![Image](image_url)

**Fig. 4.9 Mean velocity values against different sample number.**

Any readings that fell more than 10 standard deviations from the mean were discarded, as the processor occasionally sent out erroneous values on the digital lines.

### 4.2.5 Uncertainty

Uncertainty in single-point LDV measurements was a result of many factors including instrument uncertainty and flow unsteadiness. The LDV apparatus itself was a possible source of measurement uncertainty. Variation in lens focus length, laser wavelength and beam-crossing angle are considered negligible due to precise calibration by manufacturers. However, the resolution of the IFA755 processor was limited by the clock frequency and the size of the output data word. Since the processor was operated in
automatic mode, each frequency value was transferred to the computer as a 12-bit mantissa and a 4-bit exponent. Therefore, the frequency readings were considered to have an uncertainty of one-half of the least significant bit or ½ part in $4096(=2^{12})$. Also, based on the vendor's specifications, a 0.05% resolution in the frequency reading should also be considered, yielding an overall uncertainty of 0.0515% in the frequency reading. It was clear that the 0.05% resolution in frequency reading was the dominant factor in the aforementioned uncertainty and the higher the measured Doppler frequency, the higher the uncertainty in its reading. Therefore, one should take into careful consideration the amount of the imposed shift, since the higher the frequency shift, the more uncertain the frequency reading becomes.

4.3 Integral Measurements Based on Schlieren Imaging

In this research, all the injected gases are transparent and direct photography can not capture the transient jet. The Schlieren method is therefore employed in order to 'visualize' the injection process. As mentioned in Section 4.1, the integral measurement of the transient jet involves the Schlieren imaging system, fast video acquisition system, and the image processing program.

4.3.1 Schlieren Imaging System

General Principle of Schlieren Method

Schlieren is an optical visualization technique used frequently in fluid mechanics research. It is based on the principle that the gradient in the inhomogeneous refractive index field of a test section causes the light to deflect. In fluids, such gradients in refractive index field are usually rendered by density gradients in the fluids, which may
result from differences in temperature or concentration. A basic Schlieren imaging system is illustrated in Fig. 4.10. The essential parts of the system include a light source, optical lenses, a knife edge and a projection screen. A parallel beam is generated by a concave lens (or spherical mirror) and it passes through a test section. The perturbed light beam is then focused using a second lens (or spherical mirror), producing an image of the phenomena under investigation. A knife-edge is usually put at the focal point of the collated light beam to eliminate a fraction of the unperturbed portion of the light in order to enhance the effect generated by the refractive index variation (Merzkirch, 1987).

![Diagram of a basic Schlieren imaging system](image)

**Fig. 4.10 Principle of a basic Schlieren imaging system.**

**Configuration of the Schlieren Imaging System in This Study**

Fig. 4.11 shows the configuration of the Schlieren imaging system used in this research. This system is more complex than the one shown in Fig. 4.10. The optical lenses in Fig. 4.10 are replaced by the concave mirrors for converging the light and changing the direction of the light path. Several components are added, including two shielding tubes and three flat mirrors. The shielding tubes are used for screening off ambient noise light for lower noise, better image quality and for facilitating the alignment of light path. Flat mirrors 1 and 2 are attached to the shielding tubes and are able to slide along the walls of the corresponding tube in a small range, within which the focuses of the concave mirrors...
are located. Flat mirror 3 was optional. It is used here to deflect the light path by 90 degree so that the Schlieren set-up can easily fit in the available lab space.

When the system is aligned, the light from the light source (Xenon light bulb) passes the focusing lens and is focused on the aperture on the shielding tube 1. The light illuminates mirror 1, and then gets reflected to the concave mirror 1. The resulting parallel beams pass through the test section and are redirected to the concave mirror 2 by flat mirror 3. The beams are focused on the knife edge. The un-cut fraction of the light is projected on
Before using this system, tedious aligning and adjusting work had to be done. For example, the angle of flat mirror 1 and its relative distance to concave mirror 1 had to be adjusted for producing parallel beams toward the test section; so did the relative distance of the light source and the focusing lens to flat mirror 1 for the coverage of parallel beams over the quartz window.

During experiments, the injected gas had a different density than the ambient gas and the image of the jet was projected on the screen through the Schlieren imaging system. However, the injection process in this research lasted only 10 milliseconds or so. This denied any direct observation of this phenomenon, needless to say measurement of this process. Therefore, a fast recording facility was required to record the injection process.

### 4.3.2 Fast Video Acquisition System

A computer-integrated video acquisition system was set up to record the injection process and store the information on a computer in preparation for integral measurements of the transient jet. This system is composed of a Kodak Motion Corder Analyzer; a dedicated computer with a properly configured interface; and Matrox Inspector, which is Window®-based software and provides a user-friendly interface and integration between the computer and the Kodak Motion Corder Analyzer.

Kodak Motion Corder Analyzer, a fast CCD camera system capable of recording at a maximum speed of 10,000 frames per second (fps), was used here for recording the injection process. The system consists of a CCD camera; a Processor and an optional viewfinder with Hi8 VCR (see Fig. 4.12). The camera captures the projected image. The Processor controls the record rate and image resolution, etc. It also has built-in Dynamic
Random Access Memory (DRAM) for holding up the retrieved digital image sequence. The viewfinder helps in setting the record parameters and positioning of the camera and also provides a mean for quick review of the recorded movie.

![Diagram of Kodak Motion Corder Analyzer]

**Fig. 4.12 Kodak Motion Corder Analyzer.**

The Processor was connected through the data bus to a dedicated computer. In the computer, Matrox Meteor II frame grabber, a PCI card, was installed as the interface between the computer and the Processor. With the help of Matrox Inspector®, a movie stored in the Processor was retrieved by the computer and saved as an AVI file. This system is depicted at the lower left corner in Fig. 4.13.

The Kodak Motion Corder Analyzer has a number of record rate settings. Corresponding to each record rate, a number of display sizes are available (the larger display size, the better resolution). Table 4.6 lists the record rates over 250 fps and the available display sizes in pixels. As one can see from the table, it is possible to select various display sizes for a specific frame rate. Because of a fixed amount of DRAM for storage of frames, selecting a small display size will increase the number of frames that one can record. Table 4.7 lists the number of frames one can record at each display size.

A number of trials indicated that the record rate of 2000 fps was good for recording most of the injection process under investigation. For best maximum resolution, a display size
of 256×120 pixels was selected (marked as the hatched area in Table 4.6). The number of frames that could be recorded at 2000 fps was 4,368 (see Table 4.7), and this took about 2.18\(=\frac{4,368 \text{ frames}}{2000 \text{ frames/second}}\) seconds to fill up the memory. A question was brought up due to the short recording time and even shorter injection
duration, i.e., how we timed the two events, recording and injection, in order for the camera to capture the injection (less than 20 ms) and the immediately subsequent flow development. For our best interest, the start of recording needed to be synchronized with the initiation of injection. This not only ensured the capture of the injection but also provided a relatively accurate measure of the starting point of the injection and the injection duration, with the time interval between frames known.

**Synchronization of Recording and Injection**

To implement the synchronization, the TTL signal for triggering the injector was introduced to the Processor, which was capable of receiving external trigger signals to initiate recording. The recording mode of the camera was also set as ‘START’, at which the Processor starts retrieving images immediately after receiving the trigger signal and stops recording when the memory is filled up. The configuration of this synchronization circuit is illustrated in Fig. 4.13 and the schematic of the synchronizing sequence is depicted in Fig. 4.14.

Under the camera settings mentioned above, 4386 frames of images were held in the Processor after each recording. Only a fraction of these frames, i.e., those taken during injection and subsequent mixing, were saved on the computer for later analysis. The number of frames of interest depended upon the injection conditions, such as injection duration and injection pressure. The frames for storage were decided through visual examination of the Schlieren movie. After a critical number, no visible change between two consecutive images could be detected. For example, at injection pressure of 0.276 MPa (40 PSI) and injection duration of 10 ms, 80 frames were saved.
Fig. 4.13 Fast video acquisition system and the synchronization of the initiation of injection and start of recording.

Fig. 4.14 Illustration of synchronization of injection and initiation of recording.
4.3.3 Image Processing
In order to investigate the effect of different factors on the integral behavior of the transient jet, integral measurements were carried out for nearly 80 cases, incorporating changes in such factors as injection pressure and oscillation frequency of the perforated plates. There were, on average, 10 separate movies saved at each experimental condition, and there were, on average, 60 images chosen for processing for each movie sequence. This imposed a huge amount of work for data reduction. A Visual Basic program was written to automate the image processing to prepare for the subsequent extraction of values for the jet penetration depth and the spread angle.

Visual Basic Program
The Visual Basic program runs under Matrox Inspector®, which creates a Visual Basic environment and incorporates many useful subroutines. It takes the original AVI movie stored in the computer as input and it performs the following steps on each individual frame:

- Trimming Region of Interest (ROI)
- Subtracting Background Image
- Averaging
- Filtering
- Two-level Thresholding
- Tip and Boundary Searching

In the last step, the program searches for the jet tip and three points on each side of the jet boundary, and outputs the information into an Excel spreadsheet, where the jet penetration depth and the spread angle are calculated through a Macro. The Visual Basic program has been appended in Appendix D.
Trimming Region of Interest (ROI)

Fig. 4.15 shows a frame of image from a saved Schlieren movie sequence. It has a size of 768 × 576 pixels, with the information like Record Date and Frame Number (on the top) and Frame rate (on the bottom). However, the region of interest, i.e., the Schlieren image of the cubic chamber, occupies about an area about 140 pixel in width and 120 pixels in height. In order to reduce the computation time for subsequent processing, the ROI of size 140 × 120 pixels is cut out and saved. These formed smaller images are referred to as 'the cut ROI image'. A representative example is shown in Fig. 4.16 (a). The intermediate images derived from the image 4.16(a) during image processing are also included in Fig. 4.16 for comparison, and these images will be addressed below.

Fig. 4.15 A single frame from the saved Schlieren movie and the Region of Interest.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Fig. 4.16 Images used in image processing. (a) the cut ROI image; (b) the background image; (c) the image after subtracting background; (d) the averaged image; (e) the image after filtering; (f) the image after two-level thresholding.

One may notice that for the cut ROI image, the number of pixels in width is larger than that in height. This is not caused by distortion from the Schlieren imaging system. Instead, it results from the fact that the aspect ratio of the sensing element in the CCD camera is not 1. This is illustrated in Fig. 4.17.

Fig. 4.17 The aspect ratio of a sensing element gives rise to different pixel number of the Schlieren image of the ROI.

Subtracting Background Image

The cut ROI image has very dark background. And the grayness (level of grey) of the
background often varies for different cases, mainly due to the adjustment of camera aperture setting in searching for the best contrast. Subtracting of the cut ROI image from a background image, which is a cut ROI image taken prior to injection (see Fig. 4.16 (b)), was used to eliminate differences in the camera setting. The resulting image is shown in Fig. 4.16 (c). The jet material in the resulting image, either black or white due to the Schlieren effect, now has a very distinct boundary that separates it from its surrounding.

**Averaging**

In order to eliminate the randomness of a single realization, 10 or more movies were recorded for each case. An averaging process is taken over all the background-subtracted images corresponding to the same instant during injection. A resulting image is produced and shown in picture (d) in Fig. 4.16.

**Filtering**

Filtering reduces the noise level. Fig. 4.18 shows the effect of filtering on the level of grey in different pixels along a straight line across the middle of the averaged image in Fig. 4.17(d). It prepares the image for the next step — two-level thresholding.

![Fig. 4.18 The grayness of the pixels along a horizontal line across the averaged image. (a) before the filtering; (b) after the filtering.](image-url)
Filtering process is actually an averaging process, not between frames, but between a pixel and its surrounding pixels. The filtering scheme in this research is called 5×5 Filtering, a weighted averaging between one pixel and its surrounding 24 pixels. The weighting number for the pixel of interest is 36 and the weighting numbers for its surrounding pixels are listed in Table 4.8.

<table>
<thead>
<tr>
<th>1</th>
<th>4</th>
<th>6</th>
<th>4</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>16</td>
<td>24</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>24</td>
<td>36</td>
<td>24</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>24</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4.8 The weighting numbers for the 5×5 filtering scheme. The pixel of interest takes the weighting number of 36, which is in the center of the table and marked with hatched lines.

Two-Level Thresholding

A two-level thresholding process is carried out on the frames after filtering. After this process, the pixels on the image turn white whose grayness values are between the minimum and maximum thresholds and the pixels turn black whose grayness values fall outside the range between the minimum and maximum thresholds. This process is illustrated in Fig. 4.19. This process results in a frame with a black jet body (grayness of 0) and a white ambient (grayness of 255) surrounding the jet, as shown in Fig. 4.16(f). The minimum and the maximum thresholds used were held constant (213 and 42) throughout the image processing.
Tip and Boundary Searching

The image after two-level thresholding becomes black and white, as illustrated in Fig. 4.20. Therefore, a tip and boundary searching scheme can be easily implemented. As illustrated in Fig. 4.20, the position of each pixel in the image can be represented by a coordinate pair between (0, 0) and (139, 119). Starting in the middle of the jet body, the first white pixels are searched downwards along the vertical direction at 10 locations.
close to the jet centerline. The y-coordinates of these white pixels are then compared and the white pixel with the largest y-coordinate is taken as the jet tip. Its coordinates are then output to an Excel spreadsheet.

The boundary searching is initiated with white pixels at three locations on each side of the jet. The first black pixels are searched along the horizontal direction toward the jet body (see Fig. 4.20). The x and y pixel coordinates of these boundary pixels are then exported into the same Excel spreadsheet.

White pockets occasionally appeared in the jet body on the images after thresholding, especially when the jet approaches the chamber bottom. In that case, the tip position was determined by manually searching.

**Calculation of the Penetration Depth and the Spread Angle**

In order to calculate the penetration depth, the coordinates of the pixel which represents the center of the injector exit were needed. They were determined through visually checking the images and were consistent during the calculation for one case. The penetration depth $z_t$ (in cm) was then calculated by

$$z_t = \sqrt{(x_{EXIT} - x_{TIP})^2 + (y_{EXIT} - y_{TIP})^2} \times \frac{10}{120},$$

(4.9)

where, $x_{EXIT}, y_{EXIT}$ are the pixel coordinates of the injector exit, and $x_{TIP}, y_{TIP}$ are the pixel coordinates of the jet tip.

To calculate the spread angle, a best-fit straight line was determined via linear regression through the three boundary points on each side of jet body, and the cross-angle between the two straight lines was calculated by use of triangle geometry. This value was taken as the spread angle. To reduce the uncertainty of this method, it was only applied to the frames on which the penetration depth was over 5.0 cm, and an average value of spread
angle was calculated over the number of frames used. These steps were automated through a macro program in Excel.

4.3.4 Uncertainty

It is hard to estimate the uncertainty in the Schlieren method and its effect on the measured results. Schlieren method is often used as a visualization method in fluid mechanic research and quantitative Schlieren methods are still under development (Elsinga et al., 2003; Cwik and Ermert, 1993). Due to the lack of data about the numerical relationship between the density gradient and the light intensity change on the projected image, the uncertainty from Schlieren Imaging System is excluded from the following analysis and only the uncertainties resulting from the image processing are considered.

The uncertainty is composed of bias and standard deviation. Table 4.9 lists the major sources of uncertainty in each step of the image processing.

<table>
<thead>
<tr>
<th>Image processing step</th>
<th>Type of Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trimming ROI</td>
<td>/</td>
</tr>
<tr>
<td>Subtracting the background</td>
<td>/</td>
</tr>
<tr>
<td>Averaging</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>Filtering</td>
<td>Bias</td>
</tr>
<tr>
<td>Two-level thresholding</td>
<td>Bias</td>
</tr>
<tr>
<td>Tip/boundary searching</td>
<td>Standard deviation</td>
</tr>
</tbody>
</table>

Table 4.9 Uncertainty in the image processing.
Trimming ROI did not affect the measurements and thus did not contribute to the uncertainty. Subtracting the background increased the contrast of the image and thus reduced the uncertainty. From a conservative point of view, subtracting the background was not considered in the uncertainty analysis.

Bias was considered as the major source of uncertainty in filtering and two-level thresholding. However, it was difficult to evaluate the bias from both steps in this work. The filtering reduced the noise level of the image but did blur the edges of the jet; thresholding eliminates the grayness, leaving the jet body in black and the surrounding in white. Since the filtering scheme was selected to match the two-level thresholding process, these two steps could be considered as being bonded to each other and their combined bias was very much dependent on the selection of the thresholds. Even though they were chosen somewhat arbitrarily, the minimum and maximum thresholds were kept the same for all the cases that had been processed.

Standard deviation was deemed as the major contributing factor to uncertainty in the averaging and tip/boundary search steps. The standard deviation from the tip/boundary searching was half pixel size, which was about 0.042 cm in measurement of the penetration depth or 3.8° (calculation was based on jet penetration depth of 5.0 cm) in calculation of the spread angle.

The averaging step reduced the uncertainty of the measurement of both penetration depths and spread angles. The variation of the injection penetration depths could be caused by the fluctuations in injection pressure and injection temperature, but mainly by the fluctuations in injection response time, i.e., the time from the instant that the injector received the actuation signal to the instant that it was fully opened. In general, if some
variable being measured experiences random error, and this error has a normal
distribution, then the standard deviation of this variable is inversely proportional to the
square root of the number of measurements (Mendoza, 1996), that is,

\[ \Delta I_m = \frac{\Delta I}{\sqrt{m}}, \]  

(4.10)

where, \( \Delta I \) is the estimated error of the variable being measured and \( m \) is the number of
measurements. In this work, the errors caused by the fluctuations mentioned above were
considered random. To be conservative, the standard deviation of the penetration depth
measurement at one pressure was estimated with use of Eq. 4.10, based on the maximum
variation value that was ever observed for all cases with the same injection pressure.

In this study, 3.0 cm was observed as the maximum variation of measured penetration
depths for the cases with the injection pressure of 0.414 MPa and 1.83 cm was observed
as the maximum variation with the injection pressure of 0.069 MPa. This leads to a
standard deviation of 0.949 cm in the measurements of the penetration depth for cases
with the injection pressure of 0.414 MPa and 0.579 cm for cases with the injection
pressure of 0.069 MPa.

In fact, the maximum variation of penetration depth took place at an early stage of
injection and the magnitude of the variation decreased with the penetration depth (or
injection time). The variation of the standard deviation with the penetration depth (or
injection time) at one experimental condition is illustrated in Fig. 4.21. The solid line
represents the curve of penetration depth versus time and the dashed lines indicate its
range of variation.
The spread angle of a transient jet was very much independent of fluctuations in the injection pressure, injection temperature and the injector response time, but the variation of measured spread angles could be caused by fluctuations in light intensity from the light source. A maximum variation of 8 degrees had been observed in the measurements of spread angles from the individual movies taken under the same experimental conditions. This leads to the maximum standard deviation of 3.16 degrees in the measurements of spread angles using the present image averaging process.

Fig. 4.21 Trend of the standard deviation for the penetration depth.
Chapter 5  Numerical Modeling

5.1  Introduction

Numerical methods for solving engineering problems have become increasingly popular over the last decade due to their various advantages over more established analytical and experimental approaches. The advantages of numerical methods are particularly clear in problems involving turbulent flows with complex geometry or of transient nature, where analytical methods fail to capture the full physical characteristics of the complex fluid dynamics and experimental measurements can be prohibitively expensive or time-consuming.

In this research, a numerical model of the direct injection (DI) turbulence chamber was created with a modified version of the Los Alamos KIVA3V code (Amsden, 1993). In this model the perforated plates and their oscillating movement could be closely simulated. The oscillation frequencies and the strokes were easily adjusted in the model. An injector sub-model was also incorporated. The injector sub-model was able to produce a transient gaseous injection with a constant velocity for a time duration of any specified length.

The purpose of the numerical modeling in this study was two-fold. First, it provided complementary results to the experimental investigations. The LDV measurements of the turbulent flow characteristics were made only on a limited number of points inside the chamber. In contrast, the solution of the numerical model (at the same conditions as the experiments) provided results across the entire chamber space. Second, the numerical model, once completed, constituted a parametric research tool through which experiments
could be carried out numerically under operating conditions that could not be achieved in the experiments. In general, the numerical model was a tool for gaining comprehensive understanding of the chamber turbulence generated by the oscillation of the perforated plates and the behavior of a gaseous turbulent transient jet.

The feasibility of a numerical model is inevitably linked with computing time, which is in turn directly related to the complexities of numerical sub-models used and the number of nodes in the computational domain. The key sub-models used in this model included the $k$-$\epsilon$ turbulence model, the valve model for oscillating movement of the perforated plates, and the constant-velocity injection model for the gaseous transient injection. These sub-models will be explained in the Section 5.2. When working on this model, a great amount of time was invested on generating the computational mesh. In fact, two computational meshes were created, one for the DI chamber with 1.0 cm plates and the other for the DI chamber with 0.5 cm plates (a tempt to generate a mesh for the DI chamber with the 0.3 cm plates failed due to difficulty in the geometry creation step). Both meshes had over half million nodes and a detailed description of these meshes is given in Section 5.3.

Another factor contributing to the computing time is computing power available to the researcher. A dual-core (AMD Athlon 2600+, 2.0 GHz) computer system was used as the main computing power. Another dual-core (AMD Athlon 1800+, 1.6 GHz) system was also employed for sharing the computing load. Both systems were loaded with Linux operating system (SUSE 9.2) and configured to run the simulations in a parallel mode.

When running the simulation of the plate oscillation, it took an average of four days to compute ten cycles. This seems a long time when compared to a half second in the experiments with the oscillation frequency of 20 Hz. However, the simulation results,
once obtained, are for all the grid points in the chamber and they can be directly used in
the subsequent simulation of behavior of gaseous transient jets. More will be said about
the computing time in Chapter 7.

It is not hard to imagine that a huge amount of data was generated from the numerical
modeling. In fact, over 100 Gigabytes of data had been collected over all the simulations
done. In order to facilitate extraction of phenomenological information from such large
quantities of detailed flow data, advanced post-processing techniques were required. For
this purpose, General Mesh Viewer (GMV) version 2.8, a free, powerful 3-D scientific
visualization tool originally from LANL, was downloaded (in 2002) and used. Detailed
information about this software can be found from the following web link: http://www-
xdiv.lanl.gov/XCM/gmv/.

5.2 KIVA-3V Code and Numerical Sub-Models

KIVA-3V is a computer program written in FORTRAN for the numerical calculation of
transient, two and three dimensional chemically reactive flows with liquid fuel sprays. It
is capable of simulating laminar or turbulent, subsonic or supersonic, and single or two
phase flows. It uses a time-marching, finite-difference scheme which solves equations of
mass, momentum, energy and turbulence using combined Lagrangian and Eulerian
techniques in three subsequent phases. Initially, spatial differences are formed with
respect to a generalized mesh of arbitrary hexahedrons whose corner locations are
specified as functions of time. During the first solution phase (Lagrangian and explicit),
the dependent variables are updated by calculating terms other than pressure and the ones
related to convective transport. During the second phase (Lagrangian and implicit),
pressure terms and velocity dilatation terms are updated based on the SIMPLE algorithm.
During the third solution phase (Eulerian and explicit), the convective transport terms associated with moving the vertices from their second phase locations to their final locations are calculated.

KIVA-3V uses a block-structured mesh with connectivity defined through indirect addressing. Blocks are structures which are patched together to create the geometry of interest. The user can define the shape and size of different blocks. The connection and setup of the grid requires information about the coordinates in logical and physical space, specification of the boundary condition applied to each logical block, the number of points defining blocks and the way blocks are patched together. Note, however, that cell faces must always coincide between neighboring cells and there are no sliding cells. Hence, the mesh is structured to the extent that computing cells are always hexahedrons with eight cells meeting at a vertex. The KIVA-3V package includes a basic post processor that can be run interactively and provide zone plots, velocity vector plots and contour plots. However, as mentioned in the Introduction, the KIVA-3V outputs were stored and GMV was used as the post-processor.

KIVA was developed originally for simulation of combustion engines. The number of species and chemical reactions that can be accounted for in KIVA-3V are arbitrary, limited only by computer time and storage considerations. Currently KIVA-3V has an enthalpy database for 13 chemical species, including many choices for gaseous fuels such as methane and propane. The code distinguishes between slow reactions, which proceed according to their kinetics, and fast reactions, which are assumed to be at equilibrium. Chemical rate expressions are specified for the kinetic reactions in Arrhenius form, and are evaluated by a partially implicit procedure. Two implicit equation solvers are
available to compute chemical equilibrium, a fast algebraic solver for hydrocarbon-air combustion and an iterative solver for more general circumstances.

5.2.1 Governing Equations with \( k - \varepsilon \) Turbulence Model

KIVA-3V equations can be used to solve for both laminar and turbulent flows. The mass, momentum, and energy equations for the two cases differ primarily in the form and magnitude of the transport coefficients (i.e. viscosity, thermal conductivity, and species diffusivity), which are much larger in the turbulent case because of the additional transport caused by turbulent fluctuations. In the turbulent case the transport coefficients are derived from a turbulent diffusivity that depends on the turbulent kinetic energy and its dissipation rate, which can be calculated by solving turbulence model equations.

There are three turbulence models incorporated in KIVA-3V as standard options: \( k - \varepsilon \) turbulence model, RNG \( k - \varepsilon \) turbulence model and subgrid-scale model. The \( k - \varepsilon \) turbulence model was employed in this research. The \( k - \varepsilon \) turbulence model has been used extensively to represent turbulence in a wide range of situations, including jet flows and chamber flows. Its advantages and limitations have been well documented in the literature (Johnson et al., 1995). In addition, a number of trial 2-D simulations had been carried out using both \( k - \varepsilon \) and RNG \( k - \varepsilon \) turbulence models for the same cases. The results showed that there was no substantial difference between the results or the computation time obtained with these differing turbulence models.

KIVA-3V can also be used for simulation of liquid fuel sprays and is capable of accounting for an arbitrary number of species and chemical reactions. However, because liquid fuel spray and chemical reaction were not the subject of this research, terms related to sprays or chemical reactions were either bypassed or simply set to zero during the
calculation. Therefore, in the following description of governing equations, these terms are omitted.

For the complete set of equations with these terms, please refer to Amsden's (1989) report. The notation used here is somewhat different from that usually found in a common textbook, such as *Combustion* by Warnatz et al. (1999); but it is followed here for consistency with the KIVA3V manual. For compactness, vector notation is used with bold symbols representing vector quantities. The position vector $\mathbf{x}$ is defined by

$$\mathbf{x} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k},$$

The vector operator $\nabla$ is given by

$$\nabla = \frac{\partial}{\partial x} \mathbf{i} + \frac{\partial}{\partial y} \mathbf{j} + \frac{\partial}{\partial z} \mathbf{k},$$

and the fluid velocity vector $\mathbf{U}$ is given by

$$\mathbf{U} = U(x, y, z, t)\mathbf{i} + V(x, y, z, t)\mathbf{j} + W(x, y, z, t)\mathbf{k},$$

where $t$ is time.

The continuity equation for species $m$ is

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{U}) = \nabla \cdot \left[ \rho D \nabla \left( \frac{\rho_m}{\rho} \right) \right], \quad (5.1)$$

where $\rho_m$ is the mass density of species $m$, $\rho$ the total mass density, and $\mathbf{U}$ the fluid velocity. Fick's Law of diffusion is assumed with a single diffusion coefficient $D$, which will be given later. By summing Eq. 5.1 over all species we obtain the total fluid density equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0. \quad (5.2)$$

The momentum equation for the fluid mixture is
\[
\frac{\partial (\rho U)}{\partial t} + \nabla \cdot (\rho U U) = -\nabla p - A_0 \nabla \left( \frac{2}{3} \rho k \right) + \nabla \cdot \sigma + \rho g ,
\]

(5.3)

where \( p \) is the fluid pressure. In Eq. 5.3 the quantity \( A_0 \) is set to zero in laminar flow calculations and to unity when one of the turbulence models is used. The viscous stress tensor is Newtonian in form:

\[
\sigma = \mu (\nabla U + (\nabla U)^T) + \lambda \nabla \cdot U : I .
\]

(5.4)

The first and second coefficients of viscosity, \( \mu \) and \( \lambda \) are defined later. The superscript \( T \) denotes the transpose and \( I \) is the unit dyadic. The specific body force \( g \) is assumed constant.

The internal energy equation is

\[
\frac{\partial (\rho e)}{\partial t} + \nabla \cdot (\rho U e) = -\rho \nabla \cdot U + (1 - A_0) \sigma : \nabla U - \nabla \cdot J + A_0 \rho e ,
\]

(5.5)

where \( e \) is the specific internal energy, exclusive of chemical energy. The heat flux vector \( J \) is the sum of contributions due to heat conduction and enthalpy diffusion:

\[
J = -K \nabla T - \rho D \sum_m h_m \nabla \left( \frac{\rho_m}{\rho} \right) ,
\]

(5.6)

where \( T \) is the fluid temperature and \( h_m \) the specific enthalpy of species \( m \). When \( k - \varepsilon \) turbulence model is in use \( (A_0 = 1) \), two additional transport equations are solved for the turbulent kinetic energy \( k \) and its dissipation rate \( \varepsilon \) :

\[
\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho U k) = -\frac{2}{3} \rho k \nabla \cdot U + \sigma : \nabla U + \nabla \left( \frac{\mu}{Pr_t} \right) \nabla k - \rho \varepsilon ,
\]

(5.7)

\[
\frac{\partial \rho \varepsilon}{\partial t} + \nabla \cdot (\rho \varepsilon U) = -\left( \frac{2}{3} c_{\alpha} - c_{\varepsilon} \right) \rho \varepsilon \nabla \cdot U + \nabla \cdot \left( \frac{\mu}{Pr_t} \right) \nabla \varepsilon + \frac{c_{\varepsilon}}{k} (c_{\varepsilon} \sigma : \nabla U - c_{\varepsilon} \rho \varepsilon)
\]

(5.8)

These are standard \( k - \varepsilon \) equations proposed by Launder and Spalding (1972). The source
term \( \left( c_{e_1} - \frac{2}{3} c_{e_1} \right) \nabla \cdot \mathbf{U} \) in the \( \varepsilon \)-equation (Eq. 5.8) accounts for length scale changes when there is velocity dilation. The quantities \( c_{e_1} \), \( c_{e_2} \), \( c_{e_3} \), \( \Pr_k \) and \( \Pr_e \) are constants whose values are determined from experiments and some theoretical considerations. Standard values of these constants were used in this modeling, and are given below:

\[
\begin{align*}
c_{e_1} &= 1.44, \\
c_{e_2} &= 1.92, \\
c_{e_3} &= -1.0, \\
\Pr_k &= 1.0, \\
\Pr_e &= 1.3
\end{align*}
\]

The state relations are assumed to be those for an ideal gas mixture. Therefore,

\[
p = R_0 T \sum_m \left( \frac{\rho_m}{W_m} \right)
\]

(5.9)

\[
I(T) = \sum_m \left( \frac{\rho_m}{\rho} \right) I_m(T)
\]

(5.10)

\[
c_n(T) = \sum_m \left( \frac{\rho_m}{\rho} \right) c_{pm}(T)
\]

and

\[
h_m(T) = I_m(T) + R_0 T / W_m,
\]

where, \( R_0 \) is the universal gas constant; \( W_m \), the molecular weight of species \( m \); \( I_m(T) \), the specific internal energy of species \( m \); and \( c_p \), the specific heat are at constant pressure of species \( m \), the values of \( h_m(T) \) and \( c_{pm}(T) \) are taken from JANAF tables.

The transport coefficients in KIVA-3V are taken to be

\[
\mu = (1.0 - A_0) \rho \nu_0 + \mu_{ab} + A_0 \rho c_p k^2 / \varepsilon
\]

\[
\lambda = A_1 \mu
\]

(5.11)

\[
K = \frac{\mu c_p}{\Pr}
\]

and
\[ D = \frac{\mu}{\rho Sc} \]

The momentum diffusivity \( \nu_0 \) in the dynamic viscosity equation is an input constant, and \( c_\mu \) is an empirical constant with a standard value of 0.09. A Sutherland formula is used for \( \mu_{\text{air}} \):

\[ \mu_{\text{air}} = \frac{A_1 T^{3/2}}{T + A_2}, \quad (5.12) \]

where \( A_1 \) and \( A_2 \) are constants. The constant \( A_3 \) in Eq. 5.11 is taken to be \(-2/3\) in calculations of turbulent flow but can be arbitrarily specified in laminar flows. The Prandtl and Schmidt number, \( Pr \) and \( Sc \), are input constants.

The 10 equations 5.3, 5.5-5.11 (note, Eq. 5.3 is counted as three equations), and \( N_c \) occurrences of Eq. 5.1 (if \( N_c \) species are assumed) for \( N_c \) chemical species, yields \( N_c + 10 \) unknowns, \( \rho, U = (U, V, W), I, k, e, J, p, T, p_1, ..., p_{N_c} \). Therefore, the unknowns can be completely solved.

### 5.2.2 Boundary Conditions for Solid Walls

The DI chamber walls are solid walls and were assigned rigid wall boundary conditions, which are available as a standard option in KIVA-3V.

There are several types of rigid walls depending on velocity and temperature boundary conditions. The velocity boundary conditions on rigid walls can be free slip, no slip, or turbulence law-of-wall conditions. Temperature boundary condition options can be adiabatic walls and fixed temperature walls. In our simulations, rigid walls with the turbulence law-of-wall velocity boundary and fixed wall temperature were applied.

In the turbulent law-of-wall boundaries the normal gas velocity is set equal to the normal
wall velocity, i.e.

\[ \mathbf{U} \cdot \mathbf{n} = w_{\text{wall}} \mathbf{k} \cdot \mathbf{n}, \quad (5.13) \]

where the wall is assumed to be moving with speed \( w_{\text{wall}} \) in the z-direction, and \( \mathbf{n} \) is the unit vector normal to the wall.

The tangential components are determined by matching to a logarithmic profile of normalized velocity near the wall:

\[ \frac{v}{u^*} = \begin{cases} \frac{1}{\kappa} \ln(c_w \zeta^{7/8}) + B & \zeta > R_c, \\ \zeta^{1/2} & \zeta < R_c \end{cases} \quad (5.14) \]

where, \( \zeta = \frac{\rho y V}{\mu_{\text{gas}}(T)} \) is the Reynolds number based on the gas velocity relative to the wall,

\[ v = |\mathbf{U} - w_{\text{wall}} \mathbf{k}|, \] which is evaluated at a distance \( y \) from the wall, and \( u^* \) is the shear velocity, which is related to tangential components of the wall stress by

\[ (\sigma_w - \sigma_w \cdot \mathbf{n}) \mathbf{n} = \rho (u^*)^2 \frac{v}{u^*}, \quad (5.15) \]

where, \( v = \mathbf{U} - w_{\text{wall}} \mathbf{k} \).

In Eqs. 5.14 and 5.15 it is assumed that \( y \) is small enough to be in the logarithmic region or the laminar sub-layer region of the turbulence boundary layer. The Reynolds number \( R_c \) defined the boundary between these two regions. The constants \( \kappa, c_w, R_c \), and \( B \) in Eq. 5.13 are related to the \( k - \varepsilon \) model constants by

\[ \kappa = \sqrt{c_{\mu} \frac{(c_{e_2} - c_{e_1}) \Pr_e}{\mu}} \quad \text{and} \quad B = R_c^{1/2} - \frac{1}{\kappa} \ln(c_w R_c^{7/8}). \]

For standard values of \( k - \varepsilon \) constants, \( B = 5.5 \), and \( c_{\mu} = 0.15 \), we obtain \( \kappa = 0.4327 \) and \( R_c = 114 \).
For fixed temperature walls using the turbulent law-of-wall condition, the wall heat flux \( J_w \) is determined from the modified Reynolds analogy formula

\[
\frac{J_w}{\rho u^* c_p(T - T_w)} = \begin{cases} 
\frac{1}{\left( \frac{Pr_f}{u} \right)} & \zeta \leq R_c \\
\frac{1}{\left( \frac{Pr}{u} + \left( \frac{Pr_f}{Pr} - 1 \right)R_c^{1/2} \right)} & \zeta > R_c 
\end{cases}
\]  

(5.16)

where \( T_w \) is the wall temperature and \( Pr_f \) is the Prandtl number of the laminar fluid.

In addition to the wall heat loss there is a source term in the internal energy equation, which is due to friction heating. Frictional heating occurs whenever the turbulence law-of-the-wall velocity condition is used and is accounted for by the equation

\[
f_w = \sigma_w \cdot \mathbf{v} = \rho (u^*)^2 v,
\]  

(5.17)

where \( f_w \) is the heating rate per unit area of wall.

In calculations of turbulent flow, boundary conditions are also needed for the turbulent kinetic energy \( k \) and its dissipation rate \( \varepsilon \). These are taken to be

\[
\nabla k \cdot \mathbf{n} = 0
\]

and

\[
\varepsilon = c_{\mu_k} \frac{k^{3/2}}{y},
\]  

(5.18)

where \( k \) and \( \varepsilon \) are evaluated a distance \( y \) from the wall and \( c_{\mu_k} = \left[ \frac{c_\mu}{Pr_f (c_{\mu_\infty} - c_\mu)} \right]^{1/2} \).

Eqs. 5.14 and 5.16 are so-called wall functions, which are analytic solutions to simplified turbulence equations. They are used to infer wall shear stresses and heat losses instead of numerical solutions of the complete set of equations near walls, which is usually impractical because one cannot provide sufficient grid resolution. Numerically, one accomplishes this by matching the computed fluid velocities and temperatures at grid
points closest to the walls to the wall functions, which then determine the wall shear stresses and heat losses.

5.2.3 The Gaseous Injection Model
Gaseous injection can be simulated in KIVA3V in three ways: specified velocity inflows, specified pressure boundary inflows, and boundary inflows with specified mass flow rate. If necessary, all specified quantities can be time-dependent.

In this work, the gas injection has been implemented through a constant-velocity boundary inflow. This is done by specifying the faces of a group of cells with a boundary condition of ‘inflow boundary’ and supplying the value for the normal velocity $u_{nj}$. These cells will be referred to as ‘injector cells’. Additional properties are also required and these include: reference species mass densities $\rho_{m,0}$, specific turbulent kinetic energy $k_0$ and turbulence length scale $l_{e0}$ ($\sim k^{3/2}/\varepsilon$). The injection model is illustrated in Fig. 5.1.

The reference density of different species is at reference pressure $p_0$ and the density that is actually imposed at the inflow boundary for species $m$ is obtained from

$$\rho_{m,\text{in}} = \rho_{m,0} \left( \frac{P}{P_0} \right)^{1/\gamma_{\text{amb}}} \tag{5.19}$$

where $P$ is the computed pressure in the injection cells and $\gamma_{\text{amb}}$ is the ratio of specific heats of the inflow gas. Thus at an inflow boundary the species mass fractions and the entropy of the incoming fluid are actually imposed, with the densities obtained by extrapolation from the isentropic gas relation. The gas pressure is then obtained from Eq. 5.9. The inflow internal energies are obtained from pressure $P$ and densities $\rho_{m,\text{in}}$ using the state equation Eq. 5.10. The program calculates the actual $U$, $V$, $W$ velocity components to be applied based on the boundary orientation.
These injection parameters are introduced as a source term into the special boundary cells of the computational domain — the injection cells, when computation time $t$ reaches between the start of injection $t_{i,n} \text{, inj}$ and the end of injection $t_{3, \text{inj}}$. That is, at each injection time step within the interval $[t_{1, \text{inj}}, t_{3, \text{inj}}]$, the mass in the injection cells is updated using Eq. 5.20,

$$
\begin{align*}
\rho_{ic,n+1} &= \rho_{ic,n} + \frac{\dot{m}_{\text{in}} \cdot dt}{\text{vol}_{ic,n}} \\
\rho_{\text{m,ic},n+1} &= \rho_{\text{m,ic},n} + \frac{\dot{m}_{\text{in}} \cdot dt}{\text{vol}_{ic,n}} \\
\dot{m}_{\text{in}} &= \rho_{\text{m}} A u_{\text{nj}} \\
m_{ic,n} &= \rho_{ic,n} \cdot \text{vol}_{ic,n} \\
m_{ic,n+1} &= \rho_{ic,n+1} \cdot \text{vol}_{ic,n}
\end{align*}
$$

where, $\text{vol}_{ic,n}$ denotes the volume of the injection cells. The velocity of the injection cells
is kept constant using Eq. 5.21,

\[ u_{ic,n+1} = u_{ic,n} = u_{inf} \cdot b \]  \hspace{1cm} (5.21)

where, \( b \) is the vector normal to the cell faces with inflow boundary condition.

The specific internal energy is updated based on the enthalpy of the incoming jet using Eq. 5.22

\[ I_{int,ic,n+1} = \frac{I_{int,ic,n} m_{ic,n} + \dot{m}_{in} \cdot dt \cdot I_{int,in}}{m_{ic,n+1}} \]  \hspace{1cm} (5.22)

and the incoming turbulent kinetic energy is imposed to be 10\% of the incoming jet velocity squared, using Eq. 5.23,

\[ k_{ic,n+1} = \frac{k_{ic,n} m_{ic,n} + \dot{m}_{in} \cdot dt \cdot 0.1 \cdot u_{inf}^2}{m_{ic,n+1}} . \]  \hspace{1cm} (5.23)

It was found, however, that reducing the incoming TKE to even 1\% of the incoming jet velocity squared did not make a substantial difference on the computational results, and the jet developed its own turbulence characteristics.

The above procedure implements a uniform velocity profile at the injector nozzle exit. This may not represent the real situation in the injector nozzle exit, where viscosity takes effect at the boundary and causes non-uniform velocity profile across the nozzle exit. However, since information on the geometry of the flow passage inside the injector was not available, the velocity profile at the injector nozzle exit could not be determined by simulations. In addition, the flow inside the injector can be deemed to be fully developed turbulent flow with the velocity used in the present simulations, and the uniform velocity profile was still a good approximation of the real flow situation at the injector nozzle exit.
5.2.4 **Original KIVA-3V Valve Model**
The original KIVA-3V valve model was modified and applied to numerically simulate movement of the perforated plates.

The valve model is a key feature of KIVA-3V, which is mainly aimed at simulation of valves’ opening and closing in engine application and was not included in earlier versions of the code. The valve body is treated as a solid object that moves through the mesh using a special technique called ‘snapper’, which plays a significant role in simulating the moving surface across the computational mesh without deteriorating the quality of mesh. This technique is illustrated in Fig. 5.2.

As shown in the top drawing (1), plane 2 is the moving surface, i.e., one of the oscillating plate surfaces in this research. As the plane 2 moves upward, the cells immediately above it collapse, as shown in the drawing (2). When plate 2 has moved to some specified fraction of these cells’ original height, typically a half, it is ‘snapped’ back to its original position (see drawing (3)), which is marked with the black squares in the drawing (1) and (2). Plane 3 now assumes the role of the moving surface. A simple re-mapping of the flow field onto the revised mesh is then performed using volume averages where volumes of the cells originally above planes 2 and 3 are combined. When the moving surface is moving down, the procedure is reversed.

KIVA-3V can model any number of valves in the chamber. Each valve can have its own size and profile, accurate to the fineness of the grid, and its own moving history. The valves may be vertical, with the valve axis parallel to the cylinder axis, or canted at some angle with respect to the cylinder axis. However in logical space, valves can move only in a bottom-top direction. There is no provision for horizontal or annular valves at this moment.
Fig. 5.2 Schematic of a moving surface crossing the mesh (‘snapper’ technique).

The valves move according to the valve lift data, which are read from a separate input file. This file is a table of crank angles (integers) and corresponding valve lifts in cm (real
numbers). The file covers one complete engine cycle: 0° to 720° for a four stroke engine, or 0° to 360° for a two stroke engine. All crank angles for which the lift is zero may be excluded from this input file, which minimizes the length of the file. In addition, the crank angle increment from one line to the next is not required to be uniform throughout the file. The history for each valve appears in succession. At each simulation cycle, the KIVA program interpolates the lifts and velocities of the valves at the current crank angle from the input valve lift data and the vertices that lie on a valve surface move as a unit each cycle, using the current valve velocity components. If the current crank angle lies outside the range in the table, the program uses the appropriate equivalent crank angle inside the table range, permitting multiple engine cycles to be calculated.

In this study, the perforated plates were treated as valves, which only moved vertically. To accommodate the vertically moving perforated plates, the modeled DI chamber was rotated by 90 degrees, relative to the orientation of the physical chamber. The details of the perforated plates mesh and their movement are given in the section 5.3.3.

5.3 Computational Mesh

5.3.1 Mesh Generation

There is a simple mesh generator, K3PREP, included in the KIVA-3V package, but it was not capable of generating a mesh with perforated plates. Therefore, commercial mesh generation software, ICEM CFD, was used to produce the computational mesh for the chamber and perforated plates, based on their actual dimensions.

A fair amount of time was invested to study how to use that software and special techniques in creating a mesh that could accommodate perforated plates with a large number of round holes. Fig. 5.3 illustrates the four major steps in creating the mesh
through ICEM CFD. These steps are described in more detail in the following. The output mesh data file (kiva.tape17) from the software included the coordinates of all the grid points and the connectivity among the neighboring cells within the computing domain. After being renamed to ‘itape17’, it was able to be read as input by KIVA-3V.

![Diagram of mesh creation process]

**Fig. 5.3 Procedure of creating the mesh through ICEM CFD.**

**Step 1:** Creating solid model of the DI chamber (through SolidWorks®).

In this step, the solid model of the DI chamber with a single perforated plate was created, as illustrated in Fig. 5.4. The geometry information for this solid model was extracted and passed into ICEM CFD through a converter module in the SolidWorks.

**Step 2:** Completing the geometry of the DI chamber in ICEM CFD.

In this step, the geometry for the second plate and the injector nozzle exit were created in the ICEM CFD through its geometry design module. The complete solid model is shown in Fig. 5.5.
Fig. 5.4 The solid model of the DI chamber (in SolidWorks®) with one perforated plate.

Fig. 5.5 Completed solid model of the DI chamber.
Step 3: Blocking.

In this step, the solid geometry was divided into smaller hexagon units, the so-called 'blocks'. They are indicated by red quadrate shapes in Fig. 5.6. Through blocking, the complex geometry is replaced by simple-shaped 'blocks', within which the coordinates of the nodes can be computed easily. The number of cells in one row or column of blocks

Fig. 5.6 Blocks of the DI chamber, (a) top view; (b) front view.
are uniform and can be easily adjusted. This was the most time-consuming step because of the geometric complexity (many round holes).

**Step 4:** Setting up the boundary condition.

This included setting up the solid wall boundary conditions on the chamber wall, the moving surface boundary to the plate surfaces and the specified velocity inflow boundary to the injector exit surface. The graphical interface for setting the KIVA-3V boundary condition in ICEM CFD is shown in Fig. 5.7.

![Graphical interface for setting up the boundary condition for KIVA3V.](image)

*Fig. 5.7 The graphical interface for setting up the boundary condition for KIVA3V.*
5.3.2 Input Mesh of the DI Chamber

Fig. 5.8 shows the graphical representation of an input computational mesh for the DI chamber with 1.0 cm plates. For a clear view of the structure of the mesh, only the mesh for the chamber walls and the perforated plates is shown.

Compared to the orientation of the DI chamber in the experimental modeling, the numerical model of the chamber was orientated with a 90 degree rotation, with the perforated plates moving in vertical direction as the valve model requires. In the input mesh shown in Fig. 5.8, one plate is close to the center of the chamber and one close the bottom. These positions are the plates’ limit positions and are equivalent to the valves’ fully opened positions. During the initiation of the computation, the KIVA-3V program adjusts the plates to their initial positions as required.

![Input mesh of the DI chamber.](image)

Fig. 5.8 Input mesh of the DI chamber.
As shown in Fig. 5.8, the mesh for the injector nozzle exit is located at the center of a sidewall. A detailed mesh structure for the injector is given in section 5.3.4.

In the DI chamber mesh with 1.0 cm perforated plates, there are $86 \times 95 \times 65 (=531050)$ cells in x, y, and z directions, with minimum cell size of about $0.06 \text{cm} \times 0.06 \text{cm} \times 0.05\text{cm}$ (around the injector nozzle exit) and the maximum cell size of about $0.2 \text{cm} \times 0.1 \text{cm} \times 0.1\text{cm}$. Actually, there are more cells included in the input mesh data file. Those are auxiliary cells for facilitating the setting up of boundary conditions. The mesh for the perforated plate and the injector nozzle is given in the following section, together with discussion of related issues.

5.3.3 Mesh of the Perforated Plates and the Plate Movement

In Fig. 5.9, a mesh for the 1.0 cm perforated plate is shown. The hole part of the plates is represented by $8 \times 7$ cells or $8 \times 11$ cell. The denser mesh is for accommodating the injector, whose nozzle centerline is aligned with the hole with denser mesh. This can be seen in Fig. 5.9(b). As one can see, these cells fit the circle quite well. The thickness of the plates is 0.2 cm and is divided into 2 cells by the limitation of valve model. For simplicity, ribs on the edge and across the center portion in the physical plates were not modeled.

In Fig. 5.10 (a) the graphic representation of ITAPE18 (see Appendix E) used in the simulations for stroke of 2.5 cm is illustrated. Both profiles of valve lifts are sinusoidal functions, but with a 180 degree phase difference, which is translated to plates moving in opposite directions to each other. The profiles of movement for the plates in the physical DI chamber, which were displayed in the LabView visual interface in real time as Process Variable based on the signals from the potentiometers, are shown in Fig. 5.10(b).
Fig. 5.9 Mesh for the 1.0 cm plate (a) isometric view; (b) top view with clear account of the mesh for the holes.
Fig. 5.10 Profiles of the plate movement as (a) valve lifts, and (b) pneumatic cylinder process variable.

During simulations, the cells representing the plate body did not participate in the calculation because these cells were treated as solid. Therefore, their grid points were not included in the stored data file. When the data were visualized with the post-processing software, the plate material could be easily distinguished as hollow areas. Fig. 5.11 shows two meshes with plates at different locations.

Fig. 5.11 Visualization of the movement of the plates. The plates are on the way to (a) inner limit positions; (b) outer limit positions.
5.3.4 Mesh for Injector Nozzle Exit

Transient gaseous injection in this numerical model was implemented through constant-velocity boundary inflow. Therefore, a specified group of cells on the chamber wall were assigned with a constant-velocity inflow boundary condition. These cells were the injector cells and their cell faces, which are assigned with the inflow boundary condition, represented the injector nozzle exit.

Fig. 5.12 shows the meshed sidewall accommodating the nozzle exit cells and the area of the cells representing the nozzle exit (within the red circle). In this model, the diameter of the modeled injector nozzle was set to be 0.2 cm, as opposed to 0.325 cm for the real injector. The smaller nozzle diameter was used in order to produce transient jets with lower momentum injection rates. This adjustment was made in response to the preliminary results from the integral measurements based on Schlieren imaging that indicated that no strong visible effect on the transient jet was discerned due to the turbulence generated by the oscillating plates.

As illustrated in Fig. 5.12, the injector nozzle exit is made up of 3 x 3 cells, which are tangential to a red circle of 0.2 cm in diameter. Therefore, the total area of the meshed injector nozzle exit $A_{\text{nj}}$ is $3 \times 10^{-2} \text{ cm}^2$, instead of $3.1416 \times 10^{-2} \text{ cm}^2$ for the area enclosed by the red circle. In Fig. 5.13, the geometry of the injection cells and the cells immediately next to them inside the chamber are also shown.

It is generally agreed that adequate resolution is required to reproduce the structure of gas jets in numerical computations. John Abraham (1997) concluded that the resolution appears to be adequate for gas jets when the grid size is at least the size of the orifice radius. This suggests that at least two cells across the nozzle exit are required. Ouellette and Hill (2000) conducted numerical experiments regarding the grid size effect. They
Fig. 5.12 Mesh of side wall with the injector in the center and mesh for injector nozzle exit area.

Fig. 5.13 Geometry of the injection cells.
concluded that changing the number of cells within the nozzle from two to four caused only 1 percent reduction in the normalized penetration rate. Thus, in this work, three cells were situated across the injector nozzle exit. This was considered to be adequate to resolve the injector from the aspect of the jet penetration.

5.4 Boundary and Initial Conditions

The chamber wall was desired with a constant temperature wall condition with turbulence law-of-wall. The chamber fluid was air for most cases used in the numerical modeling. Table 5.1 lists the initial conditions for the chamber with air as the chamber fluid.

<table>
<thead>
<tr>
<th>Chamber Wall Temperature</th>
<th>293.15 K</th>
<th>*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber Fluid</td>
<td>Air</td>
<td>*</td>
</tr>
<tr>
<td>Temperature</td>
<td>293.15 K</td>
<td>*</td>
</tr>
<tr>
<td>Pressure</td>
<td>$1.0 \times 10^5 \text{ Pa}$</td>
<td></td>
</tr>
<tr>
<td>Composition (mass fraction)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$O_2$</td>
<td>0.2200910204</td>
<td></td>
</tr>
<tr>
<td>$N_2$</td>
<td>0.7650385386</td>
<td></td>
</tr>
<tr>
<td>$CO_2$</td>
<td>$9.913863271 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>$H_2O$</td>
<td>$4.956577746 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Initial velocity</td>
<td>0</td>
<td>*</td>
</tr>
<tr>
<td>Turbulence kinetic energy</td>
<td>0.1 cm$^2$/s$^2$</td>
<td>*</td>
</tr>
<tr>
<td>Turbulence length scale</td>
<td>0.1 cm</td>
<td>*</td>
</tr>
</tbody>
</table>

Table 5.1 Boundary and initial conditions of the chamber walls and fluid.

As seen in the table, air was modeled as a mixture of four gases. This resulted in the
The density of air $\rho_{\text{air}} = 1.182871 \text{ kg/m}^3$ at the initial chamber pressure. When a different gas was used as the chamber fluid, the parameters marked with "*" in above table were kept unchanged.

In this work, methane was used as the injected gas for most cases. The injection velocity for the methane jet was set to be either 40 m/s or 80 m/s. The Reynolds number $(Re = \frac{W_0 \cdot D}{\nu})$ of the methane jet at 40 m/s was equal to 8,000. Table 5.2 lists the boundary conditions for the injected gas. When a different gas was used as the injected gas, the parameters listed in the table were kept unchanged.

<table>
<thead>
<tr>
<th>Conditions for the Injected Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection velocity</td>
</tr>
<tr>
<td>Reference temperature</td>
</tr>
<tr>
<td>Reference pressure</td>
</tr>
<tr>
<td>Pressure, $p_0$</td>
</tr>
<tr>
<td>Initial turbulence length scale</td>
</tr>
</tbody>
</table>

Table 5.2. Boundary conditions for the injected gas (Reference temperature and pressure are required to calculate the reference density, which is used in Eq. 5.19).

The density of methane at the injector exit was calculated to be 0.658218 kg/m$^3$. Therefore, the momentum rate $(\dot{M}_n)$ of the methane jet at 40 m/s, which was calculated by $\dot{M}_n = \rho_{\text{CH}_4} \cdot (W_0)^2 \cdot A_{\text{avg}}$, was equal to 0.710876 kg m$^2$/s.

Natural convection effects were omitted from the modeling even though the density of the injected gas is different than air, since the development of the transient jet is driven by high momentum, rather than buoyancy.
Chapter 6  Results from Experiments

6.1  Introduction

In this chapter, results from the experimental modeling are discussed. Results from the LDV measurements are presented in section 6.2, with focus on the characteristics of the turbulent flow in the DI chamber, which were generated by oscillation of the perforated plates. Results from the Schlieren image processing about the integral behavior of the transient jet are reviewed in section 6.2.

To facilitate the presentation of the results, a Cartesian coordinate system is defined as shown in Fig. 6.1(a). In this system, the origin of the coordinate system coincides with the center of the injector nozzle exit, and the z-coordinate direction is the same as the injection direction. The x-coordinate is parallel to the perforated plates and the y-coordinate is perpendicular to the perforated plates. The coordinates of the DI chamber center, thus, read (0, 0, 5) in unit ‘cm’.

The instantaneous velocity components in x, y and z directions are denoted by the lower case letters $u$, $v$, and $w$, respectively, as shown on Fig. 6.1(b), and their means are denoted by capital letters, $U$, $V$ and $W$, accordingly. The instantaneous velocity fluctuation components are represented by lower case letters with a prime, $u'$, $v'$ and $w'$. Thus, we have

$$u = U + u', \quad v = V + v' \quad \text{and} \quad w = W + w'.$$

(6.1)

6.2  DI Chamber Turbulence Flow Field Characterization by LDV

In this section, the characteristics, the turbulence intensity and length scales in particular, of the turbulent flow generated by oscillation of the perforated plates are examined.
As reviewed in Chapter 2, the turbulence generated by a pair of oscillating grids displays a turbulent velocity decay law in the form,

\[ q = C f \omega A S^{1.5} M^{0.5} H^{-n}, \]  

(6.2)

where, \( q \) is the effective turbulent intensity. \( C \) is equal to 0.89 and \( n \) is equal to 1.5. Due to the difference in working fluid (gases instead of water) in the experiments and the design of the oscillating devices (perforated plates instead of grids), re-evaluation of \( C \)
and the power \( n \) were needed. To do so, the LDV measurements at the center point of the DI chamber were carried out.

Table 6.1 lists the cases that were done. The results presented in this chapter are, unless otherwise specified, from cases with 1.0 cm plates.

<table>
<thead>
<tr>
<th>Plates</th>
<th>1.0 cm plates</th>
<th>0.3 cm plates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke</td>
<td>1.4 cm</td>
<td>2.5 cm</td>
</tr>
<tr>
<td>4 Hz Oscillation</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>8 Hz Oscillation</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>12 Hz Oscillation</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>16 Hz Oscillation</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>20 Hz Oscillation</td>
<td>( \times )</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1 Experimental matrix for LDV measurements.

6.2.1 Velocity Field

LDV measurements were taken of instantaneous velocity components, \( v \) and \( w \), at the DI chamber center (see Fig. 6.2) while the perforated plates were oscillating. As mentioned in the Chapter 4, a total of 7500 samples were taken for each component at 50 Hz (equal interval sampling) in coincidence mode.

![Fig. 6.2 LDA measurement location and velocity components.](image)
From the sampled data of instantaneous velocity components, mean velocity components, \( V \) and \( W \), were calculated by (TSI Incorporated, 2000)

\[
V = \frac{\sum_{n=1}^{N} v_n}{N} \quad \text{and} \quad W = \frac{\sum_{n=1}^{N} w_n}{N}
\]

(6.3)

respectively; and the root-mean-square (rms) of turbulent velocities, \( v'_{rms} \) and \( w'_{rms} \) by,

\[
v'_{rms} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} (v_n - V)^2} \quad \text{and} \quad w'_{rms} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} (w_n - W)^2}
\]

(6.4)

respectively, where, \( N \) denotes the number of samples, which was equal to 7500; \( v_n \) and \( w_n \) were the \( n \)-th sample of the components \( v \) and \( w \) during the measurements. For strokes of 1.4 cm and 2.5 cm, the calculated mean and rms of fluctuating velocities are tabulated in Table 6.2 and Table 6.3, respectively.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>( V ) (m/s)</th>
<th>( W ) (m/s)</th>
<th>( v'_{rms} ) (m/s)</th>
<th>( w'_{rms} ) (m/s)</th>
<th>( v'<em>{rms}^{'} ) ( w'</em>{rms}^{'} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>-0.003472</td>
<td>2.69E-05</td>
<td>0.008971</td>
<td>0.00872</td>
<td>1.028788</td>
</tr>
<tr>
<td>12</td>
<td>0.0005951</td>
<td>-0.0012</td>
<td>0.009087</td>
<td>0.007966</td>
<td>1.140733</td>
</tr>
<tr>
<td>16</td>
<td>0.0016827</td>
<td>-0.0065199</td>
<td>0.013643</td>
<td>0.009867</td>
<td>1.382606</td>
</tr>
</tbody>
</table>

Table 6.2 Mean velocities and rms velocities at different frequencies with stroke \( S = 1.4 \) cm.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>( V ) (m/s)</th>
<th>( W ) (m/s)</th>
<th>( v'_{rms} ) (m/s)</th>
<th>( w'_{rms} ) (m/s)</th>
<th>( v'<em>{rms}^{'} ) ( w'</em>{rms}^{'} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.000671</td>
<td>-0.01783</td>
<td>0.015968</td>
<td>0.019597</td>
<td>0.814803</td>
</tr>
<tr>
<td>12</td>
<td>-0.00103</td>
<td>-0.02927</td>
<td>0.023008</td>
<td>0.02518</td>
<td>0.913764</td>
</tr>
<tr>
<td>16</td>
<td>0.004437</td>
<td>-0.04098</td>
<td>0.033268</td>
<td>0.03164</td>
<td>1.051451</td>
</tr>
<tr>
<td>20</td>
<td>0.002796</td>
<td>-0.04771</td>
<td>0.043894</td>
<td>0.040277</td>
<td>1.089811</td>
</tr>
</tbody>
</table>

Table 6.3 Mean velocities and rms velocities at different frequencies with stroke \( S = 2.5 \) cm.
In the above tables, the ratio of $\frac{v'_{\text{rms}}}{w'_{\text{rms}}}$ (in shaded columns) ranges from 1.0 to 1.3 except for the first two cases at Table 6.3. This indicates that the turbulent flow at the chamber center is nearly isotropic in the y-z plane. If isotropic turbulence is assumed in the x-z plane, which has been consolidated by previous investigations in oscillating-grid mixing box experiments, it can be concluded that at the chamber center a nearly isotropic turbulence is generated by the oscillating perforated plates.

Values of the z direction mean velocity component, $W$, have a uniform sign (negative), which shows that there was a mean secondary flow in the negative Z direction of magnitude of a few centimeters per second. This mean flow might increase the turbulence fluctuation in the mean flow direction, thus causing the decrease the ratio of $\frac{v'_{\text{rms}}}{w'_{\text{rms}}}$. The values of rms turbulent velocity, $v'_{\text{rms}}$ and $w'_{\text{rms}}$ are plotted against the oscillation frequency in Fig. 6.3 for both strokes. It is clear that at the same frequency, when the longer stroke is used, stronger turbulence fluctuations are generated at the chamber center; at the same stroke, the rms velocity increases with increase of oscillation frequency. There is an almost linear relationship between rms turbulent velocity and the oscillation frequency. This trend is shown in Fig. 6.3 by the dashed lines. A noticeable departure from the straight lines is the two points representing the case with stroke of 1.4 cm and frequency of 8 Hz (circled). Frequency spectrum analysis in section 6.2.4 revealed that under such conditions the flow at the center point doesn’t bear the characteristic of turbulence. A possible explanation is that the turbulent energy generated at such an oscillation frequency and stroke is so weak that it can not sustain itself long enough to be diffused to the DI chamber center due to decaying.
6.2.2 Turbulent Kinetic Energy

Turbulent kinetic energy, $k$, is defined as half the trace of the Reynolds stress tensor:

$$k = \frac{1}{2} \langle \mathbf{u}' \cdot \mathbf{u}' \rangle = \frac{1}{2} \left( u'^2 + v'^2 + w'^2 \right).$$

(6.5)

It is the mean kinetic energy per unit mass in a fluctuating velocity field. In a statistically steady turbulent flow field,

$$\langle u'^2 + v'^2 + w'^2 \rangle = \frac{1}{2} (u'^2 + v'^2 + w'^2) = \frac{1}{2} (u'^2 + v'^2 + w'^2) = u_{rms}^2 + v_{rms}^2 + w_{rms}^2 \quad (6.6)$$

In order to calculate $k$ at the DI chamber center, isotropic turbulence in the x-z plane is assumed, thus, $u'_{rms} = w'_{rms}$. Therefore, the turbulent kinetic energy can be calculated by

$$k = \frac{1}{2} \langle \mathbf{u}' \cdot \mathbf{u}' \rangle = \frac{1}{2} (u'_{rms}^2 + v'_{rms}^2 + w'_{rms}^2) = \frac{1}{2} (v'_{rms}^2 + 2 w'_{rms}^2),$$

(6.7)

where, $v'_{rms}$ and $w'_{rms}$ are calculated with Eq. 6.4.

Fig. 6.3 The effect of oscillation frequency on turbulent velocity at the chamber center.
At a stroke of 2.5 cm, $k$ at the DI chamber center is shown in Fig. 6.4 as a function of the oscillation frequency. The turbulent kinetic energy at the chamber center is of order of magnitude $10 \text{ cm}^2/\text{s}^2$ and increases with increase of the oscillation frequency.

![Graph showing turbulent kinetic energy at the DI chamber center at different oscillation frequencies.](image)

**Fig. 6.4 Turbulent kinetic energy at the DI chamber center at different oscillation frequencies.**

### 6.2.3 Integral Length Scale

The integral length scale of the flow is commonly referred to as an Eulerian length scale $l_2$, which can be determined using the spatial correlation as

$$l_2 = \int_0^\infty R_y \, dy = \int_0^V R_y \, dy$$

where, $R_y$ is the spatial correlation of the velocity taken at the same instant in time at two points a distance $y$ apart and is large in an eddy and approaches zero outside the eddy (say a distance $Y$).

The integral length scale is a measure of the average spatial extent or coherence of the fluctuations. For a particular point in the flow, the magnitude of the integral length scale
is a function of not just the quantity correlated but the direction of separation as well depending on which directional correlation is used. It is also the length scale of the largest eddy or the width of the flow.

In this research, LDV measurements were only able to be taken at one point in the DI chamber at any instant, therefore, a direct calculation of the turbulence integral length scale based on Eq. 6.8 could not be carried out. However, equal interval sampling in LDV measurements did produce the time series of velocity data at one point and this provided another means to estimate the turbulence integral length scale.

First, from the time series of velocity data, a one-point, two-time autocorrelation of fluctuation velocity could be carried out. This autocorrelation is called the Eulerian time correlation. Its autocorrelation coefficient, $R_E(\tau)$, in this direction of fluctuation is calculated by

$$R_E(\tau) = \frac{u'(t)u'(t+\tau)}{u'^2(t)} = \frac{u'(t)u'(t+\tau)}{u'_{ms}}, \quad (6.9)$$

where $R_E$ is the Eulerian time correlation coefficient; $u'$ is the fluctuating velocity component in the x direction and in practice, the fluctuation components in the other two directions can also be used for calculation of $R_E$; $t$ and $t + \tau$ are two instants in time, and the over-bar indicates a time average. The Eulerian integral time scale of the turbulence is estimated from $R_E(\tau)$ by $\tau_E = \int_0^\infty R_E(\tau)\,d\tau$. In practice, the integration cannot continue to infinity. Instead, it is taken only from zero to the first zero crossing of $R_E(\tau)$, which is equal to the area under the $R_E(\tau)$ curve, as illustrated in Fig. 6.5. In Fig. 6.6, the autocorrelation coefficient of y-direction fluctuation component $v'$ at the chamber center is drawn against time interval for four frequencies, based on the Eq. 6.9. As one can see,
the shape of the $R_e(\tau)$ curves shifts towards the right with decrease of the oscillation frequency. The calculated integral time scales at different frequencies are shown in Fig. 6.7.

Fig. 6.5 Illustration of the calculation of the integral time scale from the $R_e(\tau)$ curve.

![Diagram](image)

Fig. 6.6 Autocorrelation coefficient curves obtained for cases with different oscillation frequencies (calculation of coefficients was based on y-direction fluctuation component $v'$).

S = 2.5 cm

- 8 Hz, $v$
- 12 Hz, $v$
- 16 Hz, $v$
- 20 Hz, $v$

Decrease of oscillation frequency

![Graph](image)

133

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Fig. 6.7 Variation of the Eulerian integral time scale as a function of oscillation frequency.

In order to estimate the integral length scale of the turbulence, a formula proposed by Abdel-Gayed et al. (1987) was used, which reads

$$ L_i = \sqrt{\frac{8}{\pi} q \tau_E }, \quad (6.10) $$

where, $L_i$ is the integral length scale, $q$ is the characteristic turbulent velocity and $\tau_E$ is the Eulerian integral time scale. The integral length scales at different oscillation frequencies were calculated, based on the horizontal fluctuation component $v'$ (i.e. $q = v'$). These values are depicted in Fig. 6.8 with respect to the oscillation frequency.

As one can see, the integral length scale at the center point has an average value of 0.45 cm over the oscillation frequencies considered. With the oscillation frequency doubled (from 8 Hz to 20 Hz), the integral length scale increases only by 25%.
Before ending this section, we may spend some time to have a look at the smallest turbulence length scale, i.e., the Kolmogorov scale, for broadening our understanding of the turbulence generated by oscillating perforated plates.

An assumption is often made that the rate at which large eddies supply energy to small eddies is proportional to the reciprocal of the time scale of the large eddies (Tennekes and Lumley, 1972). From this assumption, it is not hard to conclude that the dissipation rate $\varepsilon$ is of order $q^3/l$, where, $l$ is turbulence integral length scale and is of same order of magnitude as $L_i$. $q$ is characteristic turbulent velocity and is calculated as $\sqrt{\frac{2}{3}k}$. From the definition of Kolmogorov scale $\eta$

$$\eta = \left(\frac{V}{\varepsilon}\right)^{\frac{1}{4}}, \tag{6.11}$$

we have,
where, $R_e_T$ is turbulence Reynolds number. Table 6.4 lists the Kolmogorov scales at the DI chamber at different oscillation frequencies. The smallest length scale decreases with the increase of the oscillation frequency even though the integral lengths scale in the chamber center keeps roughly constant.

$$\eta = (\nu^3)^{-\frac{1}{4}} l \sim (\nu^3)^{-\frac{1}{4}} \frac{q l}{l} \sim \left(\frac{q l}{l}\right)^{-\frac{3}{4}} R_e_T^{-\frac{3}{4}}$$

(6.12)

Table 6.4 Kolmogorov scale at the DI chamber center at different oscillation frequencies.

<table>
<thead>
<tr>
<th>$f_{osci}$ (Hz)</th>
<th>$\eta$ (cm)</th>
<th>$R_e_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.126822</td>
<td>4.418553</td>
</tr>
<tr>
<td>12</td>
<td>0.099884</td>
<td>6.095961</td>
</tr>
<tr>
<td>16</td>
<td>0.082734</td>
<td>10.34735</td>
</tr>
<tr>
<td>20</td>
<td>0.069468</td>
<td>13.2594</td>
</tr>
</tbody>
</table>

6.2.4 Energy Spectrum

The energy spectrum of turbulence bears unique information which is unattainable in any other way. The value of the spectrum at a given frequency or wavelength is the mean energy in that frequency or wavelength. The spectrum curves of turbulent flows have a distinct shape and thus they can be used as one criterion for verifying if there is strong turbulence in the flows in question.

Two types of spectrum are often referred to, space spectra, which are Fourier transform of correlations taken with a spatial separation and zero delay, and time spectra, which are obtained from correlations taken at the same point with variable time delay. It is easy to tell that the spectra produced form our experiments are time spectra or frequency spectra. From the Eulerian time correlation coefficient, Eulerian frequency spectra $E(n)$ of the
turbulence can be calculated by

\[ E(n) = \overline{u'^2} \int_0^\infty R_E(\tau) \cos 2\pi n \tau \, d\tau . \]  

(6.13)

where, \( n \) is frequency in Hz.

Measurement of the power spectral energy of fluid velocity by LDV is complicated by the random, intermittent nature of the LDV velocity signal caused by the random arrival of the particles at the measurement volume. Due to the uniform time interval between data points, direct transformation of the data using a FFT routine can be carried out through the subroutine built into the FIND software (TSI Incorporated, 2000). The window method and the number of points per FFT were required as input. In this research, the Rectangular Windowing method and 2048 points per FFT were selected and 1024 coefficient frequency spectra were produced.

Fig. 6.9 shows the spectrum for the turbulence generated by the oscillating perforated plates at the oscillation frequency of 8 Hz and stroke of 2.5 cm. At this frequency, the spectrum does exhibit a slope close to the -5/3. Noticeable in Fig. 6.9 are local maxima on this spectrum curve. The first one corresponds to the frequency of 8 Hz and the next one to 16 Hz, followed by those corresponding to multiples of the oscillation frequency. This indicates that there is residual mean flow effect at the measurement point from the interaction of the small jets and wakes generated from the plates due to the proximity of the measurement point to the plate action zone (\( D'/M = 2.7 \)).

Four frequency spectrum curves are shown in Fig. 6.10 for the cases with \( S = 2.5 \) cm and three frequency spectrum curves are shown in Fig. 6.11 for the cases with \( S = 1.4 \) cm. It is easily identified that most of the spectra shown have the distinct shape, i.e., most of the curves have a slope close to -5/3 after a certain value of frequency, except the one for \( f_{osci} \).
Fig. 6.9 Frequency spectrums for the case with $f_{osc} = 8$ Hz and $S = 2.5$ cm. (a) The spectrum is calculated based on $u'$; (b) The spectrum is calculated based on $v'$.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Fig. 6.10 Frequency spectra for the cases with $S = 2.5$ cm. (The spectra are calculated based on $v'$).

Fig. 6.11 Frequency spectra for cases with stroke $S = 1.4$ cm (The spectra are calculated based on $v'$).
= 8 Hz and $S = 1.4$ cm. Fig. 6.12 presents two spectra at oscillation frequency of 4 Hz and stroke of 2.5 cm. Both curves lose the distinct shape seen for the cases with larger oscillation frequencies. It is interesting to see that the multiples of the oscillation frequency are picked up on the spectra for the case with the measurements at 1.0 cm to the left of the DI chamber center, but not picked up on those at the DI chamber center. This hints that at this stroke, there is still residual mean flow from the oscillation of the plate at the location of 1.0 cm from the center, and the effect from this mean flow die out at the DI chamber center.

Fig. 6.12 Frequency spectra for cases with $f_{osci} = 4$ Hz and $S = 2.5$ cm (The spectra are calculated based on $v'$). The measurement point is (a) at the DI chamber center; (b) 1.0 cm to the left of the DI chamber center, i.e., (0, -1, 5).
6.2.5 Discussion

(1) Turbulent velocity decay law

In order to determine the turbulent velocity decay law, the coefficient C, which is calculated by

\[ C = \frac{q}{f_{\text{osci}} S^{1.5} M^{0.5} H^{-1}} \]  

is drawn in Fig. 6.13 against the oscillation frequency, where, \( q \) is the characteristic turbulent velocity and evaluated as \( \sqrt{2k/3} \); \( H = 6.5 \) cm at \( S = 2.5 \) cm and \( H = 7.6 \) cm at \( S = 1.4 \) cm; \( M \) is equal to 1.2 cm.

![Fig. 6.13 The calculated coefficient C versus the oscillation frequency.](image)

As shown in Fig. 6.13, the values of coefficient C show very little variation across the oscillation frequency range considered, except for the case with \( f_{\text{osci}} = 8 \) Hz and \( S = 1.4 \) cm, whose frequency spectrum does not bear the distinct \(-5/3\) slope and need not to be considered as valid data. This hints that C can be deemed as a constant at the frequencies.
and strokes considered and the turbulent velocity decay law can be written in the form

\[ q = C f_{osci} S^{1.5} M^{0.5} H^{-1}. \]  

(6.15)

In the equation above, the power \( n \) for the distance between the plates \( H \) is 1.0 instead of 1.5 in Eq. 2.10, which was obtained by Shy et al. (1997). This difference could be due to the difference in the design of the oscillating devices. In our work, the perforated plates were used, instead of the grids made of square bars, which were used by Shy et al..

(2) Constant \( C \)

Based on the data from Fig. 6.13, the average value of \( C \) is calculated to be 0.312. Compared to \( C \) of 0.89 in Eq. 2.10, which was obtained in a water tank, the smaller value of \( C \) means that the plates have to run at higher frequency or larger stroke to generate the same level of turbulent intensity as the grid running in water.

There are two factors that might contribute to the smaller value of \( C \). The first is the dynamic viscosity of the working fluid. The turbulent energy comes from the oscillating perforated plates. The energy input rate from the plates depends on the speed of the plates and the friction force between the plates and the working fluid the plates pass by. Due to the smaller dynamic viscosity, the friction force induced by the movement of the perforated plates in air is less than that in water at same speeds. Therefore, at the same speed, the turbulent energy generation rate in air is less that in water. The second factor is the kinematic viscosity of the working fluid. Air has a larger kinematic viscosity (Shames, 1992), so the dissipation rate is higher in air than in water with the same intensity field (Tennekes and Lumley, 1972), therefore, turbulent kinetic energy decay faster due to the higher turbulence dissipation rate. The perforated plates have to run at higher frequency and larger stroke to keep up with the faster decay. As one can see, both
reasons are related to the physical property of air.

Besides the property of air, the specific value is certainly affected by the plate design.

(3) Lower-limit cut-off frequency

In previous research on oscillating-grid turbulence, a cut-off frequency was identified (Fernando and Silva, 1993). When the oscillation frequency of the grids is over this cut-off frequency, there is no linear relationship between turbulent intensity and the oscillation frequency. This is illustrated in Fig. 6.14 (extracted from Shy et al., 1997). The cut-off frequency reads 8 Hz in the figure. The possible reason is the unwanted circulating motion at higher oscillation frequency.

![Fig. 6.14 The effect of grid oscillation frequency on turbulent intensity in the mid-plane between two grids (hole and node on the graph denotes the measurement position).](image)

Due to the property of the working fluid in the DI chamber and the plate design, the maximum oscillation frequency used has much exceeded the cut-off frequency obtained in oscillating-grid turbulence in water tanks. The linear relationship between the turbulent intensity and oscillation frequency is no longer valid.
intensity and the oscillation frequency is, however, still kept over the oscillation frequency used. The cut-off frequency could not be determined in our experiments due to limitations with the motion drive system. There appears to be, however, a lower limit on the oscillation frequency of choice for each oscillation stroke. Below this oscillation frequency, there is no linear relationship between the turbulent intensity and the oscillation frequency either. To make distinction with the cut-off frequency, this lower limit of the oscillation frequency is referred to as “lower limit frequency”. From the frequency spectra, it is shown that at a stroke of 2.5 cm, the lower limit frequency is 8 Hz; at a stroke of 1.4 cm, the lower limit frequency is 12 Hz.

6.3 Transient Jet Injection

The results reported in this section come from the integral measurements based on Schlieren imaging. In an effort to identify as many factors as possible that affect the behavior of the transient jets, a number of injected gases and chamber (ambient) gases were used in the experiments, together with different injection pressures and oscillation frequency. Table 6.5 lists the different combinations of injected gas and chamber gas that were tested. For two combination pairs, methane into air and Helium into air (marked with shade in Table 6.5), an experimental matrix of variations in the injection pressure and oscillation frequency was created and is listed in Table 6.6.

<table>
<thead>
<tr>
<th>Injected Gas</th>
<th>CH4</th>
<th>H2</th>
<th>He</th>
<th>CO2</th>
<th>C3H8</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>He</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO2</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Table 6.5 Injection Matrix.
<table>
<thead>
<tr>
<th>Injection Pressure, $p_0$ (gauge)</th>
<th>0.069 MPa</th>
<th>0.138 MPa</th>
<th>0.276 MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{osci}$</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>0 Hz (Quiescent)</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>4 Hz</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>6 Hz</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>8 Hz</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>12 Hz</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

Table 6.6 Experimental matrix.

A complete injection study based on the matrix was carried out for each pair. Note, both sets of perforated plates were also used but not included in the Table 6.6. For the other combination pairs listed in Table 6.5, the injection pressure was usually set to be 0.069 MPa and the chamber gas was kept quiescent, i.e., the perforated plates were set still before and during injection. Such a ‘quiescent’ chamber gas is referred to as ‘$f_{osci} = 0$ Hz’ in the following.

The pressure in the chamber $P_a$ was always kept at atmospheric pressure before injection, and the injection duration was equal to 10 ms for all the presented cases. For cases that required the oscillation of perforated plates, the injection timing was set up so that the injection initiated right at the end of the plates’ last oscillation cycle, that is, the moment that the plates ceased to move at their outer limit positions.

### 6.3.1 Penetration Rate

#### Effect of injection pressure

For methane injection into the chamber filled with air, the penetration depth versus time is shown in Fig. 6.15 for three cases with different injection pressure.
Prior to injection, the 0.3 cm plates were used and oscillated at 8 Hz. The graph clearly shows that with increase of the injection pressure, the methane jet penetrates faster. This result is not particularly surprising since higher injection pressure induces a higher pressure difference across the injector nozzle, thus a higher nozzle exit velocity. As indicated by Hill & Ouellette (1999), for free transient gaseous jets of Reynolds number over $3 \times 10^4$ and for times shorter than the injection duration, the jet penetration after reaching 20 nozzle diameter can be expressed by Eq. 2.1, which can be rewritten as:

$$\frac{z_t}{\left(\frac{M_n}{\rho_a}\right)^{1/4} t^{1/2}} = \Gamma$$

where, $z_t$ is the jet penetration, $M_n$ is the momentum injection rate at the nozzle, $t$ is the time from the beginning of the injection, and $\Gamma$ a constant whose value is $3.0 \pm 0.1$ for turbulent jets issued from round nozzles.
The results shown in Fig. 6.15 may not follow this expression because: (a) the penetration depths measured here are within 20 nozzle diameters from the nozzle; (b) Reynolds numbers of our jets range from 8,000 to 15000, which are less than the required $3 \times 10^4$; (c) wall effect may take effect when jets approach the bottom of the DI chamber; (d) jets in this study interact with ambient turbulence of certain characteristics. However, it is still interesting if the results satisfy the self-similarity behavior. The data in Fig. 6.15 were first rearranged and re-plotted in Fig. 6.16 with the horizontal coordinate as $t^{1/2}$ to investigate if they follow Eq. 6.16. In the figure, the results exhibit linearity to some extent after 1.0 ms, at which the jets have penetrated over the location ten nozzle diameters downstream from the nozzle exit.

![Fig. 6.16 Data of jet penetration depth for cases with different injection pressures.](image)

At injection pressure $p_0$ of 0.138 MPa and 0.276 MPa, the injected gas flow inside the injector might have been choked ($p_a < p^* = 0.52 \ p_0$, based on $\gamma = 1.31$ for methane...
(Munson et al. 2006)) somewhere. Considering that momentum flow rate at the nozzle $\dot{M}_n$ is proportional to that at choked position $\dot{M}^*$, one can write;

$$\dot{M}_n \propto C_f \dot{M}^* = C_f \rho^* c^2 A^* = C_f \rho^* kRT^* A^*$$

$$= C_f \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma - 1}{\gamma}} \frac{p_0}{R} \left( \frac{2}{\gamma + 1} \right) T_0 A^* = C_f \gamma \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma - 1}{\gamma}} p_0 A^*$$ (6.17)

where, $C_f$ is a coefficient, which incorporates the effect of friction and area change from the choked position to the injector nozzle exit, $A^*$ is the area at the choked position and $c$ is the sound speed. As one can see from Eq. 6.17, if the flow inside the injection becomes choked, the momentum flow rate at the nozzle $\dot{M}_n$ is proportional to the injection pressure. Now, the results in Fig. 6.16 are re-plotted in Fig. 6.17 with the similarity penetration depth, $z/(p_0/\rho_0)^{1/4}$ and square root of time, $t^{1/2}$, as coordinates.

![Graph](image-url)

**Fig. 6.17** The similarity penetration depth of transient jets, $z/(p_0/\rho_0)^{1/4}$, versus the square root of time for cases with different injection pressures.

The data for the cases with $p_0$ at 0.138 MPa and 0.276 MPa do gather close to a straight
line after some distance from the nozzle. The departure from the straight line in the nozzle vicinity is anticipated as the jet is still in the transition regime. Due to possible wall effects, the penetration slows down when the jet approaches the bottom of the DI chamber. This is reflected in Fig. 6.17. As one can see, the data points for the case with \( p_0 = 0.138 \) MPa start to deflect away from the straight line after \( t^{1/2} \) passes 1.7.

The data for the case with \( p_0 = 0.069 \) MPa are also re-plotted in Fig. 6.17 for comparison. The data points for early stages in the injection match those for the other two cases quite well. There is also a deflection from the straight line, but this deflection occurs at a much earlier moment than that for the other two cases, which may actually suggest a different proportionality coefficient between the two similarity variables.

**Effect of the injected gas composition**

Four different gases, methane, helium, hydrogen and \( \text{CO}_2 \), were injected under the same pressure \( (0.069 \) MPa) into the DI chamber filled with air at atmospheric pressure. The measured penetration depths are plotted in Fig. 6.18 with respect to the time since start of injection.

It is interesting to notice that helium, the second lightest gas, keeps up with the other gases in penetration, and \( \text{CO}_2 \), the heaviest gas, does not show any advantage in penetration. This is not surprising. As indicated by Eq. 6.16, the penetration depth of a transient gaseous jet is proportional to the momentum flow rate to its \( \frac{1}{2} \) power. Under such pressure, the flow across the injector is all subsonic and the momentum flow rate is approximately proportional to pressure difference across the injector, which was same for all cases \( (0.069 \) MPa).
Similar phenomena were also observed for the cases with higher injection pressure, under which, the flow inside the injector may become choked somewhere. From Eqs. 6.16 and 6.17, it is easy to see that when, injection is into same ambient gas at the same ambient pressure, the penetration depth of different gases is proportional to the product, 

\[ \gamma \left[ \frac{2}{\gamma + 1} \right]^\gamma, \]  

for each gas. This product is referred to as ‘the K coefficient’. The relationship between K and \(\gamma\) for gases used in this study is shown in Fig. 6.19. The ratio of K in its \(\frac{1}{4}\) power for helium and CO2 is 1.034. This ratio may explain the phenomena that with the same injection pressure (and ambient condition of transient gas jet with choking), the lighter gas with larger K coefficient can keep up with the heavier gases in terms of jet penetration.
Fig. 6.19 Relationship between K coefficient and $\gamma$.

**Effect of different ambient gases**

In this study hydrogen at same pressure was injected into the DI chamber filled with helium, air and CO$_2$, respectively. The penetration data are plotted in Fig. 6.20 with

Fig. 6.20 Penetration depth for cases with different ambient gases. $p_0 = 0.069$ MPa; $f_{osc} = 0$ Hz.
respect to the time since start of injection. The injection pressure was at 0.069 MPa and the chamber gases were at atmospheric pressure.

As seen from Fig. 6.20, the penetration depths into helium are larger and increase noticeably faster than for two other gases. Hydrogen penetrates somewhat faster into air than into CO₂. From Eq. 6.16 one can see that density of ambient gas plays an essential role. The ratio of the densities to 1/4 power for helium, air and CO₂, which is equal to 1:1.63:1.82, explains the relative positions of the penetration curves in Fig. 6.20.

**Effect of the oscillation frequency**

To investigate the effect of the ambient turbulence on the behavior of the transient jet, which is not included in Eq. 6.16, methane injection at 0.069 MPa into the chamber filled with air at atmospheric pressure was carried out. The turbulence in the DI chamber air was prepared with the oscillating plates at 4, 8, and 15 Hz, respectively, up to the moment of the start of injection. The penetration curves are shown in Fig. 6.21 for these three

![Fig. 6.21 Penetration depth for cases with different oscillation frequencies. Methane at 0.069 MPa injected into chamber air; d = 0.3 cm.](image-url)
cases together with the one for the case with methane injection into the quiescent chamber air at the same pressure conditions. Little difference is shown among the penetration curves for the cases with the oscillation frequency of 0, 4 and 8 Hz, indicating that changing oscillation frequency, i.e. altering the turbulence intensity from 0 to 0.92 cm/s (based on Eq. 6.15) does not make a noticeable difference in penetration depths of the methane transient jet at this injection pressure. Similar results were obtained for the helium injection into air under similar conditions. This is a disappointing, although not entirely surprising, result. Two factors may contribute this result: the first is the fast decay of the chamber turbulence kinetic energy (Xia and Sobiesiak, 2002); the second is the strong turbulence induced by the jet itself, which may overshadow the effect of the chamber turbulence. However, it is still interesting to notice, that the penetration curve for the case with 15 Hz is below those for all other three cases, which may suggest that the decaying turbulence generated by the perforated plates tends to make the gaseous jet penetrate slower.

**Effect of the perforation hole diameter**

Both sets of perforated plates (0.3 cm plates and 1.0 cm plates) were used to prepare the zero-mean nearly isotropic turbulent air motion inside the DI chamber in the experiments with helium injection. The injection pressure was 0.069 MPa and the oscillation frequency was set to be 8 Hz. Fig. 6.22 depicts the penetration depths versus time for both cases. Both curves show a similar shape as the ones obtained in previous discussion. The penetration depth curve for the case with 1.0 cm plates is slightly above the one with 0.3 cm plates in Fig. 6.22, but considering the uncertainty in image processing discussed in Chapter 4 (0.579 cm), no definite conclusion could be suggested.
6.3.2 Spread Angle
As an important measure for evaluation of behavior of transient jets in the confined chamber, spread angles were extracted for a number of cases and are tabulated in Table 6.7. In general, the spread angles measured from the Schlieren movie are in the range between 20 and 30 degrees. An exception is the spread angle for the hydrogen jet when injected into Helium. A much slimmer jet had been observed and the spread angle measured is 16 degrees (marked with shade in Table 6.7).

From the data in group (b), it seems that the spread angle of a transient jet increases with decrease of the density of the chamber (ambient) gas. Caution, however, should be exercised when reading the data for different gases. When Helium or Hydrogen, which is much lighter than air, is injected into air, a stronger Schlieren effect is produced than that for methane or CO2 injection due to the larger density gradients. When the same threshold values are used to detect the boundary on the Schlieren images, large errors

Fig. 6.22 Penetration depth for cases with different sets of perforated plates. Helium at 0.069 MPa injected into chamber air, \( f_{\text{osc}} = 8 \) Hz.
could result from any blurring of the boundary on the Schlieren images of methane or CO2 jet.

<table>
<thead>
<tr>
<th>Group index</th>
<th>Common conditions</th>
<th>Differing conditions</th>
<th>Spread angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>Helium@0.069 MPa</td>
<td>d = 1.0 cm</td>
<td>27.64</td>
</tr>
<tr>
<td></td>
<td>into air; $f_{osc} = 8$ Hz</td>
<td>d = 0.3 cm</td>
<td>29.1</td>
</tr>
<tr>
<td>(b)</td>
<td>Injected gas</td>
<td>CO$_2$</td>
<td>21.1</td>
</tr>
<tr>
<td></td>
<td>$p_0 = 0.069$ MPa;</td>
<td>Methane</td>
<td>23.35</td>
</tr>
<tr>
<td></td>
<td>Ambient gas: air</td>
<td>Helium</td>
<td>26.95</td>
</tr>
<tr>
<td></td>
<td>$p_a = 0$ MPa;</td>
<td>Hydrogen</td>
<td>28.1</td>
</tr>
<tr>
<td></td>
<td>$f_{osc} = 0$ Hz.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c)</td>
<td>Injected gas: H$_2$</td>
<td>Air</td>
<td>28.1</td>
</tr>
<tr>
<td></td>
<td>$p_0 = 0.069$ MPa ;</td>
<td>CO$_2$</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>$p_a = 0$ MPa;</td>
<td>Helium</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>$f_{osc} = 0$ Hz.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.7 Spread angles of transient jets for selected cases.
Chapter 7  Results from Numerical Simulations

7.1  Introduction

In this chapter, results from the numerical simulations are examined. In order to explore the effects of different factors on the transient jet behavior, a simulation case matrix was set. All the simulated cases are listed in Table 7.1. In general, all the simulation cases are categorized into three groups: without injection, injection into stirred chamber air and injection into quiescent chamber air. The individual cases differ with respect to variables such as injection velocity (W0), injection duration (D_{inj}), oscillation frequency (f_{osc}), oscillation stroke (S), plate state during injection and injection phase. Due to the lower limit frequency discussed earlier in Chapter 6, the minimum oscillation frequency was chosen to be 8 Hz.

During the experiments, in order to create a stationary zero-mean velocity isotropic turbulent flow field in the middle of the DI chamber before injection, where the turbulence characteristics change little with time, the plates were kept running for at least 500 cycles. This was easily set up through the LabView control program. The plate movement usually lasted roughly 70 seconds, for example, for the case with the oscillation frequency of 8 Hz. In numerical simulations, however, it is neither necessary nor practical to simulate the plate oscillation for that many cycles. Firstly, the simulated turbulent flows might have developed the stationary turbulent flow in the middle of the chamber long before the end of cycle 500. Secondly, it takes approximately 24 hours for the plates to complete 3 cycles, thus it would require 160 days to finish 500 cycles. Therefore, numerical experiments were carried out to determine the minimum number of
cycles, after which the turbulence characteristics could be assumed to be stationary. In these numerical experiments, turbulent kinetic energy and turbulence length scale were monitored with cycle number and an asymptotic behavior was found for both quantities. The maximum cycle number that has been simulated is 22 for two cases, one with the oscillation frequency $f_{osci} = 12$ Hz and one with $f_{osci} = 20$ Hz. Therefore, the results for the turbulent field generated by the plate oscillation that are presented here come from simulations up to the 22nd cycle. Also, the transient injection for the cases with ‘injection into stirred chamber air’ was simulated with the turbulence characteristics taken from the 22nd cycle.

For consistency in presenting of the results, the same coordinate system defined in Section 6.1 (see Fig. 6.1) is used and shown in Fig. 7.1(a). The origin coincides with the center of the injector nozzle exit. The injector nozzle centerline (‘centerline’ hereinafter) therefore coincides with z-axis and is shown as a dashed line in Fig. 7.1(a).

The simulation results are frequently visualized across a plane slicing through the computational domain. Such a plane is called a cut-plane. A cut-plane which is on the y-z plane and right across the origin is referred to as a ‘C-plane’ hereinafter (see Fig. 7.1(a)). On the C-plane, the segment of a straight-line on the y-axis between the chamber walls is defined as the ‘C-line’, which is shown as a dashed line in Fig. 7.1(b).

In Fig. 7.1(b), the limit positions of the plates are also marked with dotted lines. From now on, the planes of the plates facing the center of the chamber are referred to as ‘inner limit planes’ when the plates are in their inner limit positions. In the same way, the planes of the plates facing the walls are referred to as ‘outer limit planes’ when the plates are in their outer limit positions. The space between two inner limit planes is defined as ‘the
<table>
<thead>
<tr>
<th>Cases Variable</th>
<th>Without Injection</th>
<th>Injection into Stirred Chamber Air</th>
<th>Injection into Quiescent Chamber Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Velocity</td>
<td>W0 m/s</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Injection Duration</td>
<td>D_{\text{inj}} ms</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Hole Diameter of the Plates, d cm</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Oscillation Stroke</td>
<td>S cm</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Plate State During Injection</td>
<td>Stop</td>
<td>Run</td>
<td>Run</td>
</tr>
<tr>
<td>Injection Phase</td>
<td>-180</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Oscillation Frequency (Hz) $f_{\text{osci}}$

| 8 | × |
| 12 | × | × | × |
| 16 | × |
| 20 | × | × | × | × | × | × | × | × | × |
| 50 | × |

Table 7.1 Simulation matrix.
Fig. 7.1 The Coordinate system and terminology.
central region' and the region between the inner and outer limit planes of one plate as 'the plate sweep region'.

The simulation results for the turbulent flow field generated by the oscillation of a pair of perforated plates are presented in Section 7.2. The results on the turbulent transient injection are discussed in Section 7.3.

7.2 DI Chamber Turbulent Flow Field

In this section, the simulation results for the chamber turbulent flow without injection are examined. Focus is on the cyclic behavior of the chamber flow field, including the turbulence characteristics (turbulent kinetic energy and turbulence length scales) and the velocity field. The asymptotic behavior of the turbulence characteristics in the chamber central region is also discussed, together with the deemed asymptotic turbulence characteristics at the chamber center point.

During examination of the cyclic behavior of the turbulent flow field, the state of the perforated plates (position and direction of movement) during a cycle needs to be clearly identified. Two quantities are specified for this purpose: the distance between the mid-plane of the plate and the chamber center; the direction of the plates' movement, with 'in' denoting the plates moving towards their inner limit positions and 'out' denoting movement towards their outer limit positions. Thus only a pair of numbers is enough to specify both plates due to their symmetry to the chamber center during oscillation (running against each other). For example, if the plates in Fig. 7.1(a) are assumed to be 3 cm from the chamber center and moving towards their outer limit positions, '3.0 cm, out' is used to represent the state of both plates.

Air is the chamber gas for most cases presented, unless specified otherwise.
7.2.1 Velocity Field
With the \( k-e \) turbulence model, three ‘mean’ (time-averaged over the time step in the simulation) velocity components \( U, V, W \) are calculated from the governing equations and output at specified intervals.

Figs. 7.2 through 7.11 visualize the \( V \)-component velocity (horizontal, in the direction of plate movement) magnitude and the velocity vector across the C-plane for the case with an oscillation frequency of 12 Hz and a stroke of 2.5 cm. The figures start with the velocity field corresponding to the beginning of the 18th cycle; five instants at equal intervals are selected, with a quarter cycle interval between two consecutive instants.

Analysis of these graphs reveals that the velocity magnitude in the central region is much smaller than that in the plate sweep regions through the entire cycle. This region of weaker flow can be identified as the mass ‘blue’ area in the central part of the mean velocity vector maps or the ‘green’ area of the \( V \)-component maps.

In contrast to the central region, there are strong jets and wakes in the plate sweep regions. This is easily identified in the visualized velocity vector graphs. With the plates passing through, the chamber gas is forced through the areas of the holes and turned into the jets moving against the plates, whereas the wakes are generated behind the solid areas of the plates and follow the plates. With alternation of the directions of the plate movement, these flows also switch directions. This is clearly shown by comparing Fig. 7.4 and 7.8.

There are residual flows ahead of the plates in the directions of the plate movement, which are left over from the previous sweeping of the plates. Therefore, the two plate sweep regions are filled with these interweaved jets and wakes that are aligned with the areas of the holes and the solid parts of the plates, respectively.
For quantitative appreciation of these two distinct regions, the three velocity components U, V, W along the C-line at the five instants are displayed in Figs. 7.12, 7.13 and 7.14, respectively. Note that the C-line crosses the jet flows in the plate sweep regions. Dashed lines in the figures are drawn at the locations of the inner and outer limit planes. It is clear from Fig. 7.12 that in the central region, particularly, about one diameter of the plate holes away from the inner limit planes, the velocity component V is on the order of magnitude of 1.0 cm/s through the entire cycle. This is one order of magnitude less than the average speed (about 40 cm/s) of the small jets from the plate sweep regions, which can be roughly approximated as half of the maximum speed of the jets. The same trends are observed for the other two components in Figs. 7.13 and 7.14, except that the magnitude of these two velocity components is at least one order of magnitude lower than the V component across the whole C-line.

Generally speaking, the simulations show that a ‘weak’ flow region is formed in the central region, about two plate mesh size (M) away from the neutral planes of the oscillating plates. The reason it is termed ‘weak’ is that the order of magnitude of these flows are not only small in absolute value, but also negligible in comparison to the gaseous jet injection velocity (40 m/s). Besides, this ‘weak flow’ retains its velocity magnitude during a cycle, thus the time-averaging process over the time span of any length would result in a ‘weak’ flow of the same magnitude. In this sense, this flow within the central region can be approximated as the ‘zero mean velocity’ flow and this region can be deemed as the ‘zero mean velocity’ region.
Fig. 7.2 The field of the magnitude of the velocity $V$-component across the C-plane at the 18th cycle with the plates 4.46 cm, $f_{\text{act}} = 12$ Hz, $S = 2.5$ cm.
Fig. 7.3 Visualization of the velocity vector field across the C-plane at the 18th cycle with the plates 4.46 cm, in; $f_{onc} = 12$ Hz, $S = 2.5$ cm.
Fig. 7.4 The field of the magnitude of the velocity V-component across the C-plane at the 18th cycle with the plates 2.93 cm, in; \( f_{\text{osc}} = 12 \) Hz, \( S = 2.5 \) cm.
Fig. 7.5 Visualization of the velocity vector field across the C-plane at the 18th cycle with the plates 2.93 cm, in; $f_{act} = 12$ Hz, $S = 2.5$ cm.
Fig. 7.6 The field of the magnitude of the velocity V-component across the C-plane at the 18th cycle with the plates 2.04 cm, out; $f_{osc} = 12$ Hz, $S = 2.5$ cm.
Fig. 7.7 Visualization of the velocity vector field across the C-plane at the 18th cycle with the plates 2.04 cm, out; $f_{oc}$ = 12 Hz, $S$ = 2.5 cm.
Fig. 7.8 The field of the magnitude of the velocity V-component across the C-plane at the 18th cycle with the plates 3.57 cm, out; $f_{osc} = 12$ Hz, $S = 2.5$ cm.
Fig. 7.9 Visualization of the velocity vector field across the C-plane at the 18th cycle with the plates 3.57 cm, out; $f_{osc} = 12$ Hz, $S = 2.5$ cm.
Fig. 7.10 The field of the magnitude of the velocity V-component across the C-plane at the 18th cycle with the plates 4.46 cm, in; $f_{osc} = 12$ Hz, $S = 2.5$ cm.
4.46 cm, $f_{null} = 12$ Hz, $S = 2.5$ cm.

Fig. 7.11 Visualization of the velocity vector field across the C-plane at the 18th cycle with the plates 4.46 cm, in: $f_{null} = 12$ Hz, $S = 2.5$ cm.
Fig. 7.12 The magnitude of the y-direction velocity component $V$ along the C-line.
Fig. 7.13 The magnitude of the x-direction velocity component $U$ along the C-line.
7.2.2 Turbulent Kinetic Energy $k$

The turbulent kinetic energy $k$ (per unit mass, in $\text{m}^2/\text{s}^2$) is part of the direct numerical solution of the governing equations (see Eq. 5.7), following the use of the $k-e$ turbulence model.

Figs. 7.15 through 7.17 visualize the $k$ field across the C-plane at five instants in the cycle. The flow field is generated by the plate oscillation with the oscillation frequency of 12 Hz and the stroke of 2.5 cm. Two distinct regions can be identified from these graphs. The central region, which is shown as the blue area in the middle, exhibits low levels of $k$; the plate sweep regions contain much higher turbulent kinetic energy due to the generation activity. The maximum $k$ value appears to be right behind the solid part of the
plates, where the mean velocity gradients are largest due to the possible strong recirculation flows, which result from the interaction of the jets and wakes formed behind the perforated plates.

To have a clear appreciation of the change of $k$ during the cycle, $k$ values along the C-line at the same four instants as in Figs. 7.16 and 7.17 are shown in Fig. 7.18. As can be seen, $k$ changes throughout the cycle at locations close to the inner limit planes. Away from the inner limit planes, in the central region, the magnitude of change of $k$ during a cycle is much smaller, meaning that the flow generated by the plate oscillation does not penetrate deeply in the direction of plate movement. At positions between $y = -1$ cm and $y = 1$ cm, which are about twice the plate mesh size ($M = 1.2$ cm) away from neutral planes, the oscillating flows from the plate oscillation diminishes and the turbulent kinetic energy varies a negligible degree during the cycle, display a uniform profile in this range with quite a low value.

For the same case, the turbulent characteristic velocity $q$, which is defined by

$$ q = \sqrt[3]{\frac{2k}{3}}, \quad (7.1) $$

is shown in Fig. 7.19 along the C-line between $y = -1$ cm and $y = 1$ cm at the same instants as in Fig. 7.18. The turbulent characteristic velocity has the lowest value at the chamber center and gradually increases with distance from the center. If evaluated in terms of order of magnitude, the turbulent characteristic velocity can be taken as uniform across the range of $y$ (between -1 and 1 cm) considered within the cycle.

To follow the evolution of $k$ in the central region, $k$ values along the segment of the C-line between inner limit planes have been plotted in Fig. 7.20 and Fig. 7.21 for up to the 22nd cycle. Fig. 7.20 shows the results for the case with $f_{osci} = 20$ Hz and Fig. 7.21 for
$f_{osci} = 12$ Hz. The state of the plates, was ‘3.57 cm, out’. This instant corresponds to the end of the cycle. It can be seen from both graphs that the $k$ profiles start with the shape of ‘deep well’, then evolve over time, and eventually acquire a shape of ‘shallow bowl’. The $k$ at the chamber center increases by four orders of magnitude within nine cycles. After that the increase tends to be smaller with each cycle.

The $k$ values at chamber center are plotted in Fig. 7.22 as a function of the cycle number for these two cases. The $k$ values at the chamber center for both cases do not show noticeable change until the fifth cycle and then increase quickly with cycle number. The increase slows down after the tenth cycle. Eventually, the curves for both cases arrive to a plateau. This happens after cycle 15 for the case with $f_{osci} = 12$ Hz and after cycle 22 for the case with $f_{osci} = 20$ Hz. These results clearly show that the value of $k$ in the center has an asymptotic behavior, indicating a trend to equilibrium between the turbulent energy generation and its dissipation.

A question can be asked why it takes more cycles to get the $k$ to the plateau level of $k$ for the case with a higher oscillation frequency. The answer is derived from Fig. 7.23, in which the $k$ is plotted as a function of the elapsed oscillation time. The graph indicates that it takes a shorter time for the $k$ to reach the asymptotic value for the case with the higher oscillation frequency (about 1.1 second for case with $f_{osci} = 20$ Hz, as opposed to 1.4 second for $f_{osci} = 12$ Hz). This is not surprising, as at a higher oscillation frequency, more energetic turbulence is generated with larger characteristic turbulent velocity, and it takes less time for the turbulent eddies to move across the same distance from the plate sweep region to the DI chamber center.

From the results in Figs. 7.22 and 7.23, and the asymptotic behavior of the turbulence
length scale, which is presented in next section, it was decided to terminate the running of
the simulation at the oscillation cycle 22 for both cases.

For the stroke of 2.5 cm, five oscillation frequencies have been used in the simulations.
For the cases with \( f_{osci} = 12 \text{ Hz} \) and 20 Hz, the simulations proceed to cycle 22. For the
cases with \( f_{osci} = 8 \text{ Hz} \) and 16 Hz, the simulations proceed to cycle 15 due to limitations
on computing time. The \( k \) values at the chamber center on the last cycle are all listed in
Table 7.2 except for the case with \( f_{osci} = 50 \text{ Hz} \). Also listed in this table is the

The values of \( k \) and \( q \) are plotted in Fig. 7.24 against the oscillation frequency. The turbulent
characteristic velocity increases linearly with the oscillation frequency, as indicated by a
dashed straight line in Fig. 7.24(b).

As may be noticed in Fig. 7.24(b), the \( q \) value for the case with \( f_{osci} = 16 \text{ Hz} \) is below the
dashed line. This is anticipated. The lower the oscillation frequency is, the lower
turbulence intensity is generated in the plate sweep regions. Thus, the time it takes for the
turbulence energy in the sweep regions to diffuse to the chamber center is longer, and so
is the time it takes for the turbulence quantities in the chamber to reach their asymptotic
values. Therefore, a longer time is expected for the turbulence quantities to reach their
asymptotic values for the case with \( f_{osci} = 16 \text{ Hz} \) than that with \( f_{osci} = 20 \text{ Hz} \). However, the
\( q \) value shown in the Fig. 7.24(b) for the case with \( f_{osci} = 16 \text{ Hz} \) is taken from the end of
cycle 15, by the end of which, the perforated plates have only oscillated for 0.95 second
\((=\frac{15}{16 \text{ Hz}})\). This is even shorter than the time it takes for the turbulence quantities in the

chamber center to approach to their asymptotic values, which is 1.1 \((=\frac{22}{20 \text{ Hz}})\) seconds.

178
Therefore, we can anticipate that the $q$ value for the case with $f_{osci} = 16$ Hz is less than its asymptotic value, which is represented by the value on the dashed line in Fig. 7.24(b).

Fig. 7.15 Visualization of turbulent kinetic energy field on the C-plane at cycle 15 with $f_{osci} = 12$ Hz, $S = 2.5$ cm; the plate state '3.57, out'.
Fig. 7.16 Visualization of turbulent kinetic energy field on the C-plane at cycle 15 with $f_{ext} = 12$ Hz, $S = 2.5$ cm; the plate state (a) '4.46 cm, in'; (b) '2.93 cm, in.'
Fig. 7.17 Visualization of turbulent kinetic energy field on the C-plane at cycle 15 with $f_{out} = 12$ Hz, $S = 2.5$ cm; the plate state (a) '2.04 cm, out' (b) '3.57 cm, out'.
Fig. 7.18 Turbulent kinetic energy along the C-line at four instants within cycle \( f_{osc} = 12 \) Hz; \( S = 2.5 \) cm; in the central region.

Fig. 7.19 Turbulent characteristic velocity along the C-line between \( y = -1 \) cm and \( y = 1 \) cm at four instants within cycle \( f_{osc} = 12 \) Hz; \( S = 2.5 \) cm; in the central region.
Fig. 7.20 Cyclic turbulent kinetic energy along the C-line for the case with oscillation frequency of 20 Hz.
Fig. 7.21 Cyclic turbulent kinetic energy along the C-line for the case with oscillation frequency of 12 Hz.
Fig. 7.22 Turbulent kinetic energy at the DI chamber center versus cycle number.

Fig. 7.23 Turbulent kinetic energy at the DI chamber center versus time.
Table 7.2 Turbulent kinetic energy and turbulent intensity at the DI chamber center for different oscillation frequency.

<table>
<thead>
<tr>
<th>( f_{osc} ) (Hz)</th>
<th>( k ) at the chamber center (cm(^2)/s(^2))</th>
<th>Turbulent characteristic velocity, ( q ) (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>5.75</td>
<td>1.958</td>
</tr>
<tr>
<td>12</td>
<td>11.75</td>
<td>2.799</td>
</tr>
<tr>
<td>16</td>
<td>17.5</td>
<td>3.416</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>4.472</td>
</tr>
</tbody>
</table>

Fig. 7.24 Turbulent kinetic energy and the turbulent intensity at the DI chamber center.
7.2.3 Turbulence Length Scales

The turbulence length scale is not a variable that is directly solved using the governing equations. However, with the turbulent kinetic energy $k$ and turbulent energy dissipation rate $\varepsilon$ solved from the $k$ - $\varepsilon$ turbulence model, a turbulence length scale proportional to $k^{3/2}/\varepsilon$ can be calculated. This turbulence length scale is often called the 'turbulence macro-length scale' and denoted by $L_e$. In KIVA-3V, $L_e$ is calculated by

$$L_e = \frac{c_p^{3/4} \cdot k^{3/2}}{\kappa \cdot \varepsilon}$$  \hspace{1cm} (7.2)$$

where, $\kappa$ is the von Karman constant, and $c_p$ is one of the $k$ - $\varepsilon$ turbulence model constants.

Fig. 7.25 through Fig. 7.28 visualize the calculated $L_e$ field at four instants within cycle 18 for the case with $f_{osc} = 12$ Hz and $S=25$ mm. Similar to the $k$ field, the central region and the plate sweep regions display distinctly different behavior during the cycle. In the central region, particularly the region between $y = -1$ cm and $y = 1$ cm, $L_e$ does not show much change during the cycle. But in the sweep region, $L_e$ exhibits periodic behavior. It is easily identified that the maximum values of $L_e$ appear in the central region of the chamber and the minimum values appear on the wall boundary and around the solid parts of the plates. A quantitative appreciation of the above behavior can be found in Fig. 7.29, in which the $L_e$ values at the same instants as in Fig. 7.25 through Fig. 7.28 are drawn along the C-line. The $L_e$ between $y = -1$ and $y = 1$ cm keeps similar profile during the cycle, with a peak value in the center (the chamber center) and gradually decreasing with distance away from the center until a position about one mesh size away from the inner limit planes. At positions further away from the center, $L_e$ shows a periodic behavior, determined by the plate state. There is a negligible increase in the peak value at the end of
this cycle (with plates 3.57 cm, out), compared with that at the early instants (with plates 4.46 cm, in).

In order to examine the behavior of the $L_e$ over a number of cycles at one instant, the $L_e$ along the C-line for the case with $f_{osci} = 12$ Hz is drawn in Fig. 7.30 for up to cycle 22, starting at cycle 5. Within the range of cycles, the $L_e$ profile in the central region changes dramatically, from a shape of ‘valley’ to a ‘hill’. This result is due to the interaction of the two turbulent flows generated by each oscillating plate.

The $L_e$ values at the chamber center from Fig. 7.30 are plotted in Fig. 7.31 as a function of the cycle number. It is clearly visible that $L_e$ increases quickly for the first 15 cycles or so and then the increase becomes much slower. After the 18th cycle, $L_e$ shows a minimum increase with cycle number, an additional indication of the asymptotic behavior of the flow. The $L_e$ values at the chamber center for the case with $f_{osci} = 20$ Hz are also shown in Fig. 7.31. Only selected results for the higher cycle numbers are shown. These $L_e$ values are above those for 12 Hz and the curve is quite flat, indicating the slow increase stage.

<table>
<thead>
<tr>
<th>$f_{osci}$</th>
<th>$L_e$ (cm)</th>
<th>Percentage of increase compared with $L_e$ at 8 Hz ($\frac{L_{e_{f_{osci}}}}{L_{e_{8Hz}}} \times 100%$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 Hz</td>
<td>0.535162 (at cycle 15)</td>
<td>0</td>
</tr>
<tr>
<td>12 Hz</td>
<td>0.574038 (at cycle 22)</td>
<td>7.26%</td>
</tr>
<tr>
<td>16 Hz</td>
<td>0.550050 (at cycle 15)</td>
<td>2.78%</td>
</tr>
<tr>
<td>20 Hz</td>
<td>0.586645 (at cycle 22)</td>
<td>9.26%</td>
</tr>
</tbody>
</table>

Table 7.3 The $L_e$ at the chamber center at different oscillation frequency.
The $L_e$ at the chamber center at cycle 22 for the cases with $f_{osci} = 12$ Hz and 20 Hz are tabulated in Table 7.3, together with $L_e$ values for the cases with $f_{osci} = 8$ Hz and 16 from cycle 15. These data are re-plotted in Fig. 7.32. As seen from this graph, with increase of the oscillation frequency, there is only a slight increase in $L_e$. With the frequency doubled, the increase of $L_e$ is less that 10%. The average value of $L_e$ in the DI chamber center reads 0.55 cm over the oscillation frequency range considered.

Fig. 7.25 Visualization of $L_e$ field on the C-plane at the 18th cycle with plates 4.46 cm, in; $f_{osci} = 12$ Hz, $S = 2.5$ cm.
Fig. 7.26 Visualization of $L_z$ field on the C-plane at the 18th cycle with plates (a) 2.93 cm, in; $f_{out} = 12$ Hz, $S = 2.5$ cm; (b) 2.04 cm, out; $f_{out} = 12$ Hz, $S = 2.5$ cm.
Fig. 7.27 Visualization of $L_e$ field on the C-plane at the 18th cycle with plates 3.57 cm, out; $f_{osc} = 12$ Hz, $S = 2.5$ cm.

Fig. 7.28 Visualization of $L_e$ field on the C-plane at the 18th cycle with plates 2.93 cm, in; $f_{osc} = 12$ Hz, $S = 2.5$ cm.
Fig. 7.29 The turbulence macro-length scale along the C-line at four instant during the 18th cycle.

Fig. 7.30 The turbulence macro-length scale along the segment of C-line (between the inner limit planes) at different cycles at the instant with plates '2.04 cm, out'.
Fig. 7.31 The turbulence macro-length scale at the chamber center versus the cycle number.

Fig. 7.32 The turbulence macro-length scale at the chamber center for different oscillation frequency.
7.2.4 Discussion

**Nearly zero-mean velocity region**

The simulations with the oscillation of the perforated plates have been carried out up to 22 cycles for two cases, one with $f_{osci} = 12$ Hz and one with $f_{osci} = 20$ Hz, due to limitations on computation time.

The simulation results show that the turbulent kinetic energy is mainly generated in the plate sweep region, where the flow properties (velocity and turbulent quantities) display a periodic behavior due to the oscillation of the plates. Both the turbulent kinetic energy $k$ and turbulence macro-length scales $L_e$ in the central region go through a transition and come to a relative steady state without the periodic behavior, which is a result of interaction of the turbulent energy transported from both sides of the central region. After the 22nd cycle, a zero-mean velocity turbulent flow is formed inside the central region, about twice the plate mesh size away from the neutral planes of the oscillating plates, where the turbulent characteristic velocity is nearly uniform, and $L_e$ has a peak value at the chamber center and decreases with distance away from the chamber center.

The average value of $L_e$ across this region is about 0.44 cm, with the peak value averaging 0.55 cm. The turbulent characteristics of this region can be deemed to be 'nearly uniform' in terms of their variation across the range from $y = -1$ to $y = 1$ cm.

During simulations, the turbulent kinetic energy $k$ and the turbulence macro-length scale $L_e$ at the chamber center display asymptotic behavior with increasing number of oscillation cycles. The time to reach this asymptotic state is different for different oscillation frequencies, hinting at a different turbulence time scale for transporting the turbulent energy from the generation regions (plate sweep regions) to the chamber center.
After cycle 22 these quantities in the region mentioned above (about twice plate mesh size away from the neutral planes of the oscillating plates) can be approximated as their asymptotic values and are stationary. The transient injection simulations will be continued from this point in simulating cases involving injection into the stirred chamber air.

**Turbulence characteristic in the chamber center**

Results show that the stationary turbulent characteristic velocity, \( q \), at the chamber center shows a linear increase with increase of oscillation frequency (see Fig. 7.24b), but the turbulent length scale \( L_e \) does not show a significant increase with the increase of the oscillation frequency (see Fig. 7.32). The average value of the \( L_e \) at the chamber center is about 0.55 cm over the oscillation frequency considered.

The stationary turbulent characteristic velocity \( q \) at the chamber center is taken into Eq. 6.15 to calculate the coefficient \( C \). Calculated values of \( C \) are plotted in Fig. 7.33 versus the oscillation frequency. In the calculation, \( S = 25 \) mm and \( H = 65 \) mm.

![Fig. 7.33 The values of coefficient C from numerical simulations versus the oscillation frequency.](image)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
As one can see, the $C$ values do not show large variations with the oscillation frequency and can be deemed as constant over the oscillation frequency considered. This displays a compliance of the computed $q$ at the chamber center to the turbulence decay law correlated from experimental data obtained in the water. The arithmetic average value of $C$ is 0.343.

### 7.3 Turbulent Transient Jet

Simulation results for the turbulent transient jet are presented in this section. The transient jet behavior is described in terms of the transient jet penetration rate (the penetration depth versus injection time), spread angle, velocity and concentration field. The injected gas is methane, and the methane mass fraction $X_{CH_4}$ is employed for visualization of the concentration field. $X_{CH_4}$ is calculated as

$$X_{CH_4} = \frac{\rho_{CH_4}}{\rho}$$  \hspace{1cm} (7.3)

where, $\rho_{CH_4}$ is the methane density in a computation cell and $\rho$ is the total density of that cell.

As listed in Table 7.1, the simulations with transient jet injection were carried out into both the quiescent chamber air and the stirred chamber air from the oscillation of the perforated plates. To form the turbulent flow region of zero-mean velocity and ‘nearly uniform’ characteristics in the chamber central region prior to injection, the oscillation of the perforated plates was simulated up to cycle 22, as mentioned in previous section.

When comparing the simulation results from different cases, clarification of the conditions for different cases is required, including the injection parameters such as $W_0$ and $D_{inj}$, and the plate states prior to and during the injection. In addition to the oscillation...
frequency $f_{osc}$, the plates can have four states relative to the injection event. These combine the situations from 'plate states during injection' and 'the injection phase' (in Table 7.1). The plate state can:

(a) stop at their outer limit positions right at the moment the injection starts;
(b) stop at their inner limit positions right at the moment the injection starts;
(c) continue to oscillate during injection with the plates at their outer limit positions at the moment the injection starts;
(d) continue to oscillate during injection with the plates at their inner limit positions at the moment the injection starts.

Simulation results from states (a) and (c) are most frequently presented in this section. To facilitate specifying these states, state (a) is denoted by 'oscillation frequency (in Hz), stopped while injecting'; state (c) is denoted by 'oscillation frequency (in Hz), running while injecting'. Since the quiescent chamber air is equivalent to a flow created by the oscillation of the plates at 0 Hz, the case for the transient injection into the quiescent chamber air is specified with '0 Hz'.

In the literature, the quantities for an axisymmetric turbulent round jet are often expressed in the axial and radial directions within a cylindrical coordinate frame. Due to the use of the Cartesian coordinate system (shown in Fig. 7.1), the variables of the transient jet along the radial direction are presented along the straight lines that are parallel to the y-coordinate and intersect with the centerline (shown in Fig. 7.34). These lines are referred as 'radial lines' hereinafter, and the variable profiles along these radial lines are referred to as 'radial profiles'.
7.3.1 Penetration Depth
Penetration depth is the distance between the injector nozzle exit and the jet forefront tip.

Fig. 7.35 shows the development process of the methane transient jet through visualization of the methane mass fraction field across the C-plane. The injection duration is 30 milliseconds. There is a two-millisecond interval between two frames. This sequence starts at two millisecond since the start of the injection and ends at 6 seconds after the end of injection. As one can see, the jet tip is positioned on the centerline. However, no clear tip location can be determined due to the gradual transition of color in the jet front from these visualization frames.

In order to determine the penetration depth of the transient jet, the definition of the jet forefront tip must be established. In the literature, many different approaches to define
the tip position have been used. For example, Abraham (1997) defined the forefront tip as the point on the jet centerline whose velocity reaches 70% of its steady-state value. Johnson and Amdsen (1992) used the point on the jet centerline where the mass fraction of the injected gas is 0.05. The drawback of these methods, obviously, is their arbitrary nature which gives different values for the penetration depth when the value used to define the tip position changes. This is illustrated in Fig. 7.36 (b), which shows the mesh and the methane mass fraction contours. When a different mass fraction value is selected as the criterion for defining the forefront tip, different values of penetration depth are obtained.

Fig. 7.37 shows the details of the values of methane mass fraction along the injector nozzle centerline. The methane mass fraction starts at a value of 1.0 at the injector nozzle exit and decreases with distance away from the injector nozzle exit due to mixing with the chamber air. At locations close to the jet front, the methane mass fraction undergoes an abrupt decrease. The jet front portion of the curve is re-plotted in Fig. 7.38. It may be seen that the jet forefront is well defined but not absolutely sharp because the grid resolution is not high enough. Therefore, an appropriate definition of penetration depth may be to take the intersection of the steepest part of the methane mass fraction curve with the z-axis (point B), which was suggested by P. Ouellette and P. G. Hill (2000).

In practice, to obtain position B, the point P on the centerline with the largest mass fraction gradient is first found for positions close to the jet front (refer to Fig. 7.38), and then the position of point B is interpolated from the straight line crossing point P with the maximum gradient. To avoid calculations of values of point B outside the chamber, the centerline mass fraction curve at each instant during injection is checked visually before
the point B is calculated, as shown in Fig. 7.39. A Macro-program run under the Microsoft® Excel environment was written to search the point P, calculate the positions of the intersection points B and the penetration depth. It was executed to determine penetration depth after the centerline mass fraction data from the simulations were extracted and exported into Excel.

Fig. 7.40 shows the penetration depth of the transient jets versus the injection time for three cases with different chamber conditions. One case is for the transient injection into the quiescent chamber air, and the other two cases have the stirred chamber air with the same oscillation frequency but are at different plate state during injection, i.e. ‘20 Hz, stopped while injecting’ and ‘20 Hz, running while injecting’. As can be seen, generally speaking, these penetration depth curves do not show much difference between the three cases. But surprisingly, the stirred chamber flows from different plate states seems to have a diverging effect on the transient jets. Compared to injection into the quiescent chamber air, the jet is slowed down by the stirred chamber flow generated with plate condition ‘20 Hz, stopped while injection’ while it appears accelerated by the chamber flow stirred by the plates at the same oscillation frequency but ‘running while injecting’.

This is against our previous speculation. Compared with the decaying turbulent flow that is generated by the oscillation of the plates which stop at the instant the injection starts, the turbulent flow generated by continuing oscillation, even during injection, is expected to have the higher turbulent energy and therefore be more dissipative to the momentum of the oncoming jet through a higher turbulent momentum exchange rate. A closer look at the velocity field may shed some light on this question. Fig. 7.41 to 7.43 show the velocity vector field across the C-plane for the above three cases. As one can see, the
flow field around the jet in the central region is quite similar for the case with injection into the quiescent chamber air and the case with ‘20 Hz, stopped while injecting’. For the latter case, the flow field in the plate sweep regions shows a more stirred pattern, which comes from the residual flow from the last stroke when the plates set back to their outer limit positions. For the case with ‘20 Hz, running while injecting’ the flow field around the transient jet is more affected by the continuing oscillations from the plates, with the boundary of the jet clearly affected (dented in) by the surrounding flows. The strong interaction of the transient jet and the small jet and wake flows must produce a ‘squeezing’ or ‘punching’ effect on the jet, by which the axial momentum of the jet is enhanced and a deeper penetration results.

Fig. 7.44 shows the penetration depth versus time for three cases with W0=40 m/s and D_{inj}=10 milliseconds. Again, one case is for the transient methane injection into the quiescent chamber air, and the other two are for the transient injection into the stirred chamber flows with different oscillation frequency, 12 Hz and 20 Hz, and the same plate state, ‘running while injecting’. The penetration depth curves for both cases with injection into the stirred chamber air almost overlap throughout the injection duration, showing little sign of the effect of the oscillation frequency on jet penetration. The reason for this could be that the turbulence generated by the plate oscillation in this range of oscillation frequency is overshadowed by the turbulence induced by the jet itself. Another observation is that both curves are above the one for the case with the injection into the quiescent chamber air. This is consistent with what is observed in Fig. 7.40.

Fig. 7.45 shows the penetration depth versus time for two cases with different injection velocity. The plate states are ‘running while injecting’ for both cases. It is obvious from
the figure that the higher injection velocity produces faster penetration. However, the penetration depth at the same instant is not directly proportional to the injection velocity.
Fig. 7.35 Visualization of the development of the transient jet. $D_{inj} = 30$ ms, $W_0 = 40$ m/s.
Fig. 7.36 (a) Visualization of a methane transient jet in a DI chamber cross C-plane at 18 ms after injection. (b) Mesh and methane mass fraction contour for study of definition of penetration.
Fig. 7.37 Methane mass fraction along the jet axis at 18 ms during injection.

Fig. 7.38 Details of axial methane mass fraction at the jet front shown in Fig. 7.37.
Fig. 7.39 Methane mass fraction along the centerline at different instants during injection.
Fig. 7.40 Comparison of jet penetration at different conditions.
Fig. 7.41 The chamber velocity field across the C-plane by the transient injection into the quiescent chamber air with $W_0 = 40$ m/s; at 20 ms during injection.
Fig. 7.42 The chamber velocity field across the C-plane by the transient injection into the chamber air with $W_0 = 40$ m/s; $20$ Hz, stopped while injecting; at $20$ ms during injection.
Fig. 7.43 The chamber velocity field across the C-plane by the transient injection into the chamber air with $W_0 = 40$ m/s; 20 Hz, running while injecting; at 20 ms during injection.
Fig. 7.44 Comparison of jet penetration for different oscillation frequency.

Fig. 7.45 Comparison of jet penetration for different injection velocity.
7.3.2 Axial Velocity

The axial velocity of the transient jet along the centerline $W_0(z)$ ($= W(0,0,z)$) at different instants is shown in Fig. 7.46 for the case with '20 Hz, running while injecting'. It can be seen that $W_0(z)$ decays (i.e., $W_0(z)$ decrease) quickly with increasing distance away from the injector nozzle exit. Each of these velocity curves approaches to, but does not completely overlap with, the one at a later instant along the jet body except in the jet front portion. This displays a continual transition of the centerline axial velocity to that at a later instant, which could be deemed as being closer to the value at the jet steady state.

![Graph showing axial velocity along the centerline at different instants.](image)

Fig. 7.46 Axial velocity along the centerline at different instants.

The centerline axial velocity for four cases is shown in Fig. 7.47 at the instant when the transient jets approach the chamber bottom. Two observations are made from this figure. First, $W_0(z)$ for the case with $W_0=80$ m/s decays faster than that for the cases with $W_0 = 40$ m/s. This may be caused by the higher turbulence intensity, which results from the
higher injection velocity, The second observation is that, at the same injection velocity of 40m/s, $W_0(z)$ for the case with '20 Hz, stopped while injecting' decays faster than the other two cases. This is not that surprising as we have seen from Fig. 7.40 that the penetration depth for this case is also less than the other two cases at the same instant due to the possible faster dissipation of the jet momentum from the decaying turbulent flow generated by the plate oscillation in this manner.

![Graph showing axial velocity along the centerline](image.png)

**Fig. 7.47** Axial velocity along the centerline when the transient jets approach the chamber bottom.

The inverse of $W_0 (z)$, especially $W_0/W_0 (z)$, is plotted against $z/D$ in Fig. 7.48. Over the range of $z/D$ from 10 to 35, the ratio of $W_0/W_0 (z)$ for all the cases has a linear relationship with respect to $z/D$. The nonlinear range at $z/D < 10$ corresponds to the jet’s initial development region and the nonlinear range at $z/D >35$ to the vortex head region. The $W_0/W_0 (z)$ curves in the linear region in Fig. 7.48 are redrawn in Fig. 7.49. The
Fig. 7.48 The variation with axial distance of inversed axial velocity along the centerline.

Fig. 7.49 The linear range of the inversed axial velocity along the centerline.
equations of the best fit straight lines of these curves are listed in Table 7.4. When rearranged in the form of \( \frac{W_0(z)}{W_0} = \frac{B}{(z-z_0)/D} \), B values were calculated and are also listed in Table 7.4. The curve for the case with ‘20 Hz, stopped while injecting’ has a larger value of B, so does the one for the case with \( W_0 = 80 \) m/s. The average value of B for all the curves listed is 3.953, which is less than the B value (≈ 6) calculated for a steady turbulent round jet at \( z/D > 20 \).

<table>
<thead>
<tr>
<th>Case Parameters (( D_{mj} = 30 ) ms for all cases)</th>
<th>( y = \frac{W_0}{W_0(z)}, x = \frac{z}{D} )</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_0=40 ) m/s; 20 Hz, stopped while injecting</td>
<td>( y = 0.2552x + 0.3869 )</td>
<td>3.918</td>
</tr>
<tr>
<td>( W_0=80 ) m/s; 20 Hz, stopped while injecting</td>
<td>( y = 0.2555x + 0.3235 )</td>
<td>3.914</td>
</tr>
<tr>
<td>( W_0=40 ) m/s; 20 Hz, running while injecting</td>
<td>( y = 0.2512x + 0.1524 )</td>
<td>3.981</td>
</tr>
<tr>
<td>( W_0=40 ) m/s; 0 Hz</td>
<td>( y = 0.25x + 0.1205 )</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Table 7.4 Equations of the best fit straight lines of the \( W_0/W_0 (z) \) curves at the linear region.

The axial velocity of the transient jet at the instant of 18 ms during injection is drawn in Fig. 7.50 along a number of radial lines. This is for the case with ‘\( W_0 = 80 \) m/s; \( D_{mj}=30 \) ms; 20 Hz, running while injecting’. The z coordinates of the radial lines are specified in the legend of the figure. The axial velocity along the radial line has its maximum value on the centerline. With the increasing distance from the injector nozzle exit, the radial profile of the axial velocity becomes ‘flat’, with the peak value decreasing.

The half-width of the transient jet \( y_{0.5} \) is defined here to facilitate the presentation of the simulation results. Fig. 7.51 explains the concept of the half-width \( y_{0.5} \). As shown, it is the arithmetic average of the positive side half-width \( y^+_{0.5} \) and the negative side half-width \( y^-_{0.5} \).
Fig. 7.50 Radial profiles of axial velocity at different distance from the nozzle.

\[ W_0 = 80 \text{ m/s} \]
\[ 20 \text{ Hz, running while injecting} \]
\[ D_{inj} = 30 \text{ ms} \]
\[ t = 18 \text{ ms} \]

- \( z = 1.3 \text{ cm} \)
- \( z = 3.1 \text{ cm} \)
- \( z = 4.9 \text{ cm} \)
- \( z = 5.7 \text{ cm} \)
- \( z = 6.7 \text{ cm} \)
- \( z = 7.5 \text{ cm} \)

\[ y_f = 5 \] and \( y_0 = 5 \) are defined by:
\[ W(0, y_0^+(z), z) = 0.5W_0(z) \]
\[ W(0, -y_0^-(z), z) = 0.5W_0(z) \]

\[ y_{0.5} = 0.5(y_0^+ + y_0^-) \]

\( y_0^+ \) and \( y_0^- \) are defined by:
\[ W(0, y_0^+(z), z) = 0.5W_0(z) \]
\[ W(0, -y_0^-(z), z) = 0.5W_0(z) \]

Fig. 7.51 Illustration of the definition of half-width.
The same axial velocity of the transient jet in Fig. 7.50 is redrawn in Fig. 7.52 as normalized distance from the centerline $y/y_{0.5}$ versus the normalized velocity $W/W_0(z)$. The radial profiles of axial velocity show similarity, especially at $|y/y_{0.5}| \leq 1.5$. Fig. 7.53 shows the radial profile of the normalized axial velocity for the case with lower injection velocity (40 m/s). Again, similarity is observed for the radial profiles of the normalized axial velocity at different locations from the nozzle exit over the range of $z/D$ considered. Now the radial profiles of the normalized axial velocity of the transient jets at different conditions are brought into Fig. 7.54. The selected normalized distance of the radial lines from the nozzle exit is around 14. As one can see, when normalized with each jet’s own half width, the radial profiles of the normalized axial velocity at different conditions show similarity at $|y/y_{0.5}| \leq 2$.

![Fig. 7.52 Axial velocity against radial distance in a turbulent jet with injection velocity of 80 m/s.](image)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Fig. 7.53 Axial velocity along radial distance in a turbulent jet with injection velocity of 40 m/s.

Fig. 7.54 Axial velocity along radial distance at different conditions.
7.3.3 Methane Concentration along the Centerline

The methane concentration (expressed as mass fraction) at different instants during injection has been shown in Fig. 7.39 along the centerline for the case with \( W_0 = 40 \text{ m/s; 20 Hz, running while injecting} \). As one can see, at each instant, the concentration curve coincides with the curve at a later instant until reaching the jet front. This implies that the transient jet centerline concentration approaches its steady-state value soon after the jet front passes that point, which is consistent with Turner's assumption in his derivation of theory of transient jets (see Fig. 2.1). This phenomenon is observed for all the simulated cases. Thus one can use the centerline concentration curve behind the jet front as an approximation to the centerline concentration curve at its steady state.

The centerline concentration curves for four cases at the instants when the jets approach the chamber bottom are shown in Fig. 7.55. Similar to the axial velocities on the centerline (see Fig. 7.47), the centerline concentration decays quickly with increasing distance from the injection nozzle exit. It can be seen that at the same injection velocity, the centerline concentration for the case with \( '20 \text{ Hz, stopped while injecting'} \) decays faster than the other two cases. This is similar to the phenomena related to the axial velocity on the centerline in Fig. 7.47. Therefore, this may be due to the same reason, that is, the decaying turbulence generated in the case with \( '20 \text{ Hz, stopped while injecting'} \) dissipates the injected gas faster than the other two cases, reducing the mass fraction in the core region.

For the same oscillation frequency and plate state, the centerline mass fraction for the case with higher injection velocity decays faster than that with the lower one. This can also be explained by the fact that the higher turbulence energy, which is induced by the higher injection velocity, dissipates the methane in the central part of the jet faster than
Fig. 7.55 Methane mass fraction along the centerline for different conditions.

the case with lower turbulence energy from the lower injection velocity.

7.3.4 Radial Concentration
Concentration of a methane transient jet at the instant of 18 ms during injection is drawn in Fig. 7.56 along nine radial lines. All the curves have their maximum value at the center and approach zero with the increasing distance from the centerline.

A half-width based on the methane mass fraction $y'_{0.5}(z)$ is defined as

$$X(0, y'_{0.5}(z), z) = 0.5X(0,0,z).$$

(7.4)

Thus, the data in Fig. 7.56 are redrawn in Fig. 7.57 with a normalized distance from the
Fig. 7.56 Radial profile of methane mass fraction in a turbulent jet with injection velocity of 80 m/s.

Fig. 7.57 Non-dimensional radial profile of methane mass fraction in the same turbulent jet in Fig. 7.56.
centerline $y/y'_{0.5}(z)$. Most of these concentration curves exhibit self-similarity for $y/y'_{0.5}(z)$ between $-1$ and $1$ cm. At $z/D = 3.5$, the radial concentration curve linearly decreases with the distance away from the centerline. This suggests that the jet is still in the transition zone at such a distance from the injector nozzle exit.

At $z/D = 43.5$, the radial profile of concentration displays self-similarity for $y/y'_{0.5}(z)$ between $-1$ and $1$ as most of the curves, but drops below them for $|y/y'_{0.5}(z)| > 1$. The location of the radial line is about 87% of the penetration depth from the nozzle exit. The decreased concentration may be from the strong interaction of the vortex head and the ambient gas. Fig. 7.58 is a graph that eliminates the curves for radial lines outside the linear behavior region of the centerline velocity. This clearly indicates the self similar behavior of the jet in this region.

![Fig. 7.58 Non-dimensional radial profile of methane mass fraction.](image)

$W_0 = 80$ m/s
20 Hz, running while injecting $D_{inj} = 30$ ms
$t = 18$ ms
7.3.5 Spreading Angle

Jet spreading in the chamber is caused by the interaction between the transient jet and the chamber fluid. The spread angle is a quantitative measure of the jet spreading. From the recorded Schlieren images, the spread angle has been obtained through image processing. For the numerical simulation, depending how the angle is defined, the calculated values of the spread angle can be quite different. Three different ways to define it have been attempted in this work.

From the literature, the spreading rate SR defined by

\[
SR = \frac{dr_{0.5}(z)}{dz}
\]  

(7.5)

is a constant for a steady axisymmetrical turbulent round jet (Pope, 2000) in the range \(z/D > 20\), where \(r_{0.5}(z)\) is the half-radius for the round jet, which is defined in a similar way as the half-width. Table 7.5 lists examples of the SR values from literature. In Fig. 7.59, the half-widths on both sides of the centerline (\(y^+_{0.5}\) and \(-y^-_{0.5}\)) versus the distance from the nozzle exit are drawn. These half-width values do show a linear relationship with the distance from the nozzle exit. From this observation, a half-angle can be defined as the cross-angle between the two best-fit straight lines crossing the \(y^+_{0.5}\) and \(-y^-_{0.5}\), which is shown in Fig. 7.59 as \(\alpha_{0.5}\).

<table>
<thead>
<tr>
<th>Reference</th>
<th>SR</th>
<th>Reynolds number of jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panchapakesan and Lumley (1993)</td>
<td>0.096</td>
<td>11,000</td>
</tr>
<tr>
<td>Hussein et al. (1994), hot-wire data</td>
<td>0.102</td>
<td>95,500</td>
</tr>
<tr>
<td>Hussein et al. (1994), laser-Doppler data</td>
<td>0.094</td>
<td>95,500</td>
</tr>
</tbody>
</table>

Table 7.5 The spreading rate SR for turbulent round jets (from Panchapakesan and Lumley, 1993).
As seen from Fig. 7.59, \( \alpha_{0.5} \) is the sum of \( |\alpha^+| \) and \( |\alpha^-| \). The \( \alpha^+ \) and \( \alpha^- \) can be obtained through

\[
\tan \alpha^+ = \frac{dy^+_{0.5}(z)}{dz} \quad \tan \alpha^- = -\frac{dy^-_{0.5}(z)}{dz}
\]

(7.6)

where, \( \frac{dy^+_{0.5}(z)}{dz} \) and \( -\frac{dy^-_{0.5}(z)}{dz} \) are the slopes of the best-fit straight lines.

To obtain \( \frac{dy^+_{0.5}(z)}{dz} \) and \( -\frac{dy^-_{0.5}(z)}{dz} \), four \( y^+_{0.5} \) and four \( y^-_{0.5} \) are calculated at four positions along the centerline. They are then imported into Excel with their corresponding \( z \) values. The slope of the best fit straight lines from the four \( y^+_{0.5} \) and \( y^-_{0.5} \) are then calculated respectively. The half angle \( \alpha_{0.5} \) can be calculated by

\[
\alpha_{0.5} = \left[ \arctan \left( \frac{dy^+_{0.5}(z)}{dz} \right) - \arctan \left( \frac{dy^-_{0.5}(z)}{dz} \right) \right] \times \frac{180}{\pi}
\]

(7.7)
Table 7.6 lists the values of \( \tan \alpha^+ \), \( \tan \alpha^- \), \( \alpha^+ \), \( \alpha^- \) and \( \alpha_{0.5} \) for the case with ‘\( W_0 = 40 \) m/s; 20 Hz, stopped while injecting’.

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>( \tan \alpha^+ )</th>
<th>( \tan \alpha^- )</th>
<th>( \alpha^+ ) (radian)</th>
<th>( \alpha^- ) (radian)</th>
<th>( \alpha_{0.5} ) (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.098963</td>
<td>-0.09883</td>
<td>0.098642</td>
<td>-0.09851</td>
<td>11.29592</td>
</tr>
<tr>
<td>14</td>
<td>0.104275</td>
<td>-0.10424</td>
<td>0.1039</td>
<td>-0.10387</td>
<td>11.90415</td>
</tr>
<tr>
<td>18</td>
<td>0.101139</td>
<td>-0.10115</td>
<td>0.100796</td>
<td>-0.10081</td>
<td>11.55088</td>
</tr>
<tr>
<td>22</td>
<td>0.101211</td>
<td>-0.10122</td>
<td>0.100868</td>
<td>-0.10088</td>
<td>11.55913</td>
</tr>
<tr>
<td>26</td>
<td>0.102701</td>
<td>-0.10271</td>
<td>0.102342</td>
<td>-0.10235</td>
<td>11.72798</td>
</tr>
<tr>
<td>28</td>
<td>0.102801</td>
<td>-0.10281</td>
<td>0.102441</td>
<td>-0.10245</td>
<td>11.73949</td>
</tr>
</tbody>
</table>

Table 7.6 Half angle and the intermediate quantities determined during the calculation for the case ‘\( W_0 = 40 \) m/s; 20 Hz, stopped while injecting’.

Fig. 7.60 Change of spread angles of a turbulent jet at different instants since the start of injection. Spread angles are calculated based on the half radius.
The half-angles of the transient jets at different instants are drawn in Fig. 7.60 for four cases. As one can see, the half angles for all the cases show small-scale fluctuations during the injection and the range of the half-angles are between 11 and 12 degrees for most of the injection time. At $W_0=40$ m/s, the average half-angles for the case with '20Hz, stopped while injecting' are clearly larger than those for the other two cases, hinting at a possible stronger interaction between the transient jet and the decaying turbulence around it in terms of momentum exchange. With the same plate state during injection, the average half-angles for the cases with higher injection velocity are larger, as expected, than those with lower injection velocity, due to the interaction of the jet and the higher intensity of turbulence induced by the higher injection velocity.

Fig. 7.61 2% mass fraction contours at different instants during injection. $W_0 = 40$ m/s; 0 Hz; $D_{nj} = 30$ ms.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
An alternative way to find the jet spreading is illustrated in Fig. 7.61, which depicts the 2% methane mass fraction contour lines at different instants during injection. The straight segments of these contour lines on both sides of the jet are approximately parallel to two straight lines, shown as the dashed lines in Fig. 7.61, and the cross-angle of these two lines can be taken as a measure of the jet spreading. In this work, the cross-angle formed by the straight segments of the contour lines of the transient jet is calculated at each instant as the spread angle at that instant. Depending on the arbitrarily picked value for defining the contour line, the spread angle calculated can be very different. 2% methane mass fraction contour lines were used for calculation of the spread angle in this work.

\[ \tan \beta^+ = \text{slope} (\Gamma') \]
\[ \tan \beta^- = \text{slope} (\Gamma') \]

**Fig. 7.62** Illustration of the calculation of the cross-angle based on the mass fraction contour line.

In order to calculate the cross-angle, three points on the straight segment of each side of the contour line are sampled at each instant, as shown in Fig. 7.62(a). These points are then imported into Excel, together with their corresponding z values, and then two best-fit straight lines are determined through linear regression, as shown in Fig. 7.62(b). The...
slopes of these best-fit lines are recorded and the cross-angle between the best fit lines is calculated in a similar manner as for the half-angle calculation. Table 7.7 lists the spread angles and the intermediate quantities at the selected instants during injection for the case with the transient methane injection into the quiescent chamber air at $W_0 = 40 \text{ m/s}$. Here, the spread angle is denoted by $\alpha_x$, where, the subscript ‘X’ is used to indicate that the spread angle is based on ‘mass fraction’.

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>$\tan \alpha^+$</th>
<th>$\tan \alpha^-$</th>
<th>$\alpha^+$ (radian)</th>
<th>$\alpha^-$ (radian)</th>
<th>$\alpha_x$ (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.255399</td>
<td>-0.25511</td>
<td>0.250054</td>
<td>-0.24979</td>
<td>28.6387</td>
</tr>
<tr>
<td>12</td>
<td>0.230995</td>
<td>-0.2306</td>
<td>0.227013</td>
<td>-0.22664</td>
<td>25.99225</td>
</tr>
<tr>
<td>16</td>
<td>0.219321</td>
<td>-0.21934</td>
<td>0.215902</td>
<td>-0.21592</td>
<td>24.74144</td>
</tr>
<tr>
<td>20</td>
<td>0.230718</td>
<td>-0.22997</td>
<td>0.22675</td>
<td>-0.22604</td>
<td>25.94289</td>
</tr>
<tr>
<td>24</td>
<td>0.239297</td>
<td>-0.2372</td>
<td>0.23488</td>
<td>-0.2329</td>
<td>26.80155</td>
</tr>
<tr>
<td>28</td>
<td>0.232675</td>
<td>-0.23046</td>
<td>0.228607</td>
<td>-0.2265</td>
<td>26.07581</td>
</tr>
</tbody>
</table>

Table 7.7 The spread angles and the intermediate quantities for the case with the transient methane injection into the quiescent chamber air at $W_0 = 40 \text{ m/s}$.

The spreading angles based on 2% methane mass fraction are drawn in Fig. 7.63 against time during injection for four cases. The calculated spread angle displays a decreasing trend for all the cases after the injection and then reaches a relatively stable stage, at which the range of spread angles is between 22 and 28 degrees. A similar observation as from Fig. 7.60 is that the $\alpha_x$ for the case with ‘$W_0=40 \text{ m/s}$; 20 Hz, running while injecting’ is lower than that for the other two cases with the same injection velocity for most of time during injection, which might be caused by the ‘squeezing effect’ imposed on the jet in this case. A notable difference is that the spread angle $\alpha_x$ for the case with
‘W0=40 m/s; 0 Hz’ is larger than that for the case with ‘W0=40 m/s; 20 Hz, stopped while injecting’ after 20 ms of injection. As we know, \( \alpha_x \) is based on a value (arbitrarily selected) within the jet boundary, therefore, \( \alpha_x \) reflects more on the interaction of the surrounding flow and the jet boundary material rather than the whole jet body, as opposed to the \( \alpha_{0.5} \). Thus, a stronger interaction (mass exchange) can result in more dilution of the jet material on the boundary, pushing the 2% mass fraction contour line towards the centerline and reducing the calculated \( \alpha_x \).

![Figure 7.63](image)

**Fig. 7.63** Variation of spread angles of a turbulent jet at different instants since the start of injection. Spread angles are calculated based on the 2% mass fraction contour.

If the contour line in Fig. 7.62 were based on the density gradient of the chamber flow, the spreading angle based on density gradient can be calculated. This attempt is in response to the fact that the Schlieren image used in the accompanying experimental measurements is a reflection of the density gradient of the flow field. In this work, the y-
direction density gradient field of the transient jet flow in the chamber was calculated. Visualization of such a density gradient field across the C-plane is shown in Fig. 7.64(a) for the case with ‘W0 = 40 m/s; 20 Hz, stopped while injecting’ at the instant t = 18 ms. After calculating the density gradient field, a similar procedure as outlined in Fig. 7.62 was taken, starting with sampling 3 points on each side of the contour lines with the density gradient of 0.0002 g/cm$^4$ (see Fig. 7.64(b)). This spread angle is denoted by $\alpha_{dg}$, where the subscript $dg$ is used to indicate that the angle is based on the ‘density gradient’.

![Fig. 7.64 Density gradient field and 0.0002 g/cm$^4$](image)

The calculated spread angle $\alpha_{dg}$ for three cases at different instants during injection is presented in Fig. 7.65. All three cases have the same injection velocity of 40 m/s. Similar trends as those shown in Fig. 7.63 are found, with the curve for the case with ‘0 Hz’ above the other two cases.

From the discussion above, the spreading angle calculated with the use of different methods has different values. They reflect different aspects of the interaction of the
transient jet and the stirred chamber air. The spread angles $\alpha_{0.5}$ provide information about the effect of the flow on the whole jet body, whereas, the spreading angles $\alpha_x$ or $\alpha_{dg}$ reflect the interaction of the surrounding flow with the jet boundary materials. However, due to the large degree of variation of $\alpha_x$ and $\alpha_{dg}$ during injection and the arbitrary nature of defining these angles, it is more appropriate to use $\alpha_{0.5}$, especially in the context of mixing.

![Graph](image)

**Fig. 7.65** Variation of spread angles of a turbulent jet at different instants since the start of injection. Spread angles are calculated based on the contour of density gradient.

### 7.3.6 Flammable Mixture

As mentioned before, the investigation of the transient jet injection is about mixing between the injected gas and the chamber air, which is essential in preparation for combustion when the injected gas is a fuel. In this sense, it is a good practice to examine the amount of flammable mixture that would be formed during the transient injection.
process with methane as the injected gas. In this research, we consider any mixture within
the methane flammability limits as flammable. Flammability limits are frequently quoted
as percent fuel by volume in the mixture, or as a percentage of the stoichiometric fuel
requirement, i.e. $\Phi \times 100$, where $\Phi$ is the equivalence ratio defined by

$$\Phi = \frac{(F / A)}{(F / A)_{stoic}},$$

where, $(F / A)$ is fuel-air ratio and $(F / A)_{stoic}$ is the stoichiometric fuel-air ratio.

In this study, flammability limits are expressed in terms of $\Phi \times 100$. The flammability
limits for methane are 0.53 (lower limit) and 1.6 (upper limit) (Irving, Combustion), and
any methane and air mixture with $\Phi$ between these limits is deemed as flammable.

In KIVA-3V $\Phi$ is not computed by the governing equations. For methane injection, $\Phi$
can be calculated as follows:

$$\Phi = \frac{(F / A)}{(F / A)_{stoic}} = \frac{(\text{Moles of Fuel} / \text{Moles of Air})}{(\text{Moles of Fuel} / \text{Moles of Air})_{stoic}} = \frac{(\text{Moles of Fuel} / \text{Moles of Oxygen})}{(\text{Moles of Fuel} / \text{Moles of Oxygen})_{stoic}} = \frac{\rho_{CH_4} \cdot MW_{CH_4}}{\rho_{O_2} \cdot MW_{O_2}} = \frac{\rho_{CH_4} \cdot MW_{CH_4}}{\rho_{O_2} \cdot MW_{O_2} \cdot 0.5}$$

where, $\rho_{CH_4}$ and $\rho_{O_2}$ are the density of methane and oxygen in the mixture, respectively.

$MW_{CH_4}$ and $MW_{O_2}$ are the molar mass of methane and oxygen, and are equal to 16 and
32 kg/mole, respectively. In the above calculation, $(\text{Moles of Fuel} / \text{Moles of Oxygen})_{stoic}$
is equal to 0.5, which results from the chemical reaction

233
CH$_4$ + 2O$_2$ = CO$_2$ + 2H$_2$O.

Figs. 7.66 (a) through (o) visualize the flammable mixture across the C-plane with green color through the whole injection duration. This is for the case with transient methane injection into the quiescent chamber air ($W_0 = 40$ m/s; $D_{inj} = 30$ ms). It clearly shows that the flammable mixture forms around the boundary of the fuel rich ‘core’ (red regions in Fig. 7.66), which increases in length as more fuel is injected. The amount of methane within the flammable mixture formed by this injection was calculated at each instant and is shown in Fig. 7.67, together with the total mass of injected methane. The amount of methane within the flammable mixture limits increases with the injection time.
Fig. 7.66 Visualization of the flammable methane mixture across the C-plane for the transient methane injection into the quiescent chamber air with $W_0 = 40$ m/s; $D_{inj} = 30$ ms.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
For comparison of the formation of flammable mixtures for different cases, the percentage of the mixed flammable methane from the transient injection, $X_{\text{mixed}}$, is defined as

$$X_{\text{mixed}} = \frac{\text{Mass of methane within flammable mixture}}{\text{Mass of injected methane}}.$$  \hspace{1cm} (7.9)

Fig. 7.68 shows the change of percentage of mixed gas with time for four cases. The percentage of the mixed flammable methane increases with time for all cases. The case with injection velocity of 80 m/s has much more flammable mixture than the other cases at the same time. This is because the high velocity injection penetrates faster at the same instance during injection and has larger jet body surface interacting with the surrounding air. All three cases with the injection velocity of 40 m/s do not show large difference in $X_{\text{mixed}}$ during the injection process. This may due to the fact that the penetration depths for all three cases with 40 m/s injection velocity are very close at the same instant during

![Graph showing mass of total injected methane and mass of methane in flammable mixture.](image)

Fig. 7.67 Mass of the total injected methane and mass of the methane in flammable mixture.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
injection (see Fig. 7.40). A closer look at these three curves in Fig. 7.68 shows that, at the same time, the jet in the case with '20 Hz, stopped while injecting' produces a little more percentage of the mixed flammable methane than the jet injected into quiescent chamber air, which hints a stronger mass exchange between the jet and the stirred air flow around the jet boundary. This may also explains the slower penetration of the jet for '20 Hz, stopped while injecting', compared with the other cases with the same injection velocity, as shown in Fig. 7.40, since the mass exchange is directly related to the momentum exchange on the boundary between the jet and the surrounding flow.

![Graph showing changes of percentage of flammable methane with time.](image)

Fig. 7.68 Changes of percentage of flammable methane with time.

The data from Fig. 7.68 are re-plotted against the penetration depth in Fig. 7.69 for all cases. With increase of penetration depth, the percentage of the flammable methane increases. The curve of the percentage of flammable methane for the case with $W_0 = 80$
m/s becomes close to all other three curves but still shows a slightly higher value than the cases with '0 Hz' and '20 Hz, running while injecting' at the same penetration depth of the transient jets. This could be explained by the fact that the high velocity induces higher intensity turbulence around the jet, entraining the jet material quicker than the other two cases. For the case with '20 Hz, stopped while injecting', the decaying turbulence is more effective in entraining the jet material, thus forming more flammable mixture, therefore, its curve is also higher than '0 Hz' and '20 Hz, running while injecting'.

![Graph showing changes in flammable methane content with penetration depth.](image)

**Fig. 7.69** Changes of percentage of flammable methane with penetration depth.

In Fig. 7.68, a noticeable increase in the percentage of mixed flammable methane can be identified at about 20 ms for the case with an injection velocity of 80 m/s. It can be seen in Fig. 7.45 that at 20 ms, the jet with 80 m/s injection velocity has reached the bottom wall of the DI chamber and this increase in the percentage of mixed flammable methane may be due to the impingement of the jet and the subsequent formation of side vortices.
along the perimeter of the jet near the impingement location. Similar increase in the percentage of mixed flammable methane is also observed for the case with smaller injection velocity. As shown in Fig. 7.70, this increase occurs at about 36 seconds after the start of injection for the case with an injection velocity of 40 m/s. For this case, the jet reaches the bottom at about 36 seconds after the injection starts, as may be identified in Fig. 7.45 through extrapolation.

![Graph showing the boost of percentage of mixed flammable methane from the impingement of jet.]

**Fig. 7.70** The boost of percentage of mixed flammable methane from the impingement of jet.
Chapter 8  Comparison of Experimental and Numerical Results

8.1 Turbulent Intensity and its Power Decay Law

Turbulent characteristic velocities \( q \) (or turbulent intensity, defined as \( \sqrt[3]{\frac{2k}{3}} \)) in the DI chamber center from both the experiments and numerical simulations are plotted in Fig. 8.1 with respect to the oscillation frequency. Within the range of oscillation frequencies considered, the turbulent characteristic velocity obtained from the experiments matches quite well with that from the numerical simulations, both in value and the trend in response to oscillation frequency. The values of \( q \) from the numerical simulations are just slightly higher than those from the experiments at the corresponding oscillation frequency, but a clear linear relationship between \( q \) and oscillation frequency can be identified from both sets of data.

![Turbulent intensity in the DI chamber center versus the oscillation frequency.](image)

---

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
The turbulent intensity power decay law has been suggested to be in the form of Eq. 6.15 and the calculated values of $C$ from both the experiments and numerical simulations are plotted in Fig. 8.2 versus oscillation frequency. As shown in the figure, $C$ is independent of the oscillation frequency within the range of $f_{\text{osci}}$ considered here. The average value of $C$ from the numerical simulations is 0.343, about 10% higher than that from the experiments, 0.313. From now on, the power decay law of the turbulent intensity in the DI chamber center can be written as

$$q = 0.328 f_{\text{osci}}^{1.5} M^{0.5} H^{-1}.$$  \hspace{1cm} (8.1)

![Graph showing calculated values of $C$ versus oscillation frequency.](image)

*Fig. 8.2* Calculated values of $C$ from versus the oscillation frequency.

### 8.2 Turbulence Length Scales

In this work, turbulent integral length scales $L_i$ were calculated based on the LDV measurements, and turbulent macro-length scales $L_c$ were obtained as direct output from the numerical simulations. The $L_i$ and $L_c$ at the DI chamber center are plotted in Fig. 8.3
with respect to the oscillation frequency. The integral length scales from the experimental measurements and the turbulence macro-scales from numerical simulations are close, both in magnitude and the trend in response to variations in the plate oscillation frequency.

![Graph showing turbulence length scales from experimental measurements and numerical simulations.](image)

**Fig. 8.3** Turbulence length scales from experimental measurements and numerical simulations.

This is not a surprise. It has been shown by Tennekes and Lumley (1972) that the integral scale is directly proportional to $\frac{k^{\frac{1}{3}}}{\varepsilon}$ for equilibrium turbulence in steady, homogenous, mean shear flow. In such flow, the transport equation of turbulent kinetic energy equation reduces to (in tensor notation)

$$
\overline{-u_i' u_j' S_{ij}} = 2\nu s_{ij}' s_{ij}',
$$

where, $u_i'$ denotes the fluctuation velocity component and $\nu$ is the kinematic viscosity of fluid. The quantities $S_{ij}$ and $s_{ij}'$ are the mean and fluctuating rate of strain, respectively, which are defined by

243
Eq. 8.2 states that in the equilibrium turbulent flow mentioned above, the rate of production of turbulent energy by Reynolds stresses equals to the rate of viscous dissipation. If \( S_y \sim q/L_t \) and \(-\overline{u_i' u_j'} \sim q^2 \) (\( q \) is the characteristic turbulent velocity or turbulent intensity) are assumed and \( \varepsilon = 2\nu \overline{s_i' s_j'} \) is defined, then it follows that \( L_i \) is directly proportional to \( L_e \) under the equilibrium turbulence condition. In Fig. 8.3, \( L_i \) and \( L_e \) do not show directly proportional to each other, probably because of the errors in \( L_i \) values, which may stem from the errors in the LDV measurements of instantaneous velocity and the subsequent calculation with the measurement results.

As one can see in Fig. 8.3, the turbulence length scales in the DI chamber center are only slightly affected by change of the oscillation frequency.

The \( L_e \) along the C-line (refer to Fig. 7.1) is plotted in Fig. 8.4. Only the data at the locations within 1.0 cm from the DI chamber center is included. Within this range, \( L_e \) has a peak value at the center and decreases with the distance away from the center. Such a variation of \( L_e \) was actually not reported by Shy et al. (1997) or Srdic et al. (1996), who studied the turbulence generated by a pair of oscillating grids. Since the LDV measurements in this study were carried out only at the DI chamber center, a direct corroboration of the \( L_e \) variation trend from the experimental data can not be provided. Therefore, one may take a closer look at the experimental data presented in previous research. The integral length scales \( L_i \) measured by Shy et al. (1997) are reproduced in Fig. 8.5 (refer to Fig. 2.6 for the experimental set-up). It is easily observed that the values of \( L_i \) in the middle of the graph are actually larger than those outside the middle range (z≥...
Fig. 8.4 Variation of turbulence micro-length scales along the C-line.

Fig. 8.5 Variation of integral length scales with the distance between the grids at points e (node) and c (hole) for both horizontal and vertical components (extracted from Shy et al., 1997).
2.0 and $z \leq -2.0$), even though the suggestion of uniform $L_z$ in the middle, whose value was suggested by the solid line in the figure, was made by the authors. Therefore, we can conclude that for the turbulence flow in the DI chamber, the integral length scale is not uniform in the central region. The integral length scale reaches its largest value at the chamber center and gradually decreases with distance away from the center.

8.3 Penetration Depths of Turbulent Transient Jets

Because the injector exit velocity was not available during the integral measurements of transient jets based on Schlieren imaging, the injection velocity in numerical simulations was set up with arbitrarily selected values (40 m/s and 80 m/s). Thus, it is not very meaningful to compare the values of penetration depth obtained from the experiments with those from the numerical simulations. However, it is still a good practice to examine the trend of penetration depth development obtained from both the experiments and simulations. In Fig. 6.17, the similarity penetration depths of transient jets, $z_t/(p_{ij}/p_a)^{1/4}$ are plotted versus the square root of time for cases with different injection pressures, and in Fig. 8.6, the non-dimensional penetration depths, $z_t/(\dot{M}_n/\rho_a)^{1/4}$, which are based on the numerical simulation results, are also plotted versus the square root of time. With the help of similarity variables, the penetration depths from both the experiments and numerical simulations display a strong linear relationship with the square root of time after the jets reach locations approximately 10 times nozzle exit diameter away from the nozzle exit. Both graphs also show that the jets tend to deflect from linear dependence on the square root of time when approaching the bottom wall of the DI chamber.
The dependency of penetration depths on the momentum rate can also be identified from both graphs. As discussed in Section 6.3.1, the injection pressure is directly proportional to the momentum rate, regardless of whether or not the flow inside the injector could become choked.

Fig. 8.6 Penetration depths of transient methane jets from the numerical simulations.
Chapter 9  Conclusions and Recommendations

9.1  Overview of the Unique Aspects of the Work

A detailed study has been performed both experimentally and numerically of the behavior of a short-duration transient gaseous jet within a direct injection turbulence chamber (or DI chamber), which is equipped with a pair of perforated plates capable of oscillating at a frequency and stroke of choice within certain ranges. The study is unique in three distinct aspects.

9.1.1  Turbulence Generation in a Gaseous Media

The nearly isotropic and homogenous turbulence field in the DI chamber filled with air was created by use of a pair of oscillating perforated plates. Even though the turbulence generated by a pair of oscillating grids in water media has been studied and documented in several research papers, there has been no research and available data, to the author’s knowledge, on the use of oscillating-plate (or -grid) turbulence in gaseous media. Due to the difference in working fluid, the ranges of operating parameters (the oscillation frequency and stroke, etc.) are quite different for generation of the same level of turbulence intensity. Compared to turbulence generated from a single sweeping of a perforated plate, the turbulence from the oscillating-plate configuration can be either stationary or decaying.

9.1.2  Use of the DI Chamber in Study of Transient Gaseous Injection

The DI chamber provides a unique space for examination of the behavior of the transient injection jet with/without the influence of an ambient turbulent flow, the turbulence
frequency and stroke.

9.1.3 Numerical Modeling of the DI Chamber
Most work on oscillating-plate (or -grid) turbulence have been done through experimental modeling and study of these phenomena by use of numerical methods has not been seen in the literature. The numerical modeling of the DI chamber in this work provides a unique and fruitful way to examine the turbulence generated by the oscillation of the perforated plates and its interaction with the transient gaseous jet. Even though the model was created with air as the working fluid, it can be easily extended to be used in the applications with water as the working fluid.

9.2 Conclusions Made Regarding Research Objectives

9.2.1 Physical Model Creation
The DI chamber had been created for this study. The intended controllable turbulence field is realized through a pair of oscillating perforated plates, which were driven by a motion drive system based on the pneumatic cylinders; the transient gaseous injection was implemented through a commercial gaseous fuel injector.

Controlled with the a LabView control program, a motion drive system was able to deliver oscillatory motion to the perforated plates with frequency up to 25 Hz and stroke up to 41 mm, which, when both 10 mm plates and 3 mm plates were used, were able to generate turbulent flows in the middle of the DI chamber with a wide range of turbulence characteristics.

With the computer-integrated timing control circuit, the gas injection system was able to realize a transient gas injection at 0.414 MPa of duration up to 30 milliseconds. The Reynolds number of these transient jets was between 7,600 and 19,000.
9.2.2 Measurement Techniques
A two-component LDV system had been purchased and set up for characterizing the turbulence generated by oscillation of the perforated plates in the DI chamber. The seed particles were generated from a commercial Fogger machine. High data rates were achieved from this system, allowing equal interval sampling at 50 Hz in coincidence mode. From the sampled data, turbulence quantities could be calculated, including turbulence intensity, turbulence integral length scale and frequency spectrum. With an ancillary traverse system, LDV measurements had the capacity to take three dimensional measurements within the cubic chamber.

A technique for integral measurement of the transient gaseous injection was developed, based on the Schlieren method. To implement this technique, a Schlieren imaging system was set up, coupled with a fast video acquisition system. The injection process was captured with the system and saved onto the computer as movie files. A Visual Basic program was written for automating the image processing. Calculation of the penetration depth and the spread angle was based on the information extracted from the processed images.

9.2.3 Numerical Model Creation
The numerical model of the DI turbulence chamber was created by means of a commercial CFD code, KIVA-3V. The computational meshes of the DI chamber have been successfully created in actual dimensions with over 50,000 cells by use of commercial meshing software, ICEM CFD. Through the KIVA-3V valve model, the oscillation of the perforated plates was closely simulated. By virtue of a velocity inflow boundary, the short-duration, transient gaseous injection of constant inlet velocity was implemented with uniform velocity profile at the injector nozzle exit.
9.2.4 Turbulence Generated by the Oscillation of the Perforated Plates

Both the experiments and numerical results show that the turbulent intensity in the centre of the DI chamber follows a similar correlation that governs the turbulence generated by a pair of oscillating grids in a water tank. That is, the power law of decay of the turbulent intensity in the chamber centre reads the form,

\[ q = C f_{osc} S^{1.5} M^{0.5} H^{-n} \]

Based on the data obtained in this work, the power \( n \) in the above equation is equal to 1, instead of -1.5 by Shy et al. (1997). This difference could be due to the difference in the design of the oscillating devices. In our work, perforated plates were used, instead of grids made of square bars, which were used by Shy et al.; the constant \( C \) has an average value of 0.328, in contrast to 0.89 for the oscillating-grid turbulence in the water tank. The smaller value of \( C \) means that the plates have to run at higher frequency or larger stroke to generate the same level of turbulent intensity as the grid oscillating in the water.

Under the current experimental set-up, a cut-off frequency was not found. A lower limit for the oscillation frequency, however, was identified, below which there was no linear relationship between the turbulent intensity and the oscillation frequency. At stroke of 2.5 cm, the lower limit frequency is 8 Hz; at stroke of 1.4 cm, the lower limit frequency is 12 Hz.

The numerical results show that a region of nearly-uniform turbulent intensity is formed in the middle of the DI chamber, about two plate mesh sizes away from the neutral planes; the turbulent intensity at the edge of the region is about twice as much as that at the center of the region. In this region, the order of magnitude of the mean velocity calculated is close to 0.1 cm/s.
Both the experimental and numerical results show that the turbulence length scale at the chamber center has a slight increase with increase of the oscillation frequency.

The turbulence macro-length scale $L_e$ from the numerical simulation has a peak value at the chamber center and gradually decreases with distance away from the center.

The numerical results show that turbulence characteristic velocity and length scales in the chamber center display an asymptotic behavior. This leads to an option in the numerical simulations that the number of plate oscillation cycles simulated does not have to match that in the experiments.

9.2.5 Behavior of the Turbulent Transient Gaseous Jet

Penetration depth

Results from both the experiments and numerical simulations show that the penetration depth of the transient jet, with Re between 7,600 ~ 19,000, has strong dependency on the square root of time and the momentum rate of the jet, beyond 10 injector nozzle diameters away from the exit. That is, Eq. 2.1 still holds for transient jets under the conditions used in this work. The chamber wall to which the jet is approaching tends to slow down the jet.

Through the experiments and the numerical simulations, no significant influence on the behavior of the transient jet was observed from the zero-mean nearly isotropic homogenous turbulent flow formed in the central region of the DI chamber, even at its maximum level, which corresponds to the maximum possible oscillation frequency of the perforated plates. This is due to the strong turbulence in the transient jet itself, which overshadows the turbulence from the oscillation of the perforated plates.

Numerical results did show that the decaying turbulence in the central region of the DI
chamber, which is generated after the oscillation of the perforated plates stop, interacts with the transient jet and tends to slow down penetration of the jet and increase its spread angle, even in a very small degree under the conditions used, when compared to the transient injection into a quiescent chamber. Such an interaction gives rise to a higher percentage of flammable mixture, which hints to a stronger mass exchange between the jet and the ambient air flow. From the mixing point of view, the decaying turbulence does promote the mixing. Simulation results also show that the higher injection velocity, which induces a higher level turbulence around the jet, leads to a higher percentage of flammable mixture, when the jets reach the same penetration depth.

**Spread angles**

Three ways to define the spread angle have been examined. The calculated spread angles from all three ways display a decreasing trend from the beginning of injection and may become stable after the jet reaches the distance $z/D = 35$.

The spread angle based on the momentum half-width is about $11^\circ$. Spreading rate (SR) of the transient jet based on the half-width is close to 0.10, even at a distance close to the nozzle exit ($z/D = 15$). This SR value is close to that obtained from the experiments for a steady axisymmetrical round turbulent jet at Re of 11,000 and 95,500.

The spread angle based on the 2% mass fraction or 0.0002 density gradients on the boundary are over twice as much as the spread angle calculated from the half-width; the average spread angle based on 2% mass fraction and 0.0002 density gradient is $25^\circ$ and $26^\circ$, respectively, for all the cases presented ($z/D > 35$).

The decaying turbulence in the simulations tends to broaden the transient jet. About $1.5^\circ$ increase of the spread angle based on the half-width had been observed for cases with
injection velocity of 40 m/s.

9.3 Comments and Recommendations

9.3.1 Experimental Model Design
More freedom in choosing the oscillation strokes could be obtained if a larger DI chamber were used. The maximum oscillation frequency of the perforated plates could be increased if an upgraded DAQ card were used with higher data sampling rate. With a higher oscillation frequency, a higher turbulent intensity would be generated in the central region the DI chamber.

9.3.2 Experimental Measurements
Characterization of the turbulence generated by the oscillating perforated plates could be more complete if the measurements were taken at more positions. By doing so, the profile of turbulence integral length scale $L_t$ in the central region would be obtained in the plate oscillation direction.

The quality of the Schlieren movie image could be much improved if the lights projected to the projection screen are directly projected on the camera. This would eliminate noise in the image due to the uneven texture of the projection screen paper or any dirt on it. The camera has a means to adjust the size of the Schlieren image projected on the sensing plate, thus the accuracy of the measurement for the transient jets from the Schlieren image could be enhanced by simply increasing the size (pixel number) of the image. This has successfully been carried out in a number of trial experiments for injection at very low pressures, 0.0103 MPa and 0.0206 MPa.
9.3.3 Numerical Modeling
By use of the injector sub-model, the transient injection was modeled as a constant-velocity inflow with uniform exit velocity profile. An arbitrarily chosen value of injection velocity was assigned. Such modeling of the transient injection does not allow the direct comparison of the experimental results and the numerical results. This situation could be improved if the structure of the injector were known. Thus the flow inside of the injector could be simulated separately and its exit velocity values taken into the current injector sub-model.
References


256


Instruction Manual for FIND for Windows (version 1.4), TSI Incorporated.


Appendix A

Design of the Direct Injection Turbulence Chamber
SECTION A-A
SCALE 1:3

2x Ø5.11 ▼ 37
1/4-20 UNC - 2B ▼ 12.70

4x Ø3.30 ▼ 7.50
M4-6H ▼ 5.03

Mounting Hole for the Type 6051B1 pressure transducer (see a separate page)

8x Ø3.30 ▼ 7.50
M4-6H ▼ 7.50

R3
R25
Ø42
SECTION A-A

Pneumatic Cylinder Mount

TITLE:

SIZE DWG. NO. REV

SCALE: 1:1 WEIGHT:

SHEET 1 OF 1
Mounting hole for Kistler pressure transducer Type 6051B1
Appendix B

LabView Program Parameter
### 10 mm plate:

\( f_{osci} = 4 \text{ Hz}, S = 1.5 \text{ cm} \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>100 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>2.42</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.35500</td>
<td>-0.30500</td>
</tr>
<tr>
<td>I</td>
<td>-0.75074</td>
<td>-0.65574</td>
</tr>
<tr>
<td>D</td>
<td>-0.00132</td>
<td>-0.00111</td>
</tr>
</tbody>
</table>

\( f_{osci} = 4 \text{ Hz}, S = 2.5 \text{ cm} \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>100 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>3.27</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.25900</td>
<td>-0.22800</td>
</tr>
<tr>
<td>I</td>
<td>-0.71574</td>
<td>-0.65574</td>
</tr>
<tr>
<td>D</td>
<td>-0.00011</td>
<td>-0.00121</td>
</tr>
</tbody>
</table>

\( f_{osci} = 4 \text{ Hz}, S = 3.5 \text{ cm} \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>100 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>4.20</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.20000</td>
<td>-0.16800</td>
</tr>
<tr>
<td>I</td>
<td>-0.75574</td>
<td>-0.70574</td>
</tr>
<tr>
<td>D</td>
<td>-0.00351</td>
<td>-0.00341</td>
</tr>
</tbody>
</table>

\( f_{osci} = 8 \text{ Hz}, S = 1.5 \text{ cm} \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>160 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>2.40</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.42500</td>
<td>-0.37900</td>
</tr>
<tr>
<td>I</td>
<td>-0.88007</td>
<td>-0.72774</td>
</tr>
<tr>
<td>D</td>
<td>-0.00020</td>
<td>-0.00040</td>
</tr>
</tbody>
</table>

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>160 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>3.30</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.36400</td>
<td>-0.31700</td>
</tr>
<tr>
<td>I</td>
<td>-0.80074</td>
<td>-0.76574</td>
</tr>
<tr>
<td>D</td>
<td>-0.00030</td>
<td>-0.00100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>100 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>3.82</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.35200</td>
<td>-0.32000</td>
</tr>
<tr>
<td>I</td>
<td>-0.77574</td>
<td>-0.77574</td>
</tr>
<tr>
<td>D</td>
<td>-0.00090</td>
<td>-0.00300</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>250 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>2.35</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.46400</td>
<td>-0.41900</td>
</tr>
<tr>
<td>I</td>
<td>-0.91074</td>
<td>-0.72574</td>
</tr>
<tr>
<td>D</td>
<td>-0.00330</td>
<td>-0.00200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>200 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>3.30</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.37300</td>
<td>-0.33000</td>
</tr>
<tr>
<td>I</td>
<td>-0.80074</td>
<td>-0.79574</td>
</tr>
<tr>
<td>D</td>
<td>-0.00030</td>
<td>-0.00200</td>
</tr>
</tbody>
</table>

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$f_{\text{osci}} = 16 \text{ Hz}, S = 1.5 \text{ cm}$</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>250 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>2.35</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.55600</td>
<td>-0.47600</td>
</tr>
<tr>
<td>I</td>
<td>-0.55074</td>
<td>-0.61574</td>
</tr>
<tr>
<td>D</td>
<td>-0.00200</td>
<td>-0.00150</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$f_{\text{osci}} = 16 \text{ Hz}, S = 2.5 \text{ cm}$</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>240 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>3.30</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.43500</td>
<td>-0.37500</td>
</tr>
<tr>
<td>I</td>
<td>-0.70074</td>
<td>-0.65574</td>
</tr>
<tr>
<td>D</td>
<td>-0.00130</td>
<td>-0.00150</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$f_{\text{osci}} = 20 \text{ Hz}, S = 1.5 \text{ cm}$</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>320 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>2.35</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.60500</td>
<td>-0.53400</td>
</tr>
<tr>
<td>I</td>
<td>-0.57585</td>
<td>-0.52585</td>
</tr>
<tr>
<td>D</td>
<td>-0.00200</td>
<td>-0.00150</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$f_{\text{osci}} = 20 \text{ Hz}, S = 2.5 \text{ cm}$</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>300 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>3.25</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.46700</td>
<td>-0.39400</td>
</tr>
<tr>
<td>I</td>
<td>-0.58074</td>
<td>-0.57574</td>
</tr>
<tr>
<td>D</td>
<td>-0.00130</td>
<td>-0.00200</td>
</tr>
</tbody>
</table>

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
\[ f_{\text{osci}} = 25 \, \text{Hz}, \, S = 2.5 \, \text{cm} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>400 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>3.25</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.50000</td>
<td>-0.41000</td>
</tr>
<tr>
<td>I</td>
<td>-0.58074</td>
<td>-0.55574</td>
</tr>
<tr>
<td>D</td>
<td>-0.00130</td>
<td>-0.00200</td>
</tr>
</tbody>
</table>

**3 mm plate**

\[ f_{\text{osci}} = 4 \, \text{Hz}, \, S = 2.5 \, \text{cm} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>100 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>3.35</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.26500</td>
<td>-0.23000</td>
</tr>
<tr>
<td>I</td>
<td>-0.78574</td>
<td>-0.67574</td>
</tr>
<tr>
<td>D</td>
<td>-0.00151</td>
<td>-0.00121</td>
</tr>
</tbody>
</table>

\[ f_{\text{osci}} = 6 \, \text{Hz}, \, S = 2.5 \, \text{cm} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>100 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>3.30</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.35000</td>
<td>-0.32400</td>
</tr>
<tr>
<td>I</td>
<td>-0.61257</td>
<td>-0.59574</td>
</tr>
<tr>
<td>D</td>
<td>-0.00111</td>
<td>-0.00251</td>
</tr>
</tbody>
</table>

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>160 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>3.30</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.36400</td>
<td>-0.31700</td>
</tr>
<tr>
<td>I</td>
<td>-0.80074</td>
<td>-0.76574</td>
</tr>
<tr>
<td>D</td>
<td>-0.00030</td>
<td>-0.00100</td>
</tr>
</tbody>
</table>

- $f_{osci} = 8 \ Hz, \ S = 2.5 \ cm$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>160 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>3.30</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.36500</td>
<td>-0.32600</td>
</tr>
<tr>
<td>I</td>
<td>-0.60074</td>
<td>-0.56574</td>
</tr>
<tr>
<td>D</td>
<td>-0.00230</td>
<td>-0.00250</td>
</tr>
</tbody>
</table>

- $f_{osci} = 12 \ Hz, \ S = 2.5 \ cm$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Left tuning parameter</th>
<th>Right tuning parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>160 S/s</td>
<td></td>
</tr>
<tr>
<td>Number of cycles to stop</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>Set point max.</td>
<td>3.30</td>
<td></td>
</tr>
<tr>
<td>Set point min.</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>-0.44400</td>
<td>-0.38700</td>
</tr>
<tr>
<td>I</td>
<td>-0.80074</td>
<td>-0.76574</td>
</tr>
<tr>
<td>D</td>
<td>-0.00130</td>
<td>-0.00200</td>
</tr>
</tbody>
</table>

- $f_{osci} = 15 \ Hz, \ S = 2.5 \ cm$
Appendix C

Mix-Frequency Values for Effective Frequency-Shift Selection
<table>
<thead>
<tr>
<th>Effective Frequency</th>
<th>Mix Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shift Selection</td>
<td>Downshift (+)</td>
</tr>
<tr>
<td>10 MHz</td>
<td>30.000 MHz</td>
</tr>
<tr>
<td>5 MHz</td>
<td>35.000 MHz</td>
</tr>
<tr>
<td>2 MHz</td>
<td>38.000 MHz</td>
</tr>
<tr>
<td>1 MHz</td>
<td>39.000 MHz</td>
</tr>
<tr>
<td>500 kHz</td>
<td>39.500 MHz</td>
</tr>
<tr>
<td>200 kHz</td>
<td>39.800 MHz</td>
</tr>
<tr>
<td>100 kHz</td>
<td>39.900 MHz</td>
</tr>
<tr>
<td>50 kHz</td>
<td>39.950 MHz</td>
</tr>
<tr>
<td>20 kHz</td>
<td>39.980 MHz</td>
</tr>
<tr>
<td>10 kHz</td>
<td>39.990 MHz</td>
</tr>
<tr>
<td>5 kHz</td>
<td>39.995 MHz</td>
</tr>
<tr>
<td>2 kHz</td>
<td>39.998 MHz</td>
</tr>
<tr>
<td>0</td>
<td>40.000 MHz</td>
</tr>
</tbody>
</table>
Appendix D

Visual Basic Program for Image Processing
Public NUM As Long
Public num_frame As Long
Public S_SRC() As String
Public S_Filtered() As String
Public S_Averaged As String
Public S_Tip As String
Public Emptyfile As Integer
Public length() As Long
Const MNUM = 30  'Maximum number of files to be averaged

Sub Injectsearch()
    Input_controls()
    If NUM<1 Then Exit Sub
    Dim S_SRC_org(MNUM) As String
    Dim n As Long
    ReDim S_SRC(1 To MNUM) As String
    ReDim S_Filtered(1 To MNUM) As String
    S_Averaged = Insptr.SeqNew("")  'Prepare the output file
    Insptr.DispSetUpdate False, 0
    ***** Main program
    Load_videos()
    If NUM=1 Then
        S_Tip = S_SRC(1)
        GoTo hell
    End If
    backgrdfilter()
    For n = 1 To NUM  'Prepare the input files for averaging
        Insptr.SeqSetCur S_Filtered(n)
        S_SRC(n) = S_Filtered(n)
    Next n
    average()
    For n = 1 To NUM  'Deleting the unnecessary original files
        Insptr.SeqSetCur S_SRC(n)
        Insptr.SeqClose S_SRC(n)
    Next n
    Insptr.SeqSetCur S_Averaged
    S_Tip = S_Averaged
    hell:
    find_tip()
    plt_in_excel()
End Sub

'=====================================================================
'Discription: Input_control
'
' Input the control variables
'=====================================================================
Function Input_controls()
    'Create object type "UserDialog" and declare variable "user_input1".

    Begin Dialog UserDialog 400,406,"Input Data"
        GroupBox 10,7,380,75,"Input the number of files that you want to process"
        GroupBox 10,95,380,163,"Searching Scheme"
        GroupBox 10,266,380,105,"Output"
        TextBox 150,49,70,21,.TextBox1
        CheckBox 270,120,20,14,"",.CheckBox1
        CheckBox 270,145,20,14,"",.CheckBox2
        TextBox 270,170,70,21,.TextBox2
        TextBox 270,210,70,21,.TextBox3
        CheckBox 270,304,20,14,"",.CheckBox3
        CheckBox 270,329,20,14,"",.CheckBox4
        Text 180,28,60,14,"NUM." Text 60,120,180,14,"No need to filter background"
        Text 60,145,180,14,"No need to average files"
        Text 60,170,180,14,"No. of times to apply the filter:" Text 60,185,180,14,"(once by default; 5*5 filter)"
        Text 60,210,180,14,"Tip value threshold:" Text 60,225,180,14,"(default value: 180)"
        Text 60,304,180,14,"Table the inject tip position" Text 60,329,180,14,"Draw graph in Excel"

    End Dialog
    Dim user_input1 As UserDialog

    'Show dialog and wait for OK.
    Dialog user_input1

    'Assign user input parameters to variables.
    NUM = 0
    If user_input1.TextBox1 = "" Then Exit Function
    NUM = CInt(user_input1.TextBox1)

End Function'

'=====================================================================
'Discription: Load_videos
'
Loading as many video sequence files as needed

284
Function Load_videos()
    Dim n As Long
    Dim input_path(MNUM) As String
    Dim file_handle(MNUM) As String
    For n = 1 To NUM 'Load as many Video files as needed
        input_path(n) = GetFilePath( , "avi", , "Input Video File", 2)
        file_handle(n) = Insprtr.SeqLoad(input_path(n))
        If file_handle(n) = "" Then
            Emptyfile = 1
            Exit Function
        End If
        S_SRC(n) = Insprtr.SeqGetCur
    Next n
End Function

'Description: backgrdfilter()

Function backgrdfilter()
    Dim S_SRCa As String
    Dim S_DESTa As String
    Dim I_IMAGE43 As String
    Dim I_IMAGE44 As String
    Dim seq_index As Long
    Dim Img_index As Long
    Dim numframe As Long

    Insptr.SeqSetCur S_SRC(1)
    numframe = Insprtr.SeqGetNumFrames
    For seq_index = 1 To NUM
        S_Filtered(seq_index) = Insprtr.SeqNew("") ' in memory
        Insptr.DispSetUpdate False, 0
        Insptr.SeqSetCurEx S_SRC(seq_index), 1
        Insptr.ImgSetCurrent S_SRC(seq_index), R_Def$, ALL_BANDS
        Insptr.ImgNewROI(329,169,145,119) 'for different stoke
        Insptr.ClipCopy
        I_IMAGE43 = Insptr.ClipPaste()
        Insptr.ImgSetCurrent I_IMAGE43, R_Def$, ALL_BANDS
        For Img_index = 2 To numframe
            Insptr.ImgLockSrc2 I_IMAGE43, R_Def$, ALL_BANDS
            Insptr.SeqSetCurEx S_SRC(seq_index), Img_index

285

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Insptr.ImgSetCurrent $SRC(seq_index), R_Def$, ALL_BANDS

Insptr.ImgNewROI(329,169,145,119) 'for different stoke case
'(328, 171, 145, 120) 'for the different diameter case
'(344, 171, 145, 120) for the referred case
'(321,170,145,120) For the non motion Case
Insptr.ClipCopy
I_IMAGE44 = Insptr.ClipPaste()
Insptr.ArithSub
Insptr.ArithNeg
Insptr.SetCur S_Filtered(seq_index)
Insptr.SetInsertFrame I_IMAGE44, True
Next Img index

Insptr.SetCur $SRC(seq_index) 'close the source video file
Insptr.Close $SRC(seq_index)
Insptr.SetCurrent I_IMAGE43, R_Def$, ALL_BANDS
Insptr.Close

Next seq_index

End Function

' ==========================
' Discription: average()
' This Function averages several sequence files
'
Function average()
Dim I_IMAGE1 As String
Dim Nframe As Long 'number of frames for each file
Dim Img_index As Long
Dim sum_0 As String
Dim seq_index As Long
Dim sum_image As String

****** Outer Loop is for Frame, inner loop is for every sequence file

Insptr.SetCur $SRC(1)
Nframe = Insptr.GetNumFrames
Insptr.SetCurEx $SRC(1), 1
Insptr.SetCurrent $SRC(1), R_Def$, ALL_BANDS
sum_0 = Insptr.DupEx(0)
Insptr.SetCurrent sum_0, R_Def$, ALL_BANDS
Insptr.ArithSub

For Img_index = 1 To Nframe

** Initialization for the Sum_image

Insptr.SetCurrent sum_0, R_Def$, ALL_BANDS

286

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
sum_image = Insptr.ImgDupEx(0)
,
For seq_index = 1 To NUM
    Insptr.SeqSetCurEx S_SRC(seq_index), Img_index
    Insptr.ImgSetCurrent S_SRC(seq_index), R_Def$,
    ALL_BANDS
    I_IMAGE1 = Insptr.ImgDupEx(0)
    Insptr.ImgSetCurrent I_IMAGE1, R_Def$, ALL_BANDS
    Insptr.ArithDivConst NUM
    Insptr.ImgLockSrc2 I_IMAGE1, R_Def$, ALL_BANDS
    Insptr.ImgSetCurrent sum_image, R_Def$, ALL_BANDS
    Insptr.ArithAdd
    Insptr.ImgSetCurrent I_IMAGE1, R_Def$, ALL_BANDS
    Insptr.ImgClose
Next seq_index

    Insptr.SeqSetCur S_Averaged
    Insptr.SeqInsertFrame sum_image, True

Next Img_index

    Insptr.ImgSetCurrent sum_0, R_Def$, ALL_BANDS
    Insptr.ImgClose

End Function

' Discription: find_tip()
' This program take input sequence file S_Tip and
' calculate the tip position

Function find_tip()
    Const MaxNframe = 120
    Dim numframe As Long
    Dim I_IMAGE43 As String
    Dim I_IMAGE44 As String
    Dim index As Long
    Const vtlpixnum = 120 ‘vertical pixel number
    Const horzpixnum = 145 ‘horizontal pixel number
    Dim verpoint As Long
    Dim colour As Integer
    Dim i As Integer
    Dim n As Integer
    Dim found As Integer
    Dim output_path As String
    Dim input_path As String
    Dim file_handle As String
    Dim lineposition As Integer
    Insptr.SeqSetCur S_Averaged
    numframe = Insptr.SeqGetNumFrames
num_frame = numframe

Dim length2(1 To MaxNframe, horzpixnum) As Long
ReDim length(1 To numframe) As Long
ReDim length_left(1 To numframe) As Long
ReDim length_right(1 To numframe) As Long

*******************************************************
**** find the position of jet tip for the first 5 frames
*******************************************************
For index = 1 To 4
    Insptr.SeqSetCurEx S_Tip, index
    Insptr.ImgSetCurrent S_Tip, R_Def$, ALL_BANDS
    Insptr.FiltUser "Smooth5x5"
    calculate the tip position along five position, starting with 63
    For lineposition = 1 To 10
        i = 30
        Do
            colour = Insptr.ImgGetPixelValue(lineposition + 63, i)
            If colour < 180 Then
                found = 1
                length2(index, lineposition) = i - 1
            Else
                found = 0
            End If
        Loop Until (found = 1)
    Next lineposition
    take the biggest value as the true tip position
    length(index) = 0
    For n = 1 To 10
        If length(index) < length2(index, n) Then
            length(index) = length2(index, n)
        Next n
    Next index

*******************************************************
**** find the position of jet tip of the rest frames for both
side
*******************************************************
For index = 5 To numframe
    Insptr.SeqSetCurEx S_Tip, index
    Insptr.ImgSetCurrent S_Tip, R_Def$, ALL_BANDS
    Insptr.FiltUser "Smooth5x5"
    calculate the tip position along five position, starting with 63

288
For lineposition = 1 To 34 ' left side
    i = 15
    Start with pixel 15
    If index >= 25 Then i = 4 ' the last
    several frame starts with pixel 5
    Do
        colour = Inspr.Image.GetPixelValue(lineposition, i)
        If colour >= 180 Then
            found = 1
        Else
            found = 0
        End If
        i = i + 1
    Loop Until (found = 1 Or i = 119)
    length2(index, lineposition) = i - 2
Next lineposition
'
    length_left(index) = 120 ' take the biggest value
    For n = 1 To 34
        If length_left(index) > length2(index, n) Then
            length_left(index) = length2(index, n)
        Next n
    '
    For lineposition = 111 To 144 ' right side
        i = 15
        Start with pixel 15
        If index >= 25 Then i = 5 ' the last
        several frame starts with pixel 5
        Do
            colour = Inspr.Image.GetPixelValue(lineposition, i)
            If colour >= 180 Then
                found = 1
            Else
                found = 0
            End If
            i = i + 1
        Loop Until (found = 1 Or i = 119)
        length2(index, lineposition) = i - 2
    Next lineposition
'
    ' take the biggest value
    length_right(index) = 120
    For n = 111 To 144
        If length_right(index) > length2(index, n) Then
            length_right(index) = length2(index, n)
        Next n
    '
    length(index) = length_right(index)
    If length_right(index) > length_left(index) Then
        length(index) = length_left(index)
    Next index
**** Choose location of output table and print the results

output_path = GetFilePath("side_table_seq", "txt", "c:\ethan\temp", "Output File", 3)
Open output_path For Output As #1
For index = 5 To numframe
  Print #1, index; vbTab;
  Print #1, 120 - length_left(index); vbTab; 120 - length_right(index); vbTab; 120 - length(index)
Next index

**** mean velocity for each penetration distance
Print #1, vbTab; "displacement(L)"; vbTab; vbTab; vbTab; "displacement(R)"
Print #1, vbTab; vbTab; vbTab; "Tip Velocity(L)"; "Tip Velocity(R)"
For index = 6 To numframe
  Print #1, index; vbTab; (length_left(index-1)-length_left(index))/vtlpixnum*100; vbTab; vbTab;
  Print #1, vbTab; (length_right(index-1)-length_right(index))/vtlpixnum*100; vbTab; vbTab;
  Print #1, vbTab; vbTab; vbTab; vbTab; vbTab; vbTab; vbTab; vbTab; vbTab;
  Print #1, ((length_left(index-1)-length_left(index))/vtlpixnum*100)/0.5; vbTab;
  Print #1, ((length_right(index-1)-length_right(index))/vtlpixnum*100)/0.5
Next index
Close #1
MsgBox "Program finished."
Insptr.DispSetUpdate True, 0
Insptr.SeqSetCurEx S_Tip, 1
End Function

' Discription: plt_in_excel()

Function plt_in_excel()

' Excel Constants
Const xlXYScatterSmoothNoMarkers = 73
Const xlLocationAsNewSheet = 1
Const xlColumns = 2
Const xlCategory = 1
Const xlPrimary = 1
Const xlValue = 2

' Main function
' #Uses "C:\Program Files\Matrox Inspector 3.1\BasicFiles\DemoPathSetup.bas"
Dim NewBook As Object ' Temp. Workbook object
Dim lNumBook As Long ' Num. books in Excel
Dim lNumFrame As Long ' Num. frames in the sequence
Dim lFrameIndex As Long ' Index to loop through the frames
Dim lPosMeasId As Long ' Measurement result Id
Dim strExport As String ' Export string
Dim S_APISTON_AVI As String ' Sequence
Dim strSeqFileName As String

DemoPathSetup

If (DemoExcelSetup = True) Then
  g_Excel.SheetsInNewWorkbook = 1
  g_Excel.Workbooks. Add
  lNumBook = g_Excel.Workbooks.Count
  g_Excel.Workbooks(lNumBook). Activate
  DemoPlaceExcel

  ' Allocate a 2 dimensional double array for the x And y of the Object's position
  lNumFrame = num_frame
  Dim dAPos() As Double
  ReDim dAPos(3, 1 To lNumFrame)

  For lFrameIndex=l To 4
    Insptr.SeqSetCurEx S_Tip, lFrameIndex
    dAPos(0, lFrameIndex) = Insptr.SeqGetCurrentFrame
    dAPos(2, lFrameIndex) = Insptr.SeqGetCurrentFrame
    dAPos(1, lFrameIndex) = length(lFrameIndex)
    dAPos(3, lFrameIndex) = length(lFrameIndex)
  Next lFrameIndex

  For lFrameIndex=5 To lNumFrame
    Insptr.SeqSetCurEx S_Tip, lFrameIndex
    dAPos(0, lFrameIndex) = Insptr.SeqGetCurrentFrame
    dAPos(2, lFrameIndex) = Insptr.SeqGetCurrentFrame
    dAPos(1, lFrameIndex) = 120 + 120 - length_left(lFrameIndex)
    dAPos(3, lFrameIndex) = 120 + 120 - length_right(lFrameIndex)
  Next lFrameIndex

  ' Export string
  strExport = g_Excel.ActiveWorkbook.Name + "|Sheet1|A1|C|S|N|F"

  UtilExportArray dAPos, strExport

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
' Draw the two charts: the x and y position of the object with time
AddChart("A","B",1,lNumFrame,"Horizontal Position of the Piston", "Time (seconds)", "Horizontal Position (pixels)", "Piston's x position")

    g_Excel.Sheets("Sheet1").Select
AddChart("C","D",1,lNumFrame, "Vertical Position of the Piston", "Time (seconds)", "Vertical Position (pixels)", "Piston's y position")
g_Excel.Sheets("Sheet1").Name = "Piston's Position"
End If
End Function

'===============================================================================
' Description: This function asks excel to plot a chart where
' the first column is the x axis and the second column is the y axis
'===============================================================================
Function AddChart(strColumn1$, strColumn2$, lStartRow&, lEndRowk, strTitle$, strXLabel$, strYLabel$, strCName$)
    Dim strColRange As String
    Dim strRange As String
    g_Excel.ScreenUpdating = False
    strColRange = strColumn1 + ":" + strColumn2
    g_Excel.Columns(strColRange).Select
    g_Excel. Charts. Add
    g_Excel. ActiveChart.ChartType = xlXYScatterSmoothNoMarkers
    strRange = strColumn1 + CStr(lStartRow) + ":" + strColumn2 + CStr(lEndRow)
    g_Excel.ActiveChart.SetSourceData
    Source:=g_Excel.Sheets("Sheet1").Range(strRange), PlotBy _
        :=xColumns
    g_Excel.ActiveChart.Location Where:=xlLocationAsNewSheet
    With g_Excel.ActiveChart
        .HasTitle = True
        .ChartTitle.Characters.Text = strTitle
        .Axes(xlCategory, xlPrimary).HasTitle = True
        .Axes(xlValue, xlPrimary).HasTitle = True
        .Name = strCName$
    End With
    g_Excel.ScreenUpdating = True
End Function
Discription: posn_founder()

find the edge position for the jet

parameters which influence the results:

smooth filter 5*5
threshold values for processing: 180
number of frames
number of vertical positions: here 80
pixel value for difference between white and black: here 180

and extremely important parameter for cutoff threshold
lower, and upper

================================================

Option Explicit
Public leftpO As Long
Public rightpO As Long
Const Numvp=80 'the number of maximum vertical points
Const pixvalue = 180 'pixel value for difference between white and black:
Const startpixel = 10
Const endpixel = 80
Const startframe = 8
Const endframe = 22
'============
Const lower = 42
Const upper = 213
'============

Sub posn_founder()

Dim S_SRC As String
Dim S_DESTa As String
Dim I_IMAGE43 As String
Dim I_IMAGE44 As String
Dim input_path As String
Dim file_handle As String
Dim seq_index As Long
Dim Img_index As Long
Dim numframe As Long
Dim xcordi As Long
Dim ycordi As Long
Dim nycordi As Long
Dim n As Long
Dim found As Integer
Dim colour As Long
Dim left_l(1 To 100) As Long
Dim left_r(1 To 100) As Long
Dim right_l(1 To 100) As Long
Dim right_r(1 To 100) As Long
ReDim leftp(l To 100) As Long
ReDim rightp(l To 100) As Long

S_SRC = Insptr.SeqGetCur
If S_SRC = "" Then
    MsgBox "Please click OK to choose an Video file!"
    'Choose input video file.
    input_path = GetFilePath(, "avi", , "Input Video File", 0)
    file_handle = Insptr.SeqLoad(input_path)
    S_SRC = Insptr.SeqGetCur
    If S_SRC = "" Then Exit Sub
End If

numframe = Insptr.SeqGetNumFrames
If (DemoExcelSetup = True) Then
    g_Excel.SheetsInNewWorkbook = 1
    g_Excel.Workbooks.Add
End If

For Img_index = startframe To endframe

    ********************************************
    **** find the position of jet tip for the first 5 frames
    ********************************************
    Insptr.SeqSetCurEx S_SRC, Img_index
    Insptr.ImgSetCurrent S_SRC, R_Def$, ALL_BANDS
    Insptr.FiltUser "Smooth5x5"
    Insptr.MapThreshTwoLevel lower, upper, 0, 255, 0, False
    Insptr.FiltUser "Smooth5x5"

calculate the edge position, two step, starting with left edge

    For left edge, scanning from the left
    For ycordi = startpixel To endpixel ' Start with pixel
        xcordi = 37
        Do
            colour = Insptr.ImgGetPixelValue(xcordi, ycordi)
            If colour < 180 Then
                found=1
                left_l(ycordi) = xcordi
            Else
                found=0
            End If
            xcordi=xcordi+1
            If xcordi>79 Then
                left_l(ycordi) = 67
                found=1
            End If
        Loop Until (found=1)
    Next ycordi
    For left edge, scanning from the right
    For ycordi = startpixel To endpixel ' Start with pixel
        xcordi = 68
        Do
            colour = Insptr.ImgGetPixelValue(xcordi, ycordi)
            If colour >= pixvalue Then
                found=1
                left_r(ycordi) = xcordi-1
            Else
                found=0
            End If
            xcordi=xcordi-1
            If xcordi<= 37 Then
                left_r(ycordi) = left_l(ycordi)
                found=1
            End If
        Loop Until (found=1)
    Next ycordi

    For Right edge, scanning from the Left
    For ycordi = startpixel To 33 ' Start with pixel
        xcordi=73
        Do
            colour = Insptr.ImgGetPixelValue(xcordi, ycordi)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
If colour >= pixvalue Then
    found=1
    right_l(ycordi) = xcordi-1
Else
    found=0
End If
xcordi=xcordi+1
If xcordi>110 Then
    right_l(ycordi) = 139
    found=1
End If
Loop Until (found=1)
Next ycordi

; two stage

For ycordi=34 To endpixel ' Start with pixel
  xcordi=79
  Do
    colour = Insptr.ImgGetPixelValue(xcordi, ycordi)
    If colour >= pixvalue Then
      found=1
      right_l(ycordi) = xcordi-1
    Else
      found=0
    End If
    xcordi=xcordi+1
    If xcordi>110 Then
      right_l(ycordi) = 139
      found=1
    End If
  Loop Until (found=1)
Next ycordi

' For right edge, scanning from the right

For ycordi= startpixel To 33 ' Start with pixel
  xcordi=104
  Do
    colour = Insptr.ImgGetPixelValue(xcordi, ycordi)
    If colour < pixvalue Then
      found=1
      right_r(ycordi) = xcordi
      If xcordi>103 Then
        right_r(ycordi) = right_l(ycordi)
      End If
      If xcordi<73 Then
        right_r(ycordi) = right_l(ycordi)
        found=1
      End If
    Else
      found=0
      End If
      xcordi=xcordi-1
    End If
    If xcordi<73 Then
      right_r(ycordi) = right_l(ycordi)
      found=1
    End If
  Loop Until (found=1)
Next ycordi

For ycordi = 34 To endpixel ' Start with pixel
  xcordi=104
  Do
    colour = Insptr.ImgGetPixelValue(xcordi, ycordi)
    If colour < pixvalue Then
      found=1
      right_r(ycordi) = xcordi
      If xcordi>103 Then
        ...
right_r(ycordi) = right_l(ycordi)
End If
Else
  found=0
End If
xcordi=xcordi-l
If xcordi<79 Then
  right_r(ycordi) = right_l(ycordi)
  found=1
End If
Loop Until (found=1)
Next ycordi

average the position of Left edge
For n= startpixel To endpixel
  leftp(n)=0.5*(left_l(n)+left_r(n))
  rightp(n)=0.5*(right_l(n)+right_r(n))
Next n
plt_in_excel()

'========================================================================
Next Img_index
  Insprt.SeqSetCur S_SRC       'close the source video file
  Insprt.SeqClose S_SRC
  Insprt.ImgSetCurrent 1_IMAGE43, R_Def$, ALL_BANDS
  Insprt.ImgClose
End Sub
'========================================================================
' Discription: plt_in_excel()
'========================================================================
Function plt_in_excel()
' Excel Constants
Const xlXYScatterSmoothNoMarkers = 73
Const xlLocationAsNewSheet = 1
Const xlColumns = 2
Const xlCategory = 1
Const xlPrimary = 1
Const xlValue = 2

' Main function
' #Uses "C:\Program Files\Matrox Inspector 3.1\BasicFiles\DemoPathSetup.bas"
' #Uses "C:\Program Files\Matrox Inspector 3.1\BasicFiles\ExportToExcel.bas"
' #Uses "C:\Program Files\Matrox Inspector 3.1\BasicFiles\ExcelUtil.bas"
' #Uses "C:\Program Files\Matrox Inspector 3.1\BasicFiles\ExcelGraphUtil.bas"
Dim NewBook As Object        ' Temp. Workbook object
Dim lNumBook As Long         ' Num. books in Excel
Dim lNumPoint As Long        ' Num. frames in the sequence
Dim lPointIndex As Long      ' Index to loop through the frames
Dim lPosMeasId As Long       ' Measurement result Id
Dim strExport As String      ' Export string

DemoPathSetup

If (DemoExcelSetup = True) Then
  lNumBook = g_Excel.Workbooks.Count

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
g_Excel.Workbooks(lNumBook).Activate

DemoPlaceExcel

' Allocate a 2 dimensional double array for the
' X And Y of the Object's position
INumPoint = endpixel - startpixel + 1
Dim dAPos() As Double
ReDim dAPos(3, 1 To INumPoint)

For lPointIndex = 1 To INumPoint
    dAPos(0, lPointIndex) = lPointIndex
    dAPos(2, lPointIndex) = lPointIndex
    dAPos(1, lPointIndex) = leftp(lPointIndex + startpixel - 1)
    dAPos(3, lPointIndex) = rightp(lPointIndex + startpixel - 1)
Next lPointIndex

' Export string
strExport = "|g_Excel. ActiveWorkbook.Name|A1|C|S|N|F"
UtilExportArray dAPos, strExport

' Draw the two charts: the X and Y position of the object with time
AddChart("A", "B", 1, INumPoint, "Horizontal Position of the Piston", "Time (seconds)", _
    "Horizontal Position (pixels)", "Piston's X position")
g_Excel.Sheets("Sheet1").Select
AddChart("C", "D", 1, INumPoint, "Vertical Position of the Piston", "Time (seconds)", _
    "Vertical Position (pixels)", "Piston's Y position")
g_Excel.Sheets("Sheet1").Name = "Piston's Position"
End If
End Function

' Description: This function asks excel to plot a chart where
' the first column is the X axis and the second
' column is the Y axis
Function AddChart(strColumn1$, strColumn2$, lStartRow&, lEndRow&, strTitle$, strXLabel$, strYLabel$, strCName$)
    Dim strColRange As String
    Dim strRange As String
    g_Excel.ScreenUpdating = False
    strColRange = strColumn1 + strColumn2
    g_Excel.Columns(strColRange).Select
    g_Excel.Charts.Add
    g_Excel.ActiveChart.ChartType = xlXYScatterSmoothNoMarkers
    strRange = strColumn1 + CStr(lStartRow) + ":" + strColumn2 + 
    CStr(lEndRow)
    g_Excel.ActiveChart.SetSourceData
    Source:=g_Excel.Sheets("Sheet1").Range(strRange), PlotBy _
        :=xlColumns
    With g_Excel.ActiveChart.Location
        .HasTitle = True
        .ChartTitle.Characters.Text = strTitle
        .Axes(xlCategory, xlPrimary).HasTitle = True
        .Axes(xlValue, xlPrimary).HasTitle = True
    End With
End Function

297

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Axes(xlValue, xlPrimary).AxisTitle.Characters.Text = strYLabel
    .Name = strCName$
End With

    g_Excel.ScreenUpdating = True
End Function
Appendix E

ITAPE18: Input File for Movement of the Perforated Plates
<table>
<thead>
<tr>
<th>5</th>
<th>1.75894</th>
<th>290, 0.47538</th>
<th>215, 2.36697</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.86706</td>
<td>295, 0.51711</td>
<td>220, 2.45348</td>
</tr>
<tr>
<td>15</td>
<td>1.97352</td>
<td>300, 0.56747</td>
<td>225, 2.53388</td>
</tr>
<tr>
<td>20</td>
<td>2.07753</td>
<td>305, 0.62606</td>
<td>230, 2.60756</td>
</tr>
<tr>
<td>25</td>
<td>2.17827</td>
<td>310, 0.69244</td>
<td>235, 2.67394</td>
</tr>
<tr>
<td>30</td>
<td>2.27500</td>
<td>315, 0.76612</td>
<td>240, 2.73253</td>
</tr>
<tr>
<td>35</td>
<td>2.36697</td>
<td>320, 0.84651</td>
<td>245, 2.78288</td>
</tr>
<tr>
<td>40</td>
<td>2.45348</td>
<td>325, 0.93303</td>
<td>250, 2.82462</td>
</tr>
<tr>
<td>45</td>
<td>2.53388</td>
<td>330, 1.02500</td>
<td>255, 2.85741</td>
</tr>
<tr>
<td>50</td>
<td>2.60756</td>
<td>335, 1.12173</td>
<td>260, 2.88101</td>
</tr>
<tr>
<td>55</td>
<td>2.67394</td>
<td>340, 1.22247</td>
<td>265, 2.89524</td>
</tr>
<tr>
<td>60</td>
<td>2.73253</td>
<td>345, 1.32648</td>
<td>270, 2.90000</td>
</tr>
<tr>
<td>65</td>
<td>2.78288</td>
<td>350, 1.43294</td>
<td>275, 2.89524</td>
</tr>
<tr>
<td>70</td>
<td>2.82462</td>
<td>355, 1.54105</td>
<td>280, 2.88101</td>
</tr>
<tr>
<td>75</td>
<td>2.85741</td>
<td>360, 1.65000</td>
<td>285, 2.85741</td>
</tr>
<tr>
<td>80</td>
<td>2.88101</td>
<td>365, 1.76051</td>
<td>290, 2.82462</td>
</tr>
<tr>
<td>85</td>
<td>2.89524</td>
<td>370, 1.87307</td>
<td>295, 2.78289</td>
</tr>
<tr>
<td>90</td>
<td>2.90000</td>
<td>375, 1.98902</td>
<td>300, 2.73253</td>
</tr>
<tr>
<td>95</td>
<td>2.89524</td>
<td>380, 2.10737</td>
<td>305, 2.76794</td>
</tr>
<tr>
<td>100</td>
<td>2.88101</td>
<td>385, 2.12785</td>
<td>310, 2.60756</td>
</tr>
<tr>
<td>105</td>
<td>2.85741</td>
<td>390, 2.14945</td>
<td>315, 2.53388</td>
</tr>
<tr>
<td>110</td>
<td>2.82462</td>
<td>395, 2.17215</td>
<td>320, 2.45349</td>
</tr>
<tr>
<td>115</td>
<td>2.78288</td>
<td>400, 2.19596</td>
<td>325, 2.36697</td>
</tr>
<tr>
<td>120</td>
<td>2.73253</td>
<td>405, 2.22190</td>
<td>330, 2.27500</td>
</tr>
<tr>
<td>125</td>
<td>2.67394</td>
<td>410, 2.24903</td>
<td>335, 2.17827</td>
</tr>
<tr>
<td>130</td>
<td>2.60756</td>
<td>415, 2.27734</td>
<td>340, 2.07752</td>
</tr>
<tr>
<td>135</td>
<td>2.53388</td>
<td>420, 2.30787</td>
<td>345, 1.97352</td>
</tr>
<tr>
<td>140</td>
<td>2.45348</td>
<td>425, 2.33962</td>
<td>350, 1.86706</td>
</tr>
<tr>
<td>145</td>
<td>2.36697</td>
<td>430, 2.37260</td>
<td>355, 1.75895</td>
</tr>
<tr>
<td>150</td>
<td>2.27500</td>
<td>435, 2.40683</td>
<td>360, 1.65000</td>
</tr>
<tr>
<td>155</td>
<td>2.17827</td>
<td>440, 0.41899</td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>2.07753</td>
<td>445, 0.40476</td>
<td></td>
</tr>
<tr>
<td>165</td>
<td>1.97352</td>
<td>450, 0.40476</td>
<td></td>
</tr>
<tr>
<td>170</td>
<td>1.86706</td>
<td>455, 0.40476</td>
<td></td>
</tr>
<tr>
<td>175</td>
<td>1.75894</td>
<td>460, 0.40476</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>1.65000</td>
<td>465, 0.40476</td>
<td></td>
</tr>
<tr>
<td>185</td>
<td>1.54106</td>
<td>470, 0.40476</td>
<td></td>
</tr>
<tr>
<td>190</td>
<td>1.43294</td>
<td>475, 0.40476</td>
<td></td>
</tr>
<tr>
<td>195</td>
<td>1.32648</td>
<td>480, 0.40476</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>1.22248</td>
<td>485, 0.40476</td>
<td></td>
</tr>
<tr>
<td>205</td>
<td>1.12173</td>
<td>490, 0.40476</td>
<td></td>
</tr>
<tr>
<td>210</td>
<td>1.02500</td>
<td>495, 0.40476</td>
<td></td>
</tr>
<tr>
<td>215</td>
<td>0.93303</td>
<td>500, 0.40476</td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>0.84652</td>
<td>505, 0.40476</td>
<td></td>
</tr>
<tr>
<td>225</td>
<td>0.76612</td>
<td>510, 0.40476</td>
<td></td>
</tr>
<tr>
<td>230</td>
<td>0.69244</td>
<td>515, 0.40476</td>
<td></td>
</tr>
<tr>
<td>235</td>
<td>0.62606</td>
<td>520, 0.40476</td>
<td></td>
</tr>
<tr>
<td>240</td>
<td>0.56747</td>
<td>525, 0.40476</td>
<td></td>
</tr>
<tr>
<td>245</td>
<td>0.51712</td>
<td>530, 0.40476</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>0.47538</td>
<td>535, 0.40476</td>
<td></td>
</tr>
<tr>
<td>255</td>
<td>0.44259</td>
<td>540, 0.40476</td>
<td></td>
</tr>
<tr>
<td>260</td>
<td>0.41899</td>
<td>545, 0.40476</td>
<td></td>
</tr>
<tr>
<td>265</td>
<td>0.40476</td>
<td>550, 0.40476</td>
<td></td>
</tr>
<tr>
<td>270</td>
<td>0.40476</td>
<td>555, 0.40476</td>
<td></td>
</tr>
<tr>
<td>275</td>
<td>0.40476</td>
<td>560, 0.40476</td>
<td></td>
</tr>
<tr>
<td>280</td>
<td>0.41899</td>
<td>565, 0.40476</td>
<td></td>
</tr>
<tr>
<td>285</td>
<td>0.44259</td>
<td>570, 0.40476</td>
<td></td>
</tr>
</tbody>
</table>

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Vita Auctoris

NAME: Chunyi Xia

PLACE OF BIRTH Liaoyang, Liaoning, China

YEAR OF BIRTH 1972

EDUCATION
- Liaoyang No.1 High School, Liaoyang, China 1987-1990
- Harbin Institute of Technology, Harbin, China 1990-1994 B. A. Sc.
- University of Windsor, Windsor, Ontario 1999-2006 Ph. D.