A study of the turbulence generated behind a perforated plate in a wind tunnel.

Rui. Liu

University of Windsor

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

Recommended Citation

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.
INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.
A Study of the Turbulence Generated Behind a Perforated Plate in a Wind Tunnel

by

Rui Liu

A Thesis
Submitted to the Faculty of Graduate Studies and Research
through the Department of Mechanical, Automotive and Materials Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science at the
University of Windsor

Windsor, Ontario, Canada
2002
Abstract

Conventionally, grids composed of bars or stripes have been used to a great extent in the experimental studies of isotropic turbulence. However, little information on perforated plate turbulence is available. Perforated plates are utilized instead of grids in the present study to determine the effect of the hole diameter and plate solidity on the intensity, length scale, homogeneity and isotropy of the resulting turbulence.

A perforated plate was placed at the entrance of the test section of a wind tunnel. The turbulent flow downstream of the plate was measured using a constant temperature hot-wire anemometer in conjunction with a single normal and a single inclined hot-wire. Measurements were conducted for nine different operating conditions which consisted of planes at three downstream distances and three flow rates. Each plane contained eighty-one measuring locations. At each location, three measurements were taken, one with the single normal hot-wire probe, the other two with the single inclined hot-wire probe. Nine different plates were tested. The total number of measurements was 19,683. The signal from single normal hot-wire probe was processed to obtain the turbulence root mean square (rms) velocity in the streamwise direction, \( u' \). The turbulence integral length scale based on the Taylor's frozen turbulence hypothesis was obtained from the signal of single normal probe. The turbulence rms velocity in the lateral direction, \( v' \), was obtained by combining \( u' \) with the processed result from the single inclined probe.

Two categories of dimensionless groups were developed using dimensional analysis. One of the groups represents the turbulence parameters and the other is a combination of the plate parameters and operating conditions. The effects of the later category on the former one were determined. It was found that the Reynolds number had no obvious effect on the turbulence parameters. The turbulence intensity decreased with the downstream distance with a power law relationship, but increased with the plate solidity with an exponential relationship. The normalized length scale increased with the downstream distance and with the plate solidity. Degree of homogeneity deteriorated downstream of the plate. The plate with a 35% solidity was found to possess the highest degree of homogeneity. The turbulence was more uniform in the region where the corresponding flatness factor was in the proximity of 3.
To my family
Acknowledgements

The author would like to express his sincere gratitude to Dr. G. W Rankin and Dr. D. Ting for their excellent guidance and support during this study.

Technical assistance from Mr. Robert Tattersall, Mr. Patrick Seguin and all the staff of the University of Windsor Technical Support Centre is appreciated.

The financial support from the Natural Science and Engineering Research Council of Canada in the form of Research Assistantship and an Equipment Grant are gratefully acknowledged.

The financial support from the Department of Mechanical, Automotive and Materials Engineering in the form of a Graduate Assistantship is gratefully acknowledged.

Thanks also go to the Faculty of Graduate Studies and Research of the University of Windsor which awarded the author a University of Windsor Tuition Scholarship.

The author owes a lot to his wife who helped and encouraged the author complete the toughest part of this project.
# Table of Contents

Abstract .................................................................................................................. IV

Acknowledgements ................................................................................................. VI

Table of Contents ..................................................................................................... VII

List of Figures .......................................................................................................... X

List of Tables .......................................................................................................... XV

Nomenclature .......................................................................................................... XVI

1. Introduction .......................................................................................................... 1

Objectives ............................................................................................................... 2

2. Literature Review ................................................................................................ 3

2.1 Criteria for identification of isotropy ................................................................. 3

2.2 Return to isotropy of grid-generated wind-tunnel turbulence ......................... 5

2.3 Decay of grid-generated wind-tunnel turbulence ............................................. 6

2.4 Spectral analysis of grid generated turbulence ................................................ 7

2.5 Oscillating-grid turbulence (OGT) ................................................................. 8

2.6 Inhomogeneity of grid turbulence .................................................................. 9

3. Experimental Work ............................................................................................. 10

3.1 Experimental flow facility .............................................................................. 10

3.2 Flow facility instrumentation and data acquisition ......................................... 15

3.2.1 Single normal and single inclined hot-wire probes .................................... 15

3.2.2 Temperature compensation of the hot-wire output .................................. 16

3.2.3 Hot-wire anemometer ............................................................................ 16

3.2.4 A/D converter ....................................................................................... 17

3.2.5 IBM compatible personal computer ....................................................... 18

3.2.6 StreamWare® Version 2.08 .................................................................... 18
3.3 Hot-wire calibration facility ................................................................. 18
3.4 Experimental method ........................................................................... 20
3.5 Data analysis ......................................................................................... 21

4. Results and Discussion ........................................................................ 24
4.1 Normalized Turbulence Intensities $u'/U$ and $v'/U$ .......................... 26
  4.1.1 The effect of $Re_{DU}$ on the turbulence intensity ....................... 26
  4.1.2 Change of turbulence intensity with $X/D$ ................................. 27
  4.1.3 The effect of plate solidity $\sigma$ on the turbulence intensity ....... 29

4.2 Normalized Length scale $L/D$ .............................................................. 29
  4.2.1 The effect of $Re_{DU}$ on $L/D$ .................................................... 30
  4.2.2 The effect of $X/D$ on $L/D$ ....................................................... 30
  4.2.3 The effect of plate solidity $\sigma$ on $L/D$ ...................................... 30

4.3 Homogeneity factor $H$ ....................................................................... 31
  4.3.1 The effect of $Re_{DU}$ on $H$ ........................................................ 31
  4.3.2 The effect of $X/D$ on $H$ ............................................................. 31
  4.3.3 The effect of $\sigma$ on $H$ ............................................................... 32

5. Conclusions and Recommendations .................................................... 56
5.1 Conclusions ......................................................................................... 56
5.2 Recommendations ............................................................................... 57

References ............................................................................................... 59

Appendix A. Programs For Data Analysis ............................................... 63
A.1 Program “mass line” ........................................................................... 63
A.2 Program “time saving” ........................................................................ 64
A.3 Program “three in a shot: inclined” .................................................... 64

Appendix B. Calibration Procedure Instructions ................................... 68
B.1 Calibration of single normal and single inclined hot-wire probes ....... 68
B.2 Details of hot-wire calibration program and $K$ calculation template .... 70
Appendix C. Test Procedure Instructions .............................................. 78

Appendix D. Uncertainty Analysis ......................................................... 80
  D.1 Calibration uncertainty ............................................................. 80
  D.2 Data acquisition uncertainty ...................................................... 81
    D.2.1 Digitization uncertainty .................................................... 81
    D.2.2 Probe spatial uncertainty .................................................. 81
    D.2.3 Incoming velocity uncertainty .......................................... 82
    D.2.4 Uncertainty from the signal conditioner gain and offset settings.. 82
  D.3 Uncertainty in mean velocity $U$ and non-normalized turbulence intensities
    $\overline{u^2}$ and $\overline{v^2}$ ......................................................... 83
    D.3.1 Uncertainty propagation from the calibration and digitization uncertainty.
        .................................................................................. 83
    D.3.2 Total uncertainty in $U$ and $\overline{u^2_{ref}}$ .............................. 83
    D.3.3 Uncertainty in turbulence normal intensity $\overline{u^2}$ .................. 84
    D.3.4 Uncertainty in turbulence lateral intensity $\overline{v^2}$ .................. 84
  D.4 Uncertainty in the dimensionless turbulence parameters ................. 86
    D.4.1 Uncertainty in normalized turbulence intensity $u'/U$ and $v'/U$ .... 86
    D.4.2 Uncertainty in the normalized integral length scale $L/D$ ............ 86
    D.4.3 Uncertainty in homogeneity factor $H$ .................................... 87
    D.4.4 Uncertainty in isotropy factor $I$ ......................................... 87
    D.4.4 Uncertainty in flatness factor $F$ ......................................... 88

Vita Auctoris ....................................................................................... 89
## List of Figures

<table>
<thead>
<tr>
<th>Figure 2.1:</th>
<th>Turbulence velocities correlated in the spatial autocorrelations ( f(r) ) and ( g(r) ).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 2.2:</td>
<td>Illustration of vorticities downstream of a grid.</td>
</tr>
<tr>
<td>Figure 2.3:</td>
<td>Schematic of oscillating grid turbulence generator.</td>
</tr>
<tr>
<td>Figure 3.1:</td>
<td>The original wind-tunnel [Turchyn 1972].</td>
</tr>
<tr>
<td>Figure 3.2:</td>
<td>The new wind-tunnel situated in Room 103 Essex Hall.</td>
</tr>
<tr>
<td>Figure 3.3:</td>
<td>The slots on the bottom panel and the probe holder in position.</td>
</tr>
<tr>
<td>Figure 3.4:</td>
<td>Schematic of the plate perforation pattern in this study.</td>
</tr>
<tr>
<td>Figure 3.5:</td>
<td>The data acquisition instrumentation.</td>
</tr>
<tr>
<td>Figure 3.6:</td>
<td>Temperature probe for temperature compensation.</td>
</tr>
<tr>
<td>Figure 3.7:</td>
<td>The low-turbulence-level nozzle used in the hot-wire calibration.</td>
</tr>
<tr>
<td>Figure 3.8:</td>
<td>The Meriam 34FB2TM micro-manometer.</td>
</tr>
<tr>
<td>Figure 4.1a:</td>
<td>Wireframe graph of the mean velocity ( U ) measured at nominal mean velocity 8.5 m/s with no perforated plate, ( X = 2.03 \text{ mm (80 in.)} ).</td>
</tr>
<tr>
<td>Figure 4.1b:</td>
<td>Wireframe graph of the turbulence rms velocity ( u' ) measured at nominal mean velocity 8.5 m/s with no perforated plate, ( X = 2.03 \text{ mm (80 in.)} ).</td>
</tr>
<tr>
<td>Figure 4.1c:</td>
<td>Velocity profile of ( u' ) for the no-plate test, ( U=8.5 \text{ m/s, } X = 2.03 \text{ mm (80 in.)}, \ Y = 102 \text{ mm (-4 in.)} ).</td>
</tr>
<tr>
<td>Figure 4.2a:</td>
<td>Wireframe graph of the turbulence rms velocity ( u' ) at 20 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at ( \text{Re}_{DU} = 29000 ).</td>
</tr>
<tr>
<td>Figure 4.2b:</td>
<td>Wireframe graph of the turbulence rms velocity ( v' ) at 20 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at ( \text{Re}_{DU} = 29000 ).</td>
</tr>
<tr>
<td>Figure 4.3a:</td>
<td>Wireframe graph of the turbulence rms velocity ( u' ) at 30 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at ( \text{Re}_{DU} = 29000 ).</td>
</tr>
</tbody>
</table>
Figure 4.3b: Wireframe graph of the turbulence rms velocity $v'$ at 30 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at $Re_{DU} = 29000$. ................................................................. 35

Figure 4.4a: Wireframe graph of the turbulence rms velocity $u'$ at 40 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at $Re_{DU} = 29000$. ...................................................................................... 36

Figure 4.4b: Wireframe graph of the turbulence rms velocity $v'$ at 40 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at $Re_{DU} = 29000$. ...................................................................................... 36

Figure 4.5a: Changes of $u'/U$ with $Re_{DU}$ 20 diameters downstream of the plates with 38.1 mm hole diameter............................................... 37

Figure 4.5b: Changes of $u'/U$ with $Re_{DU}$ 30 diameters downstream of the plates with 38.1 mm hole diameter............................................... 37

Figure 4.5c: Changes of $u'/U$ with $Re_{DU}$ 40 diameters downstream of the plates with 38.1 mm hole diameter............................................... 38

Figure 4.6a: Changes of $v'/U$ with $Re_{DU}$ 20 diameters downstream of the plates with 38.1 mm hole diameter............................................... 38

Figure 4.6b: Changes of $v'/U$ with $Re_{DU}$ 30 diameters downstream of the plates with 38.1 mm hole diameter............................................... 39

Figure 4.6c: Changes of $v'/U$ with $Re_{DU}$ 40 diameters downstream of the plates with 38.1 mm hole diameter............................................... 39

Figure 4.7a: Changes of $(u'/U)^2$ with $X/D$ downstream of the plates with 25.4 mm hole diameter at $Re_{DU} = 29000$. ......................................................... 40

Figure 4.7b: Changes of $(u'/U)^2$ with $X/D$ downstream of the plates with 38.1 mm hole diameter at $Re_{DU} = 29000$. ......................................................... 40

Figure 4.7c: Changes of $(u'/U)^2$ with $X/D$ downstream of the plates with 50.8 mm hole diameter at $Re_{DU} = 29000$. ......................................................... 41

XI
Figure 4.7d: Wireframe graph of the turbulence rms velocity $u'$ at 40 diameters downstream of the plate with 38.1 mm hole diameter, 60% solidity at $Re_{DU} = 29000$ ................................................................. 41

Figure 4.8a: Changes of $\ln(u'/U)$ with $\sigma$ at $Re_{DU} = 29000$ for the plate with 25.4 mm hole diameter. .................................................................................................................. 42

Figure 4.8b: Changes of $\ln(u'/U)$ with $\sigma$ at $Re_{DU} = 29000$ for the plate with 50.8 mm hole diameter. .................................................................................................................. 42

Figure 4.8c: Changes of $\ln(u'/U)$ with $\sigma$ at $Re_{DU} = 29000$ for the plate with 50.8 mm hole diameter. .................................................................................................................. 43

Figure 4.9: Autocorrelation graph of the turbulence fluctuation velocity $u'$ .......... 43

Figure 4.10a: Wireframe graph of $L/D$ at 20 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at $Re_{DU} = 29000$ ................................................................. 44

Figure 4.10b: Wireframe graph of $L/D$ at 30 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at $Re_{DU} = 29000$ ................................................................. 44

Figure 4.10c: Wireframe graph of $L/D$ at 40 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at $Re_{DU} = 29000$ ................................................................. 45

Figure 4.11a: Changes of $L/D$ with $Re_{DU}$ 20 diameters downstream of the plates with 38.1 mm hole diameter. .................................................................................................................. 45

Figure 4.11b: Changes of $L/D$ with $Re_{DU}$ 30 diameters downstream of the plates with 38.1 mm hole diameter. .................................................................................................................. 46

Figure 4.11c: Changes of $L/D$ with $Re_{DU}$ 40 diameters downstream of the plates with 38.1 mm hole diameter. .................................................................................................................. 46

Figure 4.12a: Changes of $L/D$ with $X/D$ downstream of the plates with 25.4 mm hole diameter at $Re_{DU} = 29000$ ................................................................. 47

Figure 4.12b: Changes of $L/D$ with $X/D$ downstream of the plates with 38.1 mm hole diameter at $Re_{DU} = 29000$ ................................................................. 47

Figure 4.12c: Changes of $L/D$ with $X/D$ downstream of the plates with 50.8 mm hole diameter at $Re_{DU} = 29000$ ................................................................. 48
Figure 4.13a: Changes of $L/D$ with $\sigma$ at $Re_{DU} = 29 000$ for the plate with 25.4 mm hole diameter. .................................................................................................................. 48

Figure 4.13b: Changes of $L/D$ with $\sigma$ at $Re_{DU} = 29 000$ for the plate with 38.1 mm hole diameter. .................................................................................................................. 49

Figure 4.13c: Changes of $L/D$ with $\sigma$ at $Re_{DU} = 29 000$ for the plate with 50.8 mm hole diameter. .................................................................................................................. 49

Figure 4.14a: Relationship between $H$ and $F_{dev}$ measured at 20D, 30D and 40D downstream of the plates with a 35% solidity at $Re_{DU} = 29 000$ .............. 50

Figure 4.14b: Relationship between $H$ and $F_{dev}$ measured at 20D, 30D and 40D downstream of the plates with a 50% solidity at $Re_{DU} = 29 000$ .............. 50

Figure 4.14c: Relationship between $H$ and $F_{dev}$ measured at 20D, 30D and 40D downstream of the plates with a 35% solidity at $Re_{DU} = 29 000$ .............. 51

Figure 4.15a: Changes of $H$ with $Re_{DU}$ 20 diameters downstream of the plates with 38.1 mm hole diameter. .................................................................................................................. 51

Figure 4.15b: Changes of $H$ with $Re_{DU}$ 30 diameters downstream of the plates with 38.1 mm hole diameter. .................................................................................................................. 52

Figure 4.15c: Changes of $H$ with $Re_{DU}$ 40 diameters downstream of the plates with 38.1 mm hole diameter. .................................................................................................................. 52

Figure 4.16a: Changes of $H$ with $X/D$ downstream of the plates with 25.4 mm hole diameter at $Re_{DU} = 29 000$ .......... 53

Figure 4.16b: Changes of $H$ with $X/D$ downstream of the plates with 38.1 mm hole diameter at $Re_{DU} = 29 000$ .......... 53

Figure 4.16c: Changes of $H$ with $X/D$ downstream of the plates with 50.8 mm hole diameter at $Re_{DU} = 29 000$ .......... 54

Figure 4.17a: Changes of $H$ with $\sigma$ at $Re_{DU} = 29 000$ for the plate with 25.4 mm hole diameter. .................................................................................................................. 54

XIII
Figure 4.17b: Changes of $H$ with $\sigma$ at $Re_{DU} = 29000$ for the plate with 38.1 mm hole diameter ................................................................. 55

Figure 4.17c: Changes of $H$ with $\sigma$ at $Re_{DU} = 29000$ for the plate with 50.8 mm hole diameter ................................................................. 55

Figure A.1: Coordinate systems for name convention of data processing. ........................................ 65
Figure A.2: Flow chart of the program "mass line". ........................................................................... 66
Figure A.3: Flow chart of program "three in a shot: inclined" .......................................................... 67
Figure B.1: Option window of the hot-wire calibration program ...................................................... 75
Figure B.2: Hot-wire Calibration window for the hot-wire calibration program ......................... 75
Figure B.3: Typical calibration results for the test of the 25.4 mm (1 in.) hole diameter
50% solidity plate ..................................................................................................................... 76
Figure B.4: K calculation template which is a Microsoft Excel workbook file. ............................. 76
Figure B.5: Yaw angle $\alpha$ used in the yaw coefficient calibration ............................................... 77
Figure B.6: Flow chart for K calculation ......................................................................................... 77
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Plate parameters.</td>
<td>14</td>
</tr>
<tr>
<td>3.2</td>
<td>Details of Test Conditions.</td>
<td>23</td>
</tr>
<tr>
<td>4.1</td>
<td>The uncertainty in the turbulence parameters.</td>
<td>26</td>
</tr>
<tr>
<td>4.2</td>
<td>Results of decay coefficients ( n ) and ( b ) of the power decay law of the turbulence dissipation.</td>
<td>27</td>
</tr>
<tr>
<td>4.3</td>
<td>Results of coefficients ( c ) and ( d ) from the curve fitting ( u'/U = c \exp(d \times \sigma) ).</td>
<td>28</td>
</tr>
<tr>
<td>B.1</td>
<td>Preset ( U ) and ( \Delta p ) values for the hot-wire calibration.</td>
<td>73</td>
</tr>
<tr>
<td>B.2</td>
<td>Preset velocity value for the single inclined hot-wire calibration.</td>
<td>74</td>
</tr>
<tr>
<td>B.3</td>
<td>Preset position of the single inclined hot-wire probe.</td>
<td>74</td>
</tr>
</tbody>
</table>
### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Hot-wire calibration constant</td>
</tr>
<tr>
<td>$A/D$</td>
<td>Analog signal to digital signal</td>
</tr>
<tr>
<td>$B$</td>
<td>Hot-wire calibration constant</td>
</tr>
<tr>
<td>$C$</td>
<td>Hot-wire calibration constant</td>
</tr>
<tr>
<td>$CTA$</td>
<td>Constant Temperature hot-wire Anemometer</td>
</tr>
<tr>
<td>$CTF$</td>
<td>Compiled Text File</td>
</tr>
<tr>
<td>$D$</td>
<td>Perforated plate hole diameter</td>
</tr>
<tr>
<td>$d$</td>
<td>Exponent in the curve-fitted equation which relates the plate solidity to the turbulence intensity</td>
</tr>
<tr>
<td>$E_1(k_1)$</td>
<td>Power spectrum distribution defined by $\frac{1}{2}u^2 = \int E_1(k_1)dk_1$</td>
</tr>
<tr>
<td>$E_2(k_1)$</td>
<td>Power spectrum distribution defined by $\frac{1}{2}v^2 = \int E_2(k_1)dk_1$</td>
</tr>
<tr>
<td>$E_r$</td>
<td>Voltage reading obtained during hot-wire calibration</td>
</tr>
<tr>
<td>$EBF$</td>
<td>Exported Binary File</td>
</tr>
<tr>
<td>$F$</td>
<td>Flatness factor defined by $F = \frac{u^4}{(u')^4}$</td>
</tr>
<tr>
<td>$F_{dev3}$</td>
<td>Average flatness factor defined by $F_{dev3} = \frac{1}{3} \sqrt{\frac{\sum_{i=1}^{n} (F_i - 3)^2}{80}}$</td>
</tr>
<tr>
<td>$f$</td>
<td>Yaw function</td>
</tr>
<tr>
<td>$f_{sec}$</td>
<td>Grid oscillating frequency of oscillating grid generated turbulence</td>
</tr>
<tr>
<td>$f(r), g(r)$</td>
<td>Autocorrelation function of the same component of turbulence fluctuation velocity measured parallel and perpendicular to the direction of this the velocity component respectively</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>$H$</td>
<td>Homogeneity factor</td>
</tr>
<tr>
<td>$I$</td>
<td>Isotropy factor</td>
</tr>
<tr>
<td>$i$</td>
<td>Data index</td>
</tr>
<tr>
<td>$K$</td>
<td>Yaw coefficient of hot-wire probe</td>
</tr>
</tbody>
</table>
$k$ \hspace{1cm} \text{Magnitude of wave number}

$k_1$ \hspace{1cm} \text{Wave number in $x_1$ direction}

$l$ \hspace{1cm} \text{Yaw function defined by $df/d\alpha = -fl$}

$L$ \hspace{1cm} \text{Integral length scale of turbulence}

$M$ \hspace{1cm} \text{Standard deviation of $u'$}

$N$ \hspace{1cm} \text{Number of data points}

$n$ \hspace{1cm} \text{Exponent in the power decay law of grid-generated wind-tunnel turbulence}

$OGT$ \hspace{1cm} \text{Oscillating Grid Turbulence}

$P$ \hspace{1cm} \text{Atmospheric pressure}

$\Delta p$ \hspace{1cm} \text{Pressure difference}

$R$ \hspace{1cm} \text{Gas constant}

$Re_{du}$ \hspace{1cm} \text{Reynolds number calculated as $\frac{UD}{v}$}

$rms$ \hspace{1cm} \text{Root mean square}

$S$ \hspace{1cm} \text{Skewness factor which is defined by $S = \frac{\mu^3}{\mu^2}$}

$s$ \hspace{1cm} \text{Stroke of the oscillating grid generated turbulence}

$TBSI$ \hspace{1cm} \text{Text file containing the Basic Statistical Information}

$TMSS$ \hspace{1cm} \text{Text file containing the Mean Square values of the turbulence fluctuation velocity in the Streamwise direction}

$T$ \hspace{1cm} \text{Temperature}

$t$ \hspace{1cm} \text{Times measured by following a fluid particle from the instant it pass though the grid}

$t_0$ \hspace{1cm} \text{Virtual origin in the decay power law of grid-generated wind tunnel turbulence}

$U$ \hspace{1cm} \text{Mean flow velocity}

$U_{eff}$ \hspace{1cm} \text{Effective velocity calculated from the hot-wire calibration equation}

$U_R$ \hspace{1cm} \text{Standard velocity applied in hot-wire calibration}
\begin{itemize}
\item \(u\) \hspace{1cm} \text{Turbulence fluctuation velocity in the streamwise direction}
\item \(u'\) \hspace{1cm} \text{Root mean square of } u
\item \(u_0\) \hspace{1cm} \text{Root mean square of } u \text{ at the center point of the test plane}
\item \(u'\) \hspace{1cm} \text{Mean value of the turbulence rms velocity over the test plane}
\item \(u^2\) \hspace{1cm} \text{Mean square of } u
\item \(u'\) \hspace{1cm} \text{Effective turbulence intensity}
\item \(u^3\) \hspace{1cm} \text{Mean cubic value of } u
\item \(u^4\) \hspace{1cm} \text{Mean quartic power of } u
\item \(v\) \hspace{1cm} \text{Turbulence fluctuation velocity in the lateral direction which is parallel to the single normal hot-wire probe}
\item \(v'\) \hspace{1cm} \text{Root mean square of } v
\item \(v_0\) \hspace{1cm} \text{Root mean square of } v \text{ at the center point of the test plane}
\item \(v^2\) \hspace{1cm} \text{Mean square of } v
\item \(w\) \hspace{1cm} \text{Turbulence fluctuation velocity in the lateral direction which is perpendicular to the single normal hot-wire probe}
\item \(w^2\) \hspace{1cm} \text{Mean square of } w
\item \(X\) \hspace{1cm} \text{Downstream distance from the perforated plate}
\item \(Y\) \hspace{1cm} \text{horizontal distance from the center of the test plane}
\item \(Z\) \hspace{1cm} \text{vertical distance from the center of the test plane}
\item \(z\) \hspace{1cm} \text{Distance from the grid in the study of oscillating grid generated turbulence}
\end{itemize}

**Greek Symbols**

\begin{itemize}
\item \(\alpha\) \hspace{1cm} \text{Yaw angle}
\item \(\beta\) \hspace{1cm} \text{Uncertainty coefficient}
\item \(\gamma\) \hspace{1cm} \text{Uncertainty coefficient}
\item \(\varepsilon\) \hspace{1cm} \text{Dissipation rate of the turbulence kinetic energy}
\item \(\varepsilon\) \hspace{1cm} \text{Mean dissipation rate of turbulence kinetic energy}
\item \(\zeta\) \hspace{1cm} \text{Uncertainty coefficient}
\end{itemize}
$\zeta'$ Root mean square vorticity in the spanwise direction

$\eta$ Kolmogorov length scale

$\eta'$ Root mean square vorticity in the streamwise direction

$\lambda$ Taylor's micro-length scale

$\nu$ Kinematic viscosity of air

$\xi'$ Root mean square vorticity in the lateral direction

$\rho_{\text{air}}$ Air density

$\rho_{\text{Hg}}$ Density of mercury

$\rho_{\text{water}}$ Density of water

$\sigma$ Solidity of the perforated plate

$\mathcal{I}$ Integral time scale

$\psi$ Kolmogorov's universal constant

**Prefix**

$\Delta$ Denotes the uncertainty of a quantity
1. Introduction

Turbulence, presently, eludes a precise definition on which all researchers agree. The best one can do is to list necessary conditions with which a turbulent flow must comply. Some of these are as follows:

- Turbulence is random and unpredictable in the context of a particular realization.
- Turbulence arises at high Reynolds number as determined by case-dependent velocity and length scales.
- Turbulence is a continuum phenomenon that contains a wide range of different scales.
- Turbulence is diffusive in that it is much more efficient in transporting or mixing momentum, kinetic energy and contaminants as compared to its laminar counterpart.
- Turbulence is dissipative in that turbulence kinetic energy is converted to other energy forms at small turbulence scale via viscous effect.
- Turbulence is 3-dimensional.

The fact that turbulence is an extremely complex flow has lead many investigators to consider two simplifications. The first is homogeneous turbulence where the statistical turbulence properties are uniform throughout the flow field and hence do not change as the observation point is moved in any direction. The second more special type is isotropic turbulence. In this case the statistical properties do not change under a rotation of the coordinate axis and reflection to any plane. It is also known as spherical symmetry. Homogenous and isotropic turbulence does not exist in reality, however it can be experimentally approximated by passing a uniform air stream through a grid in a wind tunnel. The assumption of isotropy makes it possible to progress further in developing the theory of turbulence and provide a basis for the understanding of the more realistic cases.

Although some important progress has been made using this extreme simplification, the problem of this seemingly simplest case is far from being completely solved. It will take considerable further effort to establish a complete analytical approach to the study of this simplest case of turbulence. During this time experimental methods, among which wind-tunnel grid-generated turbulence is one approach, must be applied to validate the analytical results. Apart from validation of theoretical analysis, grid generated turbulence also finds its application in other engineering areas such as heat transfer and combustion engineering on
which turbulence parameters such as intensity and length and time scales exert a significant influence.

The present study utilizes a wind-tunnel in conjunction with a perforated plate for experimentally generating turbulence. Compared with the method of generating turbulence with a grid composed of bars or stripes, a perforated plate can be made with a variety of hole-patterns and sizes which, intuitively, allow turbulence to be generated relatively easily with characteristics that are different to that generated with a grid consisting of bars.

**Objectives**

It is the objective of the current study to investigate the effect of the plate parameters, such as the solidity and hole diameter and the test condition such as the mean velocity and downstream distance from the plate on the turbulence characteristics, such as intensity, turbulence scale, homogeneity and isotropy Turbulence characteristics such as intensity, turbulence scale, homogeneity and isotropy are considered. The detailed objectives are as follows:

- To apply constant hot-wire anemometry together with single normal and single inclined hot-wire probes to obtain measurements of the two components of turbulence velocities and the turbulence integral length scale.

- To conduct a dimensional analysis to determine which dimensionless groups are required to characterize the current flow.

- To investigate the relationship among the groups.
2. Literature Review

Numerous papers on grid-generated wind-tunnel turbulence have been published since Simmons and Salter [1934] first applied a uniform grid to produce relatively simple turbulence. These studies occupy a vast range of interest extending from fundamental papers which are concerned with the decay of turbulence downstream of the grid to more complicated ones which involve the introduction of a magnetic field and contaminants such as heat and particles. The present literature review is mainly concerned with grid-generated wind-tunnel turbulence which has the characteristic of being nearly isotropic in the absence of mean shear, contaminants or force fields other than gravity. These fundamental studies can generally be classified into three categories: return to isotropy of grid generated wind-tunnel turbulence, decay of grid generated wind-tunnel turbulence, and spectral analysis of grid generated wind-tunnel turbulence. Before considering the details of grid turbulence, the criteria for identifying isotropic turbulence will be first discussed. At the end of this literature review, oscillating grid generated turbulence and the inhomogeneity of grid generated turbulence are briefly considered.

2.1 Criteria for identification of isotropy

A complete requirement of isotropy is for the flow to have an invariance of the average values of all functions of the turbulence velocities. This is practically impossible to achieve. Historically, the following criteria have been used:

- Equality between the mean square value of the three components of velocity fluctuation [von Karman and Howarth 1938], i.e.,
  \[ \overline{u^2} = \overline{v^2} = \overline{w^2}, \]  
  \[ (2-1) \]
  where \( u \) is the fluctuation velocity in the streamwise direction, \( v \) and \( w \) are the fluctuation velocities in the lateral and spanwise directions, respectively. This has been widely used since the late 40's after advent of the hot-wire anemometer made the measurement of two and multi-components of velocity fluctuation easier.

- Zero value of the velocity fluctuation skewness factor, i.e.
  \[ S = \frac{\overline{u^3}}{(\overline{u^2})^{3/2}} = 0. \]
  \[ (2-2) \]
Physically, this value can be visualized as the energy flux in the streamwise direction [Maxey 1987] which, in the ideal case, is zero when the turbulence downstream of the grid is perfectly isotropic. In the study of grid generated wind-tunnel turbulence, due to the decay of turbulence kinetic energy, the skewness of the velocity fluctuation is measured to be approximately 0.04 as in the studies of van Atta and Chen [1968] and Bennett and Corrsin [1978].

☐ Compliance of experimental measurements with von Karman’s relationship between correlation coefficients $f(r)$ and $g(r)$ [von Karman 1937]

$$f(r) = g(r) + \frac{1}{2} r \frac{df(r)}{dr},$$

(2-3)

where $f(r)$ and $g(r)$ are the spatial autocorrelation functions of the same component of turbulence fluctuation velocity with spacing parallel and perpendicular to the direction of this the velocity component, respectively, as indicated in Figure 2.1. Taylor [1938] used this criterion to verify the isotropy results of Simmons et al. [1938].

![Figure 2.1 Turbulence velocities correlated in the spatial autocorrelations $f(r)$ and $g(r)$.](image)

☐ Linear decay of the square of Taylor’s microscale $\lambda$ [Taylor 1935a] in grid-generated wind-tunnel turbulence, i.e.,

$$\frac{d\lambda^2}{dt} = U \frac{d\lambda^2}{dX} = \frac{10\nu}{n},$$

(2-4)

where $U$ is the mean flow velocity, $X$ is the downstream distance from the grid, $\nu$ the kinematic viscosity, $n$ is the decay exponent that will be introduced in section 2.3. Based on the condition of isotropic turbulence and the decay power law of grid-generated wind-tunnel turbulence, the criterion was first explicitly derived and applied by Batchelor and Townsend [1947].
 Agreement between the measured transverse velocity spectrum with that predicted from 
the longitudinal spectrum using the isotropic relation:

\[ 2E_2(k_1) = E_1(k_1) - k_1 \frac{dE_1(k_1)}{dk_1}, \]  

(2-5)

where \( k_1 \) is the wave number component in the streamwise direction. \( E_1(k_1) \) and \( E_2(k_1) \) are 
power spectra defined by

\[ \frac{1}{2} \overline{u^2} = \int E_1(k_1)dk_1, \]

(2-6)

\[ \frac{1}{2} \overline{v^2} = \int E_2(k_1)dk_1. \]

(2-7)

2.2 Return to isotropy of grid-generated wind-tunnel turbulence

Grid-generated wind-tunnel turbulence has been observed to be anisotropic as indicated 
by the simple measure of the non-unity ratio between the mean square value of longitudinal-
velocity fluctuation component and that of either of the two transverse velocity fluctuation 
components, i.e., \( \overline{u^2}/\overline{v^2} \approx \overline{u^2}/\overline{w^2} > 1 \). This is believed to be due to the fact that downstream 
of the grid, the vorticities in the two transverse directions are greater than the vorticity in the 
streamwise direction as illustrated in Figure 2.2. This anisotropy can be reduced, as pointed 
out by Taylor [1935b], by introducing a secondary contraction downstream of the grid to 
impose a selective effect on the longitudinal and transverse vorticities which in turn 
selectively change the longitudinal and traverse turbulence energy level. This method was 
experimentally studied by Uberoi [1956, 1957] followed by Mills and Corrsin [1959], Uberoi 
and Wallis [1966], Warhaft [1980] and Choi and Lumley [2001]. An extensive study was 
conducted by Comte-Bellot and Corrsin [1966] whose results exhibit a persistent equality of 
turbulence fluctuation components downstream of the secondary contraction. This type of 
secondary contraction has been adopted in subsequent studies of grid-generated wind-tunnel 
turbulence [Comte-Bellot and Corrsin 1971, Gad-El-Hak and Corrsin 1974, Shliuen and 
Corrsin 1974].
The root mean square (rms) turbulence vorticity in the stream wise direction $\eta'$ is less than the lateral rms turbulence vorticities $\xi'$ and $\zeta'$. This makes the turbulence rms velocity $u'$ greater than the lateral turbulence rms velocity $v'$ and $w'$.

2.3 Decay of grid-generated wind-tunnel turbulence

Turbulence downstream of a uniform grid can be demarcated into three regions as described by Monin and Yaglom [1975]. These are: 1) The region immediately behind the grid, where turbulence is generated via the interaction between the wakes which form in the shadow of the solid area and the jets issued from the open area of the grid. The mechanism of this turbulence production is the mean velocity gradient within the shear layer between the jet and wake which is the source for turbulence production as described by Tennekes and Lumley [1972]; 2) a turbulence-generating region which may last for 5–20 mesh-sizes downstream of the grid [Simmons and Salter 1934, Baines and Peterson 1951, Checkel 1985, de Silva and Fernando 1994] depending on the particular grid configuration; and 3) the far-field region, where the flow becomes more uniform as the mean velocity gradient gradually disappears and turbulence starts to decay since there is no more kinetic energy coming from the mean flow. This decay stage consists of two parts, namely, the initial period of decay during which the decay of the turbulence kinetic energy is mainly due to the viscous effect exerted on the small scale turbulence, and the final period of decay where the turbulence becomes so weak that the viscous effect begins to act directly on large eddies after which the turbulence essentially dies out. Theoretically, based on the assumption of self-similarity, it can be shown that the initial period of decay is dictated by power law relationship
\[ \bar{u}^2 \propto (t - t_0)^{-n} \] [Taylor 1935a, von Karman and Howarth 1938, Kolmogorov 1941, Saffman 1967, George 1992]. This power law has been experimentally verified by Batchelor and Townsend [1947, 1948], Baines and Peterson [1951], Comte-Bellot and Corrsin [1966], van Atta and Chen [1968], Dickey and Mellor [1980] and Yoon and Warhaft [1990]. The symbol \( t \) is the time measured by following a fluid particle from the instant it passes through the grid. The symbol \( t_0 \) is the so-called the virtual time origin. The exponent \( n \) is found to lie within the range 1~1.4. As discussed by Mohamed and LaRue [1990], this scatter might be due to the subjective choice of the virtual origin, \( t_0 \), and the use of data in the non-homogeneous portion of the flow which can have a significant influence on the value of the parameters in the decay power law.

2.4 Spectral analysis of grid generated turbulence

Spectral analysis was introduced into the study of turbulence by Taylor [1938]. It finds application in the investigation of energy transfer between different turbulence scales and in Kolmogorov’s self-similarity hypotheses of the small scale of turbulence which states that a) properties of turbulence in the developed inertial range are only dependent on the spectral energy flux which equals the mean energy dissipation rate \( \bar{\varepsilon} \); b) properties of turbulence in the dissipative range are only dependent on the energy dissipation rate and the kinematic viscosity. Hypothesis a) leads to the famous Kolmogorov power law relationship

\[ E_k(k, t) = \psi \bar{\varepsilon}^{2/3} k^{-5/3}, \] (2-8)

where \( \psi \) is a universal constant named after Kolmogorov. Hypothesis b) leads to the expression

\[ E_k(k, t) = \bar{\varepsilon}^{1/4} \nu^{5/4} F(k\eta), \] (2-9)

where \( F(k\eta) \) is a universal function. Energy transfer between different turbulence scales in grid generated turbulence has been investigated by Uberoi [1963], van Atta and Chen [1969] and Gad-El-Hak and Corrsin [1974] whose results confirmed the dynamical equation for the three-dimensional energy spectrum in isotropic turbulence. Kolmogorov’s hypotheses have been studied by Kistler and Vrebalovich [1966], Schedvin et al. [1974], Gad-El-Hak and Corrsin [1974] and Sreenivasan [1995]. Kistler and Vrebalovich [1966] considered large
Reynolds numbers ranging from 120,000 to 2,400,000 (based on the mean flow velocity and the grid mesh size) in their study, which showed a clear tendency for the existence of an inertial range with the increasing Reynolds number. The Kolmogorov constant, $\nu$, was measured to be approximately 0.5 in the above studies.

2.5 Oscillating-grid turbulence (OGT)

Using an oscillating grid as shown in Figure 2.3 is an alternative method of generating nearly isotropic turbulence. The type of flow generated is referred to as oscillating grid turbulence (OGT). It was originally used for investigating mixing and entrainment phenomena across density interfaces following the pioneering work of Rouse and Dodu [1955]. The turbulence intensity of OGT was determined by grid geometry, frequency of oscillation, $f_{osc}$, stroke, $s$, and the distance, $z$, away from the grid. A certain power law relationship [Thompson and Turner 1975] was found to relate the OGT variables. OGT has the advantage of having a stationary\(^1\), zero-mean flow which has been called “clean turbulence”. Most of the OGT studies [Bouvard and Dumas 1967, Thompson and Turner 1975, Hopfinger and Toly 1976, McDougall 1979, Atkinson et al. 1987, Hannoun et al. 1988, de Silva and Fernando 1992] were concerned with the spatial decay (or diffusion) of turbulence away from the oscillating grid compared with the concern for temporal decay in the study of grid generated wind-tunnel turbulence. OGT generated with one oscillating grid is found to be nearly isotropic 2–3 mesh-sizes away from the grid. OGT has the disadvantage in that it is difficult to measure the temporal decay of turbulence kinetic energy due to the necessity of using an ensemble average to obtain the statistics. This drawback was addressed by studying grid-generated wind-tunnel turbulence whose decay is measured at the corresponding condition of its OGT counterpart [Checkel 1985].

![Figure 2.3 Schematic of oscillating grid turbulence generator.](image)

\(^1\) This means the invariance of the turbulence quantities with time.
2.6 Inhomogeneity of grid turbulence

It is noted that most of the previous studies on grid generated turbulence were performed using the assumption of homogeneity over a cross section perpendicular to the mean flow direction. The lack of homogeneity has been recognized by Batchelor and Townsend [1948] and Batchelor and Stewart [1950] using fine grids of mesh size 6.35 mm (1/4 in.) or less. Even with a grid of which the percentage standard deviation of the mesh size is as small as 2%, Grant and Nisbet [1957] still discovered a noticeable inhomogeneity in their measurement of streamwise turbulence intensity over the cross section 80 mesh-sizes downstream from the grid. This might be explained by the extreme sensitivity of turbulence to the boundary and initial conditions. Unfortunately, there are so few papers available on this aspect that it is not possible to give a complete and reasonable review at this point.
3. Experimental Work

The analog signal from the hot-wire anemometer is fed into the multi-purpose data acquisition board and converted into digital signal. This digital signal is saved and processed later. Specifications of the instruments applied in a typical test are described as follows. The operating condition of each test is outlined at the end of this chapter.

3.1 Experimental flow facility

The wind-tunnel is a modification of that which was originally part of the Ph.D. project of Turchyn [1972]. As shown in Figure 3.1, it consists of six basic sections. These are the intake safety box, blower, expansion section, flow settling chamber and contraction section, to which the test section is connected. The outlet of the original contraction section was designed to be a 610 mm (24 in.) by 305 mm (12 in.) rectangle with long side situated horizontally. The mean flow velocity was measured to be approximately 50 m/s with a turbulence level of less than 1.6%. The flow velocity was controlled manually by adjusting the position of the guide vane of the blower. This wind-tunnel was moved and revitalized by Ibrahim and Mazumbu [1999] whose objective was to add the new blower air intake safety box and larger test section. This new wind-tunnel is shown in Figure 3.2. A part of the contraction section was removed to accommodate the larger test section. The current dimension of the outlet of the contraction section is 860 mm across by 660 mm vertically and there is a small discontinuity between the outlet of the contraction section and the inlet of the test section which is suspected to have some effect on the turbulence downstream of the inlet. This effect was investigated as part of the preliminary test of the current project and will be discussed in more detail later in the thesis. The perforated plate is situated at the inlet to the test section.

The wind-tunnel test section is 2.38 m long with a cross section measuring 860 mm across by 660 mm vertically. It consists of four wall panels. The top and the two side panels are made of acrylic. The bottom panel is made of plywood of 20 mm thick. Four brackets are bolted on the top panel to reduce the vibration caused by the blower. Five slots are cut along the direction perpendicular to the mean flow on the bottom panel in order to allow positioning of the probe and the probe holder. These slots as well as the probe and probe holder are shown in Figure 3.3.
Figure 3.1 The original wind-tunnel [Turchyn 1972].
a) The front view of the entire wind-tunnel.

b) The back view of the wind-tunnel.


Figure 3.2 The new wind-tunnel situated in Room 103 Essex Hall.
Figure 3.3 The slots on the bottom panel and the probe holder in position.

The 9 perforated plates used in this study all had the pattern shown in Figure 3.4 but had different hole diameters and hole spacing to provide different solidity. All perforated plates are made of 3 mm thick aluminum sheet. The plate solidity, hole diameter and the percentage standard deviation of hole spacing are listed in Table 3.1. The hole spacing referred in this table is the distance between the edges of the two neighboring holes that situate on the same horizontal line. The hole spacing is measured within a square portion of the plate measuring 406 mm (16 in.) that is co-centered with the plate is measured. The percentage standard deviation is estimated as the ratio of the standard deviation of the hole spacing to the average of the hole spacing.
The nine plates used in this study were different in their hole diameters and hole spacing.

Figure 3.4 Schematic of the plate perforation pattern in this study.

Table 3.1: Plate parameters.

<table>
<thead>
<tr>
<th>Plate No.</th>
<th>Plate solidity $\sigma$</th>
<th>Hole diameter $D$ (mm)</th>
<th>Percentage Standard Deviation of hole spacing %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60%</td>
<td>50.8</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>50%</td>
<td>50.8</td>
<td>1.6</td>
</tr>
<tr>
<td>3</td>
<td>35%</td>
<td>50.8</td>
<td>3.1</td>
</tr>
<tr>
<td>4</td>
<td>60%</td>
<td>38.1</td>
<td>2.1</td>
</tr>
<tr>
<td>5</td>
<td>50%</td>
<td>38.1</td>
<td>4.7</td>
</tr>
<tr>
<td>6</td>
<td>35%</td>
<td>38.1</td>
<td>4.2</td>
</tr>
<tr>
<td>7</td>
<td>60%</td>
<td>25.4</td>
<td>3.4</td>
</tr>
<tr>
<td>8</td>
<td>50%</td>
<td>25.4</td>
<td>1.2</td>
</tr>
<tr>
<td>9</td>
<td>35%</td>
<td>25.4</td>
<td>6.2</td>
</tr>
</tbody>
</table>
3.2 Flow facility instrumentation and data acquisition

The instrumentation used in a typical test is shown in Figure 3.5. The entire setup is composed of two single hot-wire probes, a temperature probe, a constant temperature hot-wire anemometer (CTA), an A/D converter and an IBM compatible personal computer. The specifications of each device are described as follows.

![Figure 3.5 The data acquisition instrumentation. 1. Probe and probe holder. 2. CTA. 3. Personal computer.](image)

3.2.1 Single normal and single inclined hot-wire probes

In this study, the turbulence quantities are measured using a single normal hot-wire probe of DISA type 55P11 along with a single inclined hot-wire probe of DISA type 55P12. The sensors on both probes are made of platinum-plated tungsten. Both sensors are 5 μm in diameter and 1.25 mm in length giving an aspect ratio of 210. To obtain the values of turbulence quantities at a certain spatial point, the single normal probe is first positioned perpendicular to the mean flow to acquire a set of raw data which is processed later to get \( \overline{u^2} \). This value is combined with the data obtained by positioning the single inclined probe with its sensor at +45° and -45° to the mean flow to get the value of \( \overline{v^2} \). The alternative to this two-single-probes method is to use an X-array hot-wire probe. This second method is time-saving and more accurate but requires the installation of an additional hot-wire anemometer which is costly and hence not used in this work.
3.2.2 Temperature compensation of the hot-wire output

The hot-wire anemometer technology is based on the convection of heat between the hot-wire sensor and the fluid medium. The output of the hot-wire anemometer will be modified if flow temperature is different from that of the calibration condition. A temperature probe is placed by the side of the hot-wire probe as shown in Figure 3.6 to obtain the value of air temperature in order to make temperature compensation to the hot-wire output. The temperature probe is connected to the temperature transducer inside the Dantec 90N10 frame. The method of temperature compensation adopted in this study makes corrections to the hot-wire calibration coefficients which is related to the fluid properties such as thermal conductivity, density and dynamic viscosity that vary with temperature. Details of this method can be found in Appendix A.

![Figure 3.6 Temperature probe for temperature compensation.](image)

The temperature probe is indicated by the arrow.

3.2.3 Hot-wire anemometer

The hot-wire anemometer used in this study is a Dantec Streamline® 55C90 CTA module installed within a Dantec 90N10 frame. The 90N10 frame consists of three major parts: the power supply, the controller and a temperature transducer. The power supply provides all the power needed for the operation of the StreamLine® system. The controller acts as a gateway between the computer and the StreamLine® system via a serial interface. The controller receives a signal from the thermistor temperature sensor. The signal is linearized in the controller and directed to the computer via the serial interface. The 55C90 module contains a constant temperature anemometer and a signal conditioner. The
anemometer has two bridge configurations, 1:20 and 1:1, with selectable top-resistors. The 1:20 bridge configuration, which is used in this study, incorporates an internal high precision decade resistance, whose setting determines the operating temperature of the hot-wire probe. The decade allows the probe over-heat temperature to be adjusted with a resolution better than 0.1%. The error voltage from the bridge is amplified in a shaping servo amplifier whose gain characteristic can be selected to compensate for probe frequency fall off. The gain settings determine the overall system bandwidth which can be adjusted in steps up to 2 MHz. There is also a protection circuit within the module which prevents the hot-wire probe from burn out in case the probe is disconnected unintentionally when in operation or when the servo loop oscillates dangerously during a square-wave test. The signal conditioner is used to match the CTA bridge output voltage to the input range of the A/D converter board. It also performs filtering of the signal. It contains an OFFSET circuit that subtracts up to 10 volts from the bridge output with a resolution of 1 mV and a GAIN function that amplifies the resulting signal up to 1024 times. The low pass filtering is done with a third order filter that goes up to 300 kHz. The high pass filtering is made with a first order filter that goes down to 10 Hz. The stability of the output from the signal conditioner is maintained via the implementation of an internal offset compensation.

3.2.4 A/D converter

The A/D converter used in this study is a National Instrument AT-MIO-16E-10 which is a multifunction data acquisition board. It has a 12-bits resolution and a maximum sample rate of 100 Kilosamples/second. It has an input range from $\pm 0.05$ to $\pm 10$ V and an output up to $\pm 10$ V. This board is plugged into the ISA port on the mainboard of the computer. Its communication with the hot-wire anemometer is made possible via an SCB-68 shielded I/O connector block which is connected to the ISA port on the board. The driver of this board comes from the National Instrument’s software Ni-DAQ4.85 which is designed for the Windows 9x operating system. The control of this board is made possible via calling the functions provided with the Ni-DAQ4.85. These functions can be called within program languages such as Visual Basic, Borland C++ and Visual C++. 

17
3.2.5 IBM compatible personal computer

The personal computer used to collect the raw data has an Intel Pentium 450 MHz CPU, a 64 MB SDRAM type memory and an 8.4 GB hard drive. The operating system is Windows 98. It has one ISA port which is available for the AT-MIO-16E-10 data acquisition board. One of the COM ports of the computer is connected to the serial interface of the hot-wire anemometer via a serial cable. The software needed for the data acquisition is installed before the test.

3.2.6 StreamWare® Version 2.08

The StreamWare® application software offers a complete user interface for controlling the StreamLine® hardware system and for acquiring, processing and presenting data. It allows one to define a hardware configuration and to setup the individual CTA modules. A default setup procedure is used to acquire and reduce data. Data are presented in worksheets and can be copied to other Windows applications, like Excel for example. Turbulence quantities such as the mean flow velocity, the turbulence intensity, the autocorrelation coefficient and the power spectrum can be obtained with the built-in functions. The raw data can also be exported into binary files to be processed according to the specific needs of the user.

3.3 Hot-wire calibration facility

To ensure accurate measurements with the hot-wire anemometer, the hot-wire probes were calibrated before carrying out each test to establish the relationship between the voltage output from hot-wire anemometer and the velocity. Ideally, this calibration should be implemented under the same conditions applied to the test. In this study, it was necessary to perform the calibrations at a different location from that of the measurements. The devices used in the calibration include a nozzle of low turbulence level, a Pitot-static tube and a micro-manometer.

The jet which issued from the nozzle shown in Figure 3.7 functions as a low turbulence-level-flow generator. The potential core of the jet flow is uniform. Velocities inside the potential core can be varied from 0 to 30 m/s by adjusting valves upstream of the nozzle. The turbulence level inside the potential core is less than 0.4%.
The velocity inside the potential core is measured by sensing the pressure difference between the total and static pressure of the flow with a Pitot-static tube. This pressure difference is measured using the Meriam 34FB2TM micro-manometer shown in Figure 3.8. It has a resolution of 0.0254 mm (0.001 in.) of water.

The program written to facilitate acquisition of voltage readings from the hot-wire anemometer is included in Appendix B. Also listed in Appendix B is the detailed calibration procedure.

Figure 3.7 The low-turbulence-level nozzle used in the hot-wire calibration.
3.4 Experimental method

For each perforated plate, the tests were conducted on three 203-by-203 mm (8-by-8 in.) planes located 20, 30 and 40 diameters downstream of the plate in the center region of the test section. In each plane, time records of instantaneous velocity were taken at 81 regularly spaced points for each of the three preset Reynolds numbers (15 000, 22 000 and 29 000). Reynolds numbers were calculated on the basis of the mean flow velocity and the plate hole diameter. The limits of the preset Reynolds number were determined by the upper and lower limits of the wind-tunnel free stream velocity as well as by the values of the plate hole diameters. Details of the plane position and the value of mean velocities corresponding to the preset Reynolds numbers are listed in Table 3.2.

A typical test was started with setting the mean velocity corresponding to the preset Reynolds number with the probe holder positioned at the second last slot on the bottom panel of the test section. Then the probe holder was moved to the position where the actual data collection was to be performed. The probe holder was adjusted manually to traverse the hot-wire probe over the test plane to obtain the raw data at each of the 81 points. At each test point, the mean velocity was adjusted to achieve each of the desired Reynolds numbers. For
each test plane, the entire measurement was split into two days work with the single normal hot-wire measurement conducted in the first day and the single inclined hot-wire measurement conducted in the next day. All the raw data was obtained with the sample rate and sample number of the A/D converter set at 10 kHz and 262144, respectively. The details of the test procedure can be found in Appendix C.

A no-plate test was conducted with the probe holder positioned at the last slot in the bottom panel of the test section to investigate the background flow profile over the test plane. This slot corresponded to 2.03 m (80 in.) from the inlet of the test section. The measurements were taken at 25 regularly spaced points on the 20-by-20 mm test plane. The nominal mean velocity was 8.5 m/s.

3.5 Data analysis

The raw data acquired with the StreamWare® software were first exported into binary files. Three programs were written to perform the data processing with these binary files. One of these programs called “mass line” is for the data processing of the single normal wire data. This program gives the turbulence statistical quantities at each point on the test plane. These quantities include the local mean velocity, $U$, the turbulence rms velocity, $u'$, the skewness factor, $S$, and flatness factor, $F$, of the turbulence fluctuation velocity, $u$, the autocorrelation coefficient of the turbulence fluctuation velocity $u$ and the integral time scale, $\mathcal{I}$, calculated from the autocorrelation coefficient. The integral time scale, $\mathcal{I}$, was multiplied by the local mean velocity, $U$, to obtain an estimation of the integral length scale, $L$, at the particular location. Details of the equations that were used to determine these quantities are given in Appendix A. The other two programs were used for data processing of the single inclined hot-wire data. One of them called “time saving” was used to extract data from the binary files and to compile the data into the proper format needed for the program “three in a shot: inclined” to do the further processing. The program “three in a shot: inclined” was used to determine the values of $\overline{v^2}$ and $\overline{uv}$. The details of the three programs can be found in Appendix A.

In order to plot the final results, the turbulence rms velocities $u'$ and $v'$ were normalized with the local mean velocity $U$. The integral length scale was normalized with the hole
diameter $D$ of the perforated plate. All graphs generated as result of the current study can be found in the attached CD.
<table>
<thead>
<tr>
<th>Plate No.</th>
<th>Downstream distance $X$ (Diameter)</th>
<th>Reynolds number $Re_{DU}$</th>
<th>Mean velocity corresponding to the preset $Re$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2, 3</td>
<td>20D</td>
<td>15 000</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22 000</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29 000</td>
<td>8.5</td>
</tr>
<tr>
<td>4, 5, 6</td>
<td>30D</td>
<td>15 000</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22 000</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29 000</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>40D</td>
<td>15 000</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22 000</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29 000</td>
<td>8.5</td>
</tr>
<tr>
<td>7, 8, 9</td>
<td>20D</td>
<td>15 000</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22 000</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29 000</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td>30D</td>
<td>15 000</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22 000</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29 000</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td>40D</td>
<td>15 000</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22 000</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29 000</td>
<td>11.3</td>
</tr>
</tbody>
</table>
4. Results and Discussion

As a result of the dimensional analysis, the present results can be characterized by the following dimensionless groups:

- Normalized turbulence intensities $u'/U$ and $v'/U$, where $u'$ and $v'$ are the root mean square (rms) of the turbulence velocity fluctuation in the streamwise and lateral directions, respectively, and $U$ is the local mean flow velocity.

- Normalized length scale $L/D$, where $L$ is the turbulence integral length scale, $D$ is the plate hole diameter.

The three dimensionless groups ($u'/U$, $v'/U$, $L/D$) represent the turbulence parameters of concern in the present study. The dependency of these groups on certain independent dimensionless groups is investigated. The independent dimensionless groups are:

- Reynolds number, $Re_{DU}$, which uses the mean velocity $U$ as the characteristic velocity and the plate hole diameter $D$ as the characteristic length. Three different Reynolds numbers are tested, namely, 15 000, 22 000 and 29 000.

- Normalized distance $X/D$ downstream from the plate. Three different $X/D$ values are tested, namely, 20, 30 and 40.

- Plate solidity $\sigma$, which is the ratio of the area of the blockage portion of the plate to the total area of the plate. Three different $\sigma$ values are used, namely, 35%, 50% and 60%.

The homogeneity and isotropy of the turbulence are also of concern in this work. There is no proper method to directly develop dimensionless groups related to these two turbulence characteristics through the dimensional analysis. A homogeneity factor $H$ is arbitrarily defined in this study as

$$H = \frac{1}{u'\sqrt{80}} \sqrt{\sum (u_i - \overline{u'})^2}$$

(4-1)

where $u_i$ is the rms turbulence fluctuation velocity at points on the test plane; $\overline{u'}$ is the average rms turbulence velocity fluctuation on the same test plane. The value of $H$ increases as the deviation of the rms turbulence fluctuations increase from its homogeneous state. For the isotropy aspect, an arbitrary isotropy factor $I = \frac{\overline{u'^2}}{\overline{v'^2}}$ was adopted following the convention in the study of grid-generated turbulence [Comte-bellot and Corrsin 1966].

24
Also considered in this work is the flatness factor, $F$ [Tennekes and Lumley 1975], which is defined as $F = \frac{\mu^4}{(\mu')^4}$. The uncertainties in $H$, $I$ and $F$ as well as those in the aforementioned three turbulence parameters are developed in Appendix D and listed in Table 4.1. The uncertainty analysis indicates that the relative uncertainty in $I$ is nearly 40% which makes it inappropriate to carry out the discussion of $I$ with the current results.

The results from the no-plate test, which was conducted at nominal mean velocity of $U = 8.5$ m/s, are plotted as wireframe graphs generated with Surfer® [2001] and shown in Figures 4.1a and 4.1b. Three points can be made from the two graphs. First, the mean velocity is virtually uniform on the test plane. Secondly, the turbulence level indicated from this graph is as low as 0.6% which is small compared with the typical value of turbulence level found in the perforated-plate-generated wind-tunnel turbulence in this study. Thirdly, the turbulence rms velocity fluctuation in the lower right and upper left of the test plane is slightly larger than that at the other part of the plane. The profile of $\nu'$ was measured at 102 mm (4 in.) to the left of the center of the test plane at the same nominal velocity. The result is plotted as shown in Figure 4.1c. It appears that $\nu'$ slightly increases with the vertical distance, $Z$, from the center point when $Z$ is larger than 102 mm (4 in.). The $\nu'$ value measured near the bottom of the test section is significantly larger than that of the other points. This is understandable since the measuring point is within the turbulence boundary layer developed as the stream moves downstream.
Table 4.1: The uncertainties in the turbulence parameters.

<table>
<thead>
<tr>
<th>Turbulence Parameter</th>
<th>Relative uncertainty %</th>
</tr>
</thead>
<tbody>
<tr>
<td>rms velocity ( u' )</td>
<td>8</td>
</tr>
<tr>
<td>rms velocity ( v' )</td>
<td>20</td>
</tr>
<tr>
<td>Normalized turbulence intensity ( u'/U )</td>
<td>7</td>
</tr>
<tr>
<td>Normalized turbulence intensity ( v'/U )</td>
<td>20</td>
</tr>
<tr>
<td>Normalized length scale ( L/D )</td>
<td>13</td>
</tr>
<tr>
<td>Homogeneity factor ( H )</td>
<td>9</td>
</tr>
<tr>
<td>Isotropy factor ( I )</td>
<td>39</td>
</tr>
<tr>
<td>Flatness factor ( F )</td>
<td>20</td>
</tr>
</tbody>
</table>

In the following discussion one of the three independent dimensionless groups is varied while holding the other two constant.

4.1 Normalized Turbulence Intensities \( u'/U \) and \( v'/U \)

All the intensity values in the following discussion are taken from the central point of the test plane. The selection of these values is justified by the fact that for most of the plates, the central points are within the region in which the turbulence intensity has a relatively uniform behavior as illustrated in Figures 4.2a to 4.4b inclusive. These are typical wireframe graphs generated with Surfer® [2001] at \( Re_{DU} = 29000 \). In these graphs, \( u'_0 \) and \( v'_0 \) are the rms turbulence fluctuation velocity at the central point of the test plane. It can also be indicated from these graphs that the turbulence was not homogeneous over the test plane. This is in agreement with the results of Grant and Nisbet [1957] who discovered a noticeable inhomogeneity in their measurement of streamwise turbulence intensity over the cross section 80 mesh-sizes downstream from the grid.

4.1.1 The effect of \( Re_{DU} \) on the turbulence intensity

Figures 4.5a to 4.5c include plots of the normalized turbulence intensity, \( u'/U \), against the Reynolds number, \( Re_{DU} \), determined using the results of the plates with 38.1mm hole diameter. The normalized turbulence intensity \( v'/U \) is plotted for the same conditions of
$u'/U$ in Figures 4.6a to 4.6c. It is observed that by holding the other two independent parameters, $X/D$ and $\sigma$, constant, the normalized turbulence intensities remain nearly unchanged with the varying Reynolds number. This is consistent with the results of Kistler and Vrebalovich [1965] who investigated the effect of $Re_{du}$ in the range of $1.2 \times 10^5$ to $2.4 \times 10^6$. In their study, even though there was a general tendency that $u'/U$ and $v'/U$ decreased with $Re_{du}$, there were no noticeable variations in the normalized turbulence intensities within the Reynolds number range of $1.2 \times 10^5$ to $5 \times 10^5$. This implies that the turbulence velocities increase approximately linearly with the mean flow velocity. Since all the turbulence energy comes from the mean flow, it appears that for a given plate pattern the mean flow transfers a fixed percentage of its energy to the turbulent part of the flow as the mean flow velocity changes. It can also be implied from these graphs that the turbulence intensities increase with the plate solidity.

4.1.2 Change of turbulence intensity with $X/D$

For the purpose of comparing the results of the current study with those of other studies, $(u'/U)^2$ is used to represent the normalized turbulence intensity in place of $u'/U$. Figures 4.7a to 4.7c include plots of $\ln(u'/U)^2$ against $\ln(X/D)$ determined using the results of the plates for $Re_{du} = 29000$. A function in the form of $\ln(u'/U)^2 = \ln b - n \ln(X/D)$ is used to fit all the data and the resulting $n$ and $b$ values are listed in Table 4.2. Most of the $n$ values fall within the range of 1 to 1.4, which are in agreement with those found by Mohamed and LaRue [1990]. It should be noted that the results for the plate with a 50.8 mm hole diameter and a 50% solidity have a considerable deviation from the homogeneous state which makes it unsuitable to use to obtain the $n$ and $b$ values. This is the case since the power decay law holds only in the nearly isotropic region downstream of the plate [Mohamed and LaRue 1990]. It should also be noted that the $n$ values for the plate with a hole diameter of 38.1 mm and a solidity of 60% deviates largely from 1. This is due to the fact that, at 40 diameters downstream of this plate, the turbulence is observed to be inhomogeneous, as shown in Figure 4.7d, within the proximity of the center points where the value for discussion is selected. This makes the selection of the value at the center point inappropriate for this plate.
Table 4.2: Results of decay coefficients $n$ and $b$ of the power decay law of the turbulence dissipation.

<table>
<thead>
<tr>
<th>Plate hole diameter and solidity</th>
<th>Value of $n$ and $b$ from curve fitting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Re_{DU} = 15,000$</td>
</tr>
<tr>
<td>Hole diameter D (mm)</td>
<td>Plate solidity $\sigma$</td>
</tr>
<tr>
<td>50.8</td>
<td>60%</td>
</tr>
<tr>
<td>50.8</td>
<td>50%</td>
</tr>
<tr>
<td>50.8</td>
<td>35%</td>
</tr>
<tr>
<td>38.1</td>
<td>60%</td>
</tr>
<tr>
<td>38.1</td>
<td>50%</td>
</tr>
<tr>
<td>38.1</td>
<td>35%</td>
</tr>
<tr>
<td>25.4</td>
<td>60%</td>
</tr>
<tr>
<td>25.4</td>
<td>50%</td>
</tr>
<tr>
<td>25.4</td>
<td>35%</td>
</tr>
</tbody>
</table>

Table 4.3: Results of coefficients $c$ and $d$ from the curve fitting $u'/U = c \exp(d \times \sigma)$.

<table>
<thead>
<tr>
<th>Plate hole diameter D (mm) and distance from the plate</th>
<th>Value of $c$ and $d$ from curve fitting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Re_{DU} = 15,000$</td>
</tr>
<tr>
<td></td>
<td>$c$</td>
</tr>
<tr>
<td>50.8, 20$D$</td>
<td>2.27</td>
</tr>
<tr>
<td>50.8, 30$D$</td>
<td>1.65</td>
</tr>
<tr>
<td>50.8, 40$D$</td>
<td>1.735</td>
</tr>
<tr>
<td>38.1, 20$D$</td>
<td>2.75</td>
</tr>
<tr>
<td>38.1, 30$D$</td>
<td>2.02</td>
</tr>
<tr>
<td>38.1, 40$D$</td>
<td>1.11</td>
</tr>
<tr>
<td>25.4, 20$D$</td>
<td>2.36</td>
</tr>
<tr>
<td>25.4, 30$D$</td>
<td>1.92</td>
</tr>
<tr>
<td>25.4, 40$D$</td>
<td>1.66</td>
</tr>
</tbody>
</table>
4.1.3 The effect of plate solidity $\sigma$ on the turbulence intensity

Figures 4.8a to 4.8c are typical graphs of $\ln(u'/U)$ versus $\sigma$ at $Re_{du} = 29000$. A function of the form $\ln(u'/U) = \ln c + d\sigma$ is found to fit most of the data and the resulting $c$ and $d$ values are listed in Table 4.3. It appears that most of the $d$ values fall within the range of 0.015 to 0.02. This implies that the influence of the plate solidity persists as the turbulence is convected downstream. There is a clear tendency that the $c$ value decreases with the downstream distance, which indicates that the turbulence is decaying. For the case of 40 diameters downstream of the plate with the 50.8mm hole diameter, it is difficult to justify fitting the above function to the data as shown in Figure 4.8c.

4.2 Normalized Length scale $L/D$

The non-normalized integral length scale, $L$, is obtained by first calculating the integral time scale, the details of which can be found in Appendix A. The length scale, $L$, is then estimated as the product of the time scale and the mean flow velocity at the particular point assuming that Taylor’s frozen turbulence hypothesis [Mathieu and Scott 2000] holds under the test condition. In addition to the requirement of Taylor’s hypothesis, one drawback of this method is that the value of time scale will overshoot if the autocorrelation function fluctuates as the autocorrelation coefficient approaches zero. This is illustrated in Figure 4.9 and will consequently result in an unreasonably large value of $L$. An observation of the calculated length scale shows that, unlike that of the turbulence intensity, no fixed point or region on the test plane can be isolated to represent the behavior of the length scale over the particular plane. The minimum length scale value on the test plane is investigated for the purpose of the following discussion. The value selected in the foregoing method makes it inappropriate to conduct a quantitative analysis, so that only a qualitative analysis is presented as follows. Figures 4.10a to 4.10c are wireframe graphs generated with the results of the plate with 38.1 mm hole diameter and a plate solidity of 35% at $Re_{du} = 29000$. An overall observation is that the length scale, $L$, is characterized by the plate-hole-diameter and increases with the downstream distance from the plate.
4.2.1 The effect of $Re_{du}$ on $L/D$

Similar to what happens in the case of turbulence intensity, $Re_{du}$ seems to have little influence on the normalized length scale, $L/D$. The typical graphs plotted as $Re_{du}$ against $L/D$ are shown in Figures 4.11a to 4.11c inclusive. It can be seen that, for the three Reynolds numbers, $L/D$ stays nearly constant.

4.2.2 The effect of $X/D$ on $L/D$

Figures 4.12a to 4.12c include plots of $L/D$ against $X/D$ determined using the results of the plates at $Re_{du} = 29,000$. The integral length scale appears to, in most of the cases, increase with the downstream distance which is also indicated by the results of Checkel [1985]. Convected by the mean flow further downstream, the energy-containing large-scale turbulence disappears as it transfers its energy to the small-scale turbulence which is finally dissipated through the viscous effects. As the number of energy-containing eddies reduce, the largest scale turbulence which is less energy-containing become more and more dominant. The fact that the integral length scale increases with the downstream distance doesn’t mean that the turbulence is expanding itself, however, it indicates which portion of the turbulence is more active and dominant at that stage.

4.2.3 The effect of plate solidity $\sigma$ on $L/D$

Figures 4.13a to 4.13c include plots of $L/D$ against $\sigma$ using the results at $Re_{du} = 29,000$. The normalized length scale shown in Figure 4.13b is observed to decrease with the decreasing plate solidity. The smaller the solidity, the less the spacing between the holes in the perforated plate. The wake region corresponding to the spacing between the holes diminishes with the decreasing hole spacing as does the size of the vortex inside the wake. As the vortex is entrained inside the jet region, it has a substantial influence on the eddies which form as a result of the interaction between the entrained vortex and the jet flow.
4.3 Homogeneity factor $H$

An overall observation of the flow's basic statistical properties shows that there is an interesting correlation between the homogeneity factor, $H$, and the flatness factor, $F$. This is shown in Figures 4.14a to 4.14c which include plots of $H$ against $F_{dev3}$ using the results at 20D, 30D and 40D downstream of the plate at $Re_{DU} = 29000$. $F_{dev3}$ is defined as:

$$F_{dev3} = \frac{1}{3} \sqrt{\frac{\sum_{i=1}^{N} (F_i - 3)^2}{80}} \quad (4-2)$$

which is a measure of the average closeness of the flatness factors on a test plane to 3. In the portion of the test plane where the turbulence appears to be more nearly homogeneous, the corresponding flatness factors lie within the proximity of three. This might be an indication that the probability density function of a homogeneous turbulence is Gaussian [Mathieu and Scott 2000].

4.3.1 The effect of Re$_{DU}$ on $H$

As with the turbulence intensities and length scale, it seems there is no obvious dependence of the degree of homogeneity on the Reynolds number for the plates with 35% and 50% solidity. However, this is not true for the plates with 60% solidity. This is shown in Figures 4.15a to 4.15c which correspond to the results of the plate with a 38.1 mm hole diameter. In this case, the $H$ value decreases with the increasing Reynolds number for the 60% solidity plate.

4.3.2 The effect of $X/D$ on $H$

Figures 4.16a to 4.16c include plots of the homogeneity factor, $H$, against the downstream distance, $X/D$, which is created using the results of the plates with a 38.1 mm hole diameter at $Re_{DU} = 29000$. The homogeneity appears to deteriorate as the turbulence is convected farther downstream. This is contradictory to the expectation that turbulence should show more uniformity as the turbulence redistributes the energy over the test plane by way of turbulence momentum transport with no extraneous energy brought to the test field.
4.3.3 The effect of $\sigma$ on $H$

Figures 4.17a to 4.17c are plots of homogeneity, $H$, against the plate solidity, $\sigma$, which are made with the results of the plates with a 38.1 mm hole diameter. It is expected that as the solidity decreases, the degree of homogeneity should increase due to the smaller downstream distance needed for the jet and wake to completely mix with each other. Eventhough no such obvious tendency is observed with the current data, it does appear that turbulence downstream of the plate with a 35% solidity possess the highest degree of homogeneity as indicated by the homogeneity factor.

![Wireframe graph of the mean velocity $U$ measured at nominal mean velocity 8.5 m/s with no perforated plate, $X = 2.03$ m (80 in.).](image)

Figure 4.1a Wireframe graph of the mean velocity $U$ measured at nominal mean velocity 8.5 m/s with no perforated plate, $X = 2.03$ m (80 in.).
Figure 4.1b Wireframe graph of the turbulence rms velocity $u'$ measured at nominal mean velocity 8.5 m/s with no perforated plate, $X = 2.03$ m (80 in.).

Figure 4.1c Velocity profile of $u'$ for the no-plate test, $U=8.5$ m/s, $X = 2.03$ m (80 in.), $Y = -102$ mm (-4 in.).
Figure 4.2a Wireframe graph of the turbulence rms velocity $u'$ at 20 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at $Re_{DU} = 29 000$.

Figure 4.2b Wireframe graph of the turbulence rms velocity $v'$ at 20 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at $Re_{DU} = 29 000$.
Figure 4.3a Wireframe graph of the turbulence rms velocity $u'$ at 30 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at $Re_{DU} = 29000$.

Figure 4.3b Wireframe graph of the turbulence rms velocity $v'$ at 30 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at $Re_{DU} = 29000$. 
Figure 4.4a Wireframe graph of the turbulence rms velocity $u'$ at 40 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at $Re_{DU} = 29000$.

Figure 4.4b Wireframe graph of the turbulence rms velocity $v'$ at 40 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at $Re_{DU} = 29000$. 
Figure 4.5a Changes of $u'/U$ with $Re_{DU}$ 20 diameters downstream of the plates with 38.1 mm hole diameter.

Figure 4.5b Changes of $u'/U$ with $Re_{DU}$ 30 diameters downstream of the plates with 38.1 mm hole diameter.
Figure 4.5c Changes of $u'/U$ with $Re_{DU}$ 40 diameters downstream of the plates with 38.1 mm hole diameter.

Figure 4.6a Changes of $v'/U$ with $Re_{DU}$ 20 diameters downstream of the plates with 38.1 mm hole diameter.
Figure 4.6b Changes of $v/U$ with $Re_{DU}$ 30 diameters downstream of the plates with 38.1 mm hole diameter.

Figure 4.6c Changes of $v/U$ with $Re_{DU}$ 40 diameters downstream of the plates with 38.1 mm hole diameter.
Figure 4.7a Changes of $\langle u'/U \rangle^2$ with $X/D$ downstream of the plates with 25.4 mm hole diameter at $Re_{DU} = 29000$.

Figure 4.7b Changes of $\langle u'/U \rangle^2$ with $X/D$ downstream of the plates with 38.1 mm hole diameter at $Re_{DU} = 29000$. 
Figure 4.7c Changes of \((u'/U)^2\) with \(X/D\) downstream of the plates with 50.8 mm hole diameter at \(Re_{Du} = 29000\).

Figure 4.7d Wireframe graph of the turbulence rms velocity \(u'\) at 40 diameters downstream of the plate with 38.1 mm hole diameter, 60% solidity at \(Re_{Du} = 29000\).
Figure 4.8a Changes of $\ln(u'/U)$ with $\sigma$ at $Re_{DU} = 29000$ for the plate with 25.4 mm hole diameter.

Figure 4.8b Changes of $\ln(u'/U)$ with $\sigma$ at $Re_{DU} = 29000$ for the plate with 38.1 mm hole diameter.
Figure 4.8c Changes of $\ln(u'/U)$ with $\sigma$ at $Re_{Dh} = 29000$ for the plate with 50.8 mm hole diameter.

Figure 4.9 Autocorrelation graph of the turbulence fluctuation velocity $u'$. This graph is created with the data acquired at the center of the test plane 30 diameters downstream of the plate with 25.4mm hole diameter and 35% solidity. The resulting length scale $L/D$ from this set of data is 5.2.
Figure 4.10a Wireframe graph of $L/D$ at 20 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at $Re_{DU} = 29000$.

Figure 4.10b Wireframe graph of $L/D$ at 30 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at $Re_{DU} = 29000$. 

44
Figure 4.10c Wireframe graph of $L/D$ at 40 diameters downstream of the plate with 38.1 mm hole diameter, 35% solidity at $Re_{DU} = 29000$.

Figure 4.11a Changes of $L/D$ with $Re_{DU}$ 20 diameters downstream of the plates with 38.1 mm hole diameter.
Figure 4.11b Changes of $L/D$ with $Re_{DU}$ 30 diameters downstream of the plates with 38.1 mm hole diameter.

Figure 4.11c Changes of $L/D$ with $Re_{DU}$ 40 diameters downstream of the plates with 38.1 mm hole diameter.
Figure 4.12a Changes of $L/D$ with $X/D$ downstream of the plates with 25.4 mm hole diameter at $Re_{DU} = 29\,000$.

Figure 4.12b Changes of $L/D$ with $X/D$ downstream of the plates with 38.1 mm hole diameter at $Re_{DU} = 29\,000$. 
Figure 4.12c Changes of $L/D$ with $X/D$ downstream of the plates with 50.8 mm hole diameter at $Re_{Du} = 29000$.

Figure 4.13a Changes of $L/D$ with $\sigma$ at $Re_{Du} = 29000$ for the plate with 25.4 mm hole diameter.
Figure 4.13b Changes of $L/D$ with $\sigma$ at $Re_{DU} = 29\,000$ for the plate with 38.1 mm hole diameter.

Figure 4.13c Changes of $L/D$ with $\sigma$ at $Re_{DU} = 29\,000$ for the plate with 50.8 mm hole diameter.
Figure 4.14a Relationship between $H$ and $F_{dev3}$ measured at 20D, 30D and 40D downstream of the plates with a 35% solidity at $Re_{DU} = 29000$.

Figure 4.14b Relationship between $H$ and $F_{dev3}$ measured at 20D, 30D and 40D downstream of the plates with a 50% solidity at $Re_{DU} = 29000$. 

50
Figure 4.14c Relationship between $H$ and $F_{dev3}$ measured at 20D, 30D and 40D downstream of the plates with a 60% solidity at $Re_{DU} = 29000$.

Figure 4.15a Changes of $H$ with $Re_{DU}$ 20 diameters downstream of the plates with 38.1 mm hole diameter.
Figure 4.15b Changes of $H$ with $Re_{DU}$ 30 diameters downstream of the plates with 38.1 mm hole diameter.

Figure 4.15c Changes of $H$ with $Re_{DU}$ 40 diameters downstream of the plates with 38.1 mm hole diameter.
Figure 4.16a Changes of $H$ with $X/D$ downstream of the plates with 25.4 mm hole diameter at $Re_{DU} = 29000$.

Figure 4.16b Changes of $H$ with $X/D$ downstream of the plates with 38.1 mm hole diameter at $Re_{DU} = 29000$. 
Figure 4.16c Changes of $H$ with $X/D$ downstream of the plates with 50.8 mm hole diameter at $Re_{Du} = 29000$.

Figure 4.17a Changes of $H$ with $\sigma$ at $Re_{Du} = 29000$ for the plate with 25.4 mm hole diameter.
Figure 4.17b Changes of $H$ with $\sigma$ at $Re_{Du} = 29000$ for the plate with 38.1 mm hole diameter.

Figure 4.17c Changes of $H$ with $\sigma$ at $Re_{Du} = 29000$ for the plate with 50.8 mm hole diameter.
5. Conclusions and Recommendations

The objective was to study the effects of the perforated plate parameters \( D, \sigma, \) etc on the resulting turbulence parameters. The turbulence quantities were quantified using a hot-wire anemometer. The following conclusions and recommendations are made from this work.

5.1 Conclusions

- \( u' \) and \( v' \) were measured using a constant temperature hot-wire anemometer along with a single normal and a single inclined wire.
- A dimensional analysis was conducted. The characteristic dimensional groups were found and classified into two categories as following:
  - Dependent turbulence parameters:
    - Normalized turbulence intensity \( u'/U \) and \( v'/U \),
    - Normalized length scale \( L/D \).
  - Independent test parameters:
    - Reynolds number \( Re_{DU} \),
    - Normalized downstream distance \( X/D \),
    - Plate solidity \( \sigma \).
- A homogeneity factor, \( H \), was defined as the ratio of the standard deviation of the turbulent fluctuation rms velocity at points on the test plane to the average turbulence rms velocity on the same test plane.
- An isotropic factor, \( I = u'^2/v'^2 \), was adopted following the convention in the study of grid-generated turbulence.
- A flatness factor, \( F = u'^4/(u')^4 \), was adopted to investigated its relationship with \( H \).
- The effects of the independent test parameters on the turbulence parameters as well as that on the homogeneity factor and isotropic factor were determined as follows:
  - Reynolds number \( Re_{DU} \) has no obvious effect on the four turbulence parameters, \( u'/U, v'/U, L/D \) and \( H \).
Turbulence intensity decreases as the downstream distance increases. This decrease is dictated by a power law relationship, \( (u'/U)^2 = b(X/D)^n \). The power exponent found in this study lies within the range of 1 to 1.4.

Turbulence intensity increases with the plate solidity following an exponential relationship \( u'/U = c \exp(d \times \sigma) \). The \( d \) value was found to lie within the range 0.015 to 0.02. The \( c \) value was found to decrease with downstream distance from the plate.

Normalized length scale \( L/D \) increases with the downstream distance due to the dissipation of kinetic energy at the small scale turbulence by means of the viscous effect.

The normalized length scale was found to increase with the plate solidity.

Degree of homogeneity deteriorates downstream of the plate which is suspected to be due to the external energy transfer.

The plate with a 35\% solidity was found to possess the highest degree of homogeneity.

The turbulence behaves more uniform in the region where the corresponding flatness factor is in the proximity of 3.

Due to the unexpected high uncertainty in the isotropy factor, the dependence of the isotropy factor on the test parameters can not be determined.

### 5.2 Recommendations

- A differential pressure transducer that well behaves in the range of 0 to 25.4 mm (1 in.) \( H_2O \) could be used in place of the micro-manometer to reduce the time needed for calibrating the hot-wire probe from approximately 2 hours to roughly 20 minutes.

- Using an extra anemometer module along with an X-array probe in place of the single normal and single inclined hot-wire probes could save two-thirds of the time spent on acquiring the raw data. Raw data acquired in this way could be processed immediately to obtain additional information on the flow which cannot be achieved by using two single hot-wire probes. The additional information includes the instantaneous value of the
turbulence fluctuation velocity in the lateral direction which can be further processed to obtained power spectrum estimation in the this velocity component.

- The uncertainty analysis shows that the improper settings of the signal conditioner accounts for approximately 80% of the uncertainty of the turbulence intensity $u^3$. More attention should be paid to this issue in future studies.

- In this study, the hot-wire probe was manually moved to each measuring location, which is a time-consuming process. An automated traverse device is recommended for use in future studies.
References


Rouse, H., and Dodu, J. 1955 Diffusion turbulente a travers une discontinuite de densite
(Turbulent diffusion across a density discontinuity). La Houille Blanche. 10, 530.
27, 581.
Schedvin, J. and Stegen, G.R. and Gibson, C.H. 1974 Universal similarity at high
Shlien, D.J. and Corrsin, S 1974 A measurement of Lagrangian velocity autocorrelation in
Simmons, L.F.G. and Salter, C. 1934 Experimental investigation and analysis of the velocity
Simmons, L.F.G. and Salter, C. and Taylor, G.I. 1938 An experimental determination of
Sreenivasan, K. R. 1995 On the universality of the Kolmogorov constant. Phys. Fluid 7(11),
2778.
Tennekes, H. and Lumley, J.L. 1972 A first course in turbulence. MIT Press, Cambridge,
MA.
Thompson, M. and Turner, J.S. 1975 Mixing across an interface due to turbulence
Turchyn, A. 1972 Some internal flow investigations in Cascades and axial-flow
Ontario.
23, 754.
Uberti, M.S. 1957 Equipartition of energy and local isotropy in turbulent flows. J. Appl.
Phys. 28, 1165.
Uberti, M.S. 1963 Energy transfer in isotropic turbulence. Phys. Fluids. 6(8), 1048.
Uberti, M.S. and Wallis, S. 1966 Small axisymmetric contraction of grid turbulence. J.
Fluid Mech. 25, 539.


Appendix A. Programs For Data Analysis

There are build-in functions which are included with the StreamWare® software. These are available for the calculations of the basic statistical properties such as mean velocity, turbulence intensity in the mean flow direction, skewness, flatness and autocorrelation coefficients. However, it is time-consuming to process the data using the build-in functions in a sequential manner. Three programs were written to automate the process and to reduce the inconvenience. Before running the following programs, raw data from the tests are exported to binary files that can be processed by one of the following three programs. The format of these Export Binary Files (EBF) is as described in the Help document of the StreamWare® software. Each EBF name contains 3 digits. The first digit from left takes one of the values of 4, 6, or 8 which stands for the velocity value. The second digit stands for the Y location of the test point, and has an integer value from 0 to 8. The third digit stands for the Z location of the test point, and has an integer value from 0 to 8. The coordinate system is as shown in Figure A.1.

A.1 Program “mass line”

The program “mass line” is used for the data processing of raw data from the single normal probe. It requires as input, 243 EBFs, each containing instantaneous velocity values for one test point calculated with the StreamWare® software. It outputs four kinds of files, namely,

- 243 Compiled Text Files (CTF), one corresponding to each of the 243 EBFs. Each contains the compiled instantaneous velocity values extracted from the corresponding EBF. The name convention of these CTFs is the same as those EBFs, except for the extension name.
- 243 binary files containing the values of autocorrelation coefficients. Name convention is the same as those EBFs.
- 3 text files containing the basic statistical information (TBSI). Each file name contains one digit taking one of the values of 4, 6 or 8, standing for velocity. There are totally 81 rows of data in each file. These 81 rows are divided into 9 equal groups, corresponding to \( Y = 0,1,\ldots,8 \). Data in each group corresponds to \( Z = 0,1,\ldots,8 \). In each row, the first value is
mean velocity, the second is the average deviation, the third is the standard deviation, the fourth is the standard variance, the fifth is the skewness, and the sixth is the flatness.

- 3 text files containing the time scale calculated from the integration of the autocorrelation coefficients. File format and name convention are the same as that of the TBSI, except that there is only one value in each row which is the time scale value.

The flow chart for "mass line" is shown in Figure A.2.

A.2 Program "time saving"

This program is written to accomplish the following tasks:

- Make 243 CTFs from the two sets of 243 EBFs containing the raw voltage data of the single inclined probe. Each set of EBFs contains voltage values which are taken by setting the inclined probe at respectively positive 45° degrees and negative 45° degrees to the mean flow direction. Each CTF contains two columns corresponding respectively to the positive and negative voltage values.

- Extract the temperature data corresponding respectively, to positive and negative probe position, and save them into 3 text files. The file format and name convention are the same as that of the TBSI in "mass line" program, except that there are two values in each row which correspond respectively to the positive and negative probe position.

A.3 Program "three in a shot: inclined"

This program is written for the purpose of obtaining the mean square values of lateral turbulence fluctuation velocity, \( \overline{v^2} \), and the Reynolds stress value, \( \overline{uv} \). It requires as input, 3 text files containing the mean square values of turbulence velocity fluctuation in the streamwise direction (TMSS), 3 text files containing the required temperature data for purpose of temperature compensation and 243 CTFs from the "time saving" program. It outputs 3 text files.

- The file format and name convention for TMSS is the same as that of the TBSI in "mass line" program, except that there is only one value in each row which is the mean square value of turbulence normal fluctuation.
The file format and name convention for the 3 output text files are the same as those for the BSIF except that there are three values in each column which, from the left, the $\bar{u}$, $\bar{v}$ and $\bar{uv}$ respectively.

The flow chart for the “three in shot: incline” program is shown in Figure A.3.

Source codes for all the forgoing programs mentioned above as well as the K calculation template can be found on a CD attached to this theis.

Figure A.1 Coordinate system for name convention of data processing.
Start

Input:
Instantaneous velocity values $\bar{u}$ calculated by using the Dantec StreamWare

Compile the velocity values $\bar{u}$ to files in folder specified as foldername_Compiled

Calculate values of Autocorrelation Coefficients $R(r\Delta t)$, mean velocity $U$, turbulence intensity $u$, skewness $S$ and flatness $F$ by using the data read from the compiled text files in folder specified by foldername_Compiled.

\[
R(r\Delta t) = \frac{1}{N-1} \sum_{n=0}^{N-r} u(n\Delta t)u(n\Delta t+\Delta t) \quad u^2, \quad r = 1, 2, ..., m . \text{This calculation stops at the first point where } R(r\Delta t) = 0
\]

\[
U = \frac{1}{N} \sum_{n=0}^{N-1} u(n\Delta t)
\]

\[
u = \left( \frac{\sum_{n=0}^{N-1} (u(n\Delta t) - U)^2}{N-1} \right)^{0.5}
\]

\[
S = \frac{\sum_{n=0}^{N-1} (u(n\Delta t) - U)^3}{Nu^3}
\]

\[
F = \frac{\sum_{n=0}^{N-1} (u(n\Delta t) - U)^4}{Nu^4}
\]

Calculate the values of integral time scales $T$ using the autocorrelation coefficients data from the last step.

\[
T = \frac{1}{\Delta t} \sum_{r=0}^{m} (R(r\Delta t) + R((r+1)\Delta t))\Delta t/2
\]

Save $U, u, S, F$ into files in folder specified by foldername_stats, $R(r\Delta t)$ into files specified as foldername_auto, $T$ into files specified as foldername_scale.

End

Figure A.2 Flow chart of the program “mass line”.

66
Figure A.3 Flow chart of program “three in a shot: inclined”.
Appendix B. Calibration Procedure Instructions

This appendix is comprised of two sections. In section B.1, detailed calibration instructions for the hot-wire probes are presented. Section B.2 includes the details of a program called "hot-wire calibration" which has been written to facilitate the calibration process.

B.1 Calibration of single normal and single inclined hot-wire probes

It is assumed that the data acquisition board and the StreamWare® software are installed before this calibration.

The following steps must be taken to achieve the calibrations of both the single normal and inclined hot-wire probes.

1) Connect the PC and the StreamLine® frame to the power line and with the power switched off.

2) Connect the PC serial communication port (COM1) to the Serial Interface connector on the rear of the StreamLine® frame via the Null Modem cable.

3) Connect Analog Output connector No. 1 on the back panel of the Frame to the SCB-68 shielded connector block channel no. 0 with a 50 ohm BNC cable. The connector block is connected, in turn, to the A/D board in the PC via a 68-pin parallel cable.

4) Connect the 4m probe cable with 55H20 probe support and single normal/inclined probe to the probe connector on the CTA Module front plate.

5) Connect the temperature probe (thermistor) to the frame via its 4m cable and place it in the vicinity of the hot-wire probe.

6) Place the probe inside the potential core region of the jet formed by the nozzle beside the pitot static tube which is connected to the Meriam 34FB2TM micro-manometer.

7) Switch on both the PC and the Streamline® frame and open up the StreamWare® software.

8) Following the steps listed in Streamline®, Installation and User's Guide, carry out the system configuration which includes the overheat adjustment, square wave test and setup of the parameters for signal conditioning.

9) Open up the program "hot-wire calibration", which display an option window (Figure B.1). Choose the "Unipolar" and "referenced single-ended" mode. In the textboxes, type
in the appropriate information. The atmospheric pressure and room temperature are needed for the program to calculate the air density at the time of calibration. The value in the “Angle(degree)” textbox is the angle between the velocity vector and the normal of the probe, which should always be zero for the normal probe and be 45 for inclined probe at this step. “OK” is clicked, when all information has been entered.

10) A “hot-wire calibration” window (Figure B.2) should appear. If instantaneous voltage reading is not wanted, this “Stop” should be clicked.

11) Ensure that the indicating fluid meniscus in the inclined tube of the micro-manometer is at the reference calibrating point. Adjust the wheel on the micro-manometer to the well to a pre-set position corresponding to a particular pressure difference value as listed in Table B.1. Turn on the valve upstream of the nozzle to bring the meniscus back to the reference calibration point. At this point click “Read” to get the average voltage reading at this particular flow velocity. When the average voltage reading is available in the “E (volts)” textbox input the pressure difference in the “Manometer (inch)” textbox then click “ADD” to save this pair of data.

12) Click the “UP” button and repeat step 11) for 9 times to get another 9 pairs of data.

13) Input the name of the file where the 10 pairs of data will be saved. Click “Save” to save the results.

14) Copy the velocity and voltage value to the StreamWare® software to obtain the calibration coefficients and the errors associated with this calibration. Typical results can be found in Figure B.3.

For a single normal probe, the calibration process ends at this point. In the case of inclined probe calibration, the following additional steps must be conducted in order to calculated the K value, i.e., yaw coefficient.

15) Set the well of the micro-manometer to the position preset for a particular subsequent test as listed in Table B.2. Adjust the valve to bring the meniscus back to the reference calibration point. The velocity inside the potential core of the nozzle is the constant velocity as described by Bruun [1995].

16) Close the “hot-wire calibration” window. Rotate the probe holder to one of the preset positions as listed in Table B.3. Input the corresponding angle value in the “Angle(degree)” textbox, then click “OK”.

69
17) The "hot-wire calibration" window should again appear. In the "Manometer(inch)" textbox input the pressure difference value corresponding to the constant velocity that was set in step 14). Click "Read" to obtain the average voltage reading at this particular angle. Input the same file name as in step 13). Click "save".

18) Repeat steps 16)-17) for the other 9 different angles.

19) Close the "hot-wire calibration" window. Click "END" to save the value of atmospheric pressure, room temperature and the air density.

20) Obtain K value by copying the data obtained in steps 15)-18) to the K calculation template which is a spreadsheet and shown in Figure B.4.

B.2 Details of hot-wire calibration program and K calculation template.

The program called "hot-wire calibration" is developed in the Visual Basic environment. Its major usage is to facilitate the process of obtaining the voltage reading from the hot-wire anemometer.

The function of each command button and the relevance of the values entered in each textbox are explained as follows.

➤ "Option" window

✓ "Channel for HW": Value in this box refers to the No. of the channel on the A/D board to which the analog signal from the hot-wire anemometer sent.

✓ "No. Point": This refers to the number of pairs of voltage-velocity data that is expected to be collected in the subsequent calibration process.

✓ "Pressure (mm Hg)" and "Room Temp (C)"; Pressure refers to the atmospheric pressure in the units of mm Hg, which is denoted by the program as, $P$. Room temperature should be in the units of Celsius degrees. It is denoted as, $T$, and will be converted by the program to degrees Kelvins. These two values are used to calculate air density with the formula $\rho_{air} = \frac{P}{RT}$, where $R$ is the gas constant.

✓ "Angle (degree)"; This refers to the angle, $\alpha$, between the direction of velocity vector and that of the normal of the hot-wire probe as illustrated in Figure B.5.

✓ "InVal of Manometer"; This refers to the value which indicates the initial position of the well of the micro-manometer.
✓ "Date": This is the date on which a specific calibration is conducted. The value entered here is used as the name of the text file which is a backup for the calibration raw data.

✓ Command Button "OK": The following tasks are carried out when this button is clicked:
  ♦ Determine whether all the required information is available in the textboxes.
  ♦ Calculate density of Mercury (kg/m³) at the specific room temperature T(°C) as follows.
    $$\rho_{Hg} = 13556.786(1 - 0.0001818(T - 15.5556)).$$
  ♦ Calculated density of water (kg/m³) at the specific room temperature as following
    $$\rho_{water} = 999.8395 + 0.067982999T - 0.0091060255T^2 + 0.00010052729T^3$$
    $$- 0.0000011267135T^4 - 6.5917956e-09T^5.$$
  ♦ Calculate density of air (kg/m³) as following
    $$\rho_{ar} = \frac{\rho_{Hg} g P \times 1e-06}{R(T + 273.15)}.$$
  ♦ Initiate the "Hot-wire Calibration" window.

➢ Hot-wire Calibration window

✓ Every time this window is loaded, the program sets the configuration of the A/D board by calling the function: `AI_Configure(deviceNumber, chan, inputMode, inputRange, polarity, driveAIS)`, which is in the library provided by National Instrument Inc. along with the A/D board.

✓ A "timer" function, timer1, is started in order to call the `AI_VRead(deviceNumber, chan, gain, reading)` function every 0.01 second to achieve the instantaneous voltage reading. This `AI_VRead()` function also is provided by National Instrument Inc. The voltage reading is displayed in textbox "E (volt)".

✓ Textbox "Manometer(inch)": This is where the pressure difference value, ΔP, which is in the units of inches of water is to be input.

✓ Textbox "E (volt)"": This where the instantaneous/averaged voltage value is displayed.
Textbox “File name”: This refers to the name of the text file, in which the raw calibration data are to be saved. An extension name “.txt” should be included.

“UP” and “DOWN arrow” buttons which are located at the upper right part: These two buttons are useful in navigating through the array of raw calibration data before saving the raw data at the last step.

Command button “Start/stop”: While the caption of this button is “stop”, which is the case when the Hot-wire Calibration windows is loaded, a click on this button will initiate the following operation:
- Make the “Read”, “Add”, “UP” and “DOWN” command buttons visible.
- Stop the “timer1” function for the instantaneous voltage reading.
- Change the caption to “Start”.
While the caption of this button is “Start”, a click on this button will initiate the following operation:
- Make the “Read”, “Add”, “UP” AND “DOWN” command buttons invisible.
- Start the “timer1” function for the instantaneous voltage reading.
- Change the caption to “Stop”.

“Read” button: A click of this button will initiate a timer function “timer_Avg”. The timer starts the “AVI_Read( ) function” 250 times at the rate of 100 times/sec. The 250 voltage values are averaged and the averaged value E is displayed in “E (volt)”.

“ADD” button: A click of this button initiated the following steps:
- Check to determine if the pressure difference value, \( \Delta p \), has been entered in “Manometer (inch)”.
- Assign the pairs of data \( \Delta p \) & \( E_r \) to the corresponding data arrays.
- Calculate the velocity, \( U_r \), corresponding to the pressure difference, \( \Delta p \), with the following formula:
  \[
  U_r = \left( \frac{2\Delta p \times 25.4 \times 0.001 \times \rho_{water} g}{\rho_{air}} \right)^{0.5}.
  \]
- Save the number of pairs of data as indicated by the “ADD” textbox, average voltage value \( E_r \), velocity \( U_r \), pressure difference \( \Delta p \), and angle \( \alpha \) to the backup file “data.txt”.
✓ "Save" button: A click of this button will do the following:

- Check to determine if the "File name" is empty.
- Save all $E_K$, $\alpha$, $\Delta p$ and $U_R$ value to the text file specified in the "File name" textbox.

Details of the calculation of $K$ for a single inclined hot-wire probe are described by Bruun [1995]. This method is illustrated as in Figure B.6.

<table>
<thead>
<tr>
<th>No. of Point</th>
<th>25.4 mm plate $\Delta p$ (mm of H$_2$O)</th>
<th>25.4 mm plate $U_R$ (m/s)</th>
<th>38.1 mm plate $\Delta p$ (mm of H$_2$O)</th>
<th>38.1 mm plate $U_R$ (m/s)</th>
<th>50.8 mm plate $\Delta p$ (mm of H$_2$O)</th>
<th>50.8 mm plate $U_R$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.97</td>
<td>7.00</td>
<td>1.22</td>
<td>4.50</td>
<td>0.53</td>
<td>3.00</td>
</tr>
<tr>
<td>2</td>
<td>4.42</td>
<td>8.55</td>
<td>1.85</td>
<td>5.5</td>
<td>0.86</td>
<td>3.78</td>
</tr>
<tr>
<td>3</td>
<td>6.17</td>
<td>10.11</td>
<td>2.64</td>
<td>6.61</td>
<td>1.24</td>
<td>4.56</td>
</tr>
<tr>
<td>4</td>
<td>8.23</td>
<td>11.67</td>
<td>3.56</td>
<td>7.67</td>
<td>1.73</td>
<td>5.33</td>
</tr>
<tr>
<td>5</td>
<td>10.57</td>
<td>13.22</td>
<td>4.60</td>
<td>8.72</td>
<td>2.26</td>
<td>6.11</td>
</tr>
<tr>
<td>6</td>
<td>13.20</td>
<td>14.78</td>
<td>5.79</td>
<td>9.78</td>
<td>2.87</td>
<td>6.89</td>
</tr>
<tr>
<td>7</td>
<td>16.13</td>
<td>16.33</td>
<td>7.09</td>
<td>10.83</td>
<td>3.56</td>
<td>7.67</td>
</tr>
<tr>
<td>8</td>
<td>19.35</td>
<td>17.89</td>
<td>8.56</td>
<td>11.89</td>
<td>4.32</td>
<td>8.44</td>
</tr>
<tr>
<td>9</td>
<td>22.86</td>
<td>19.44</td>
<td>10.13</td>
<td>12.94</td>
<td>5.13</td>
<td>9.22</td>
</tr>
<tr>
<td>10</td>
<td>26.67</td>
<td>21.00</td>
<td>11.86</td>
<td>14.00</td>
<td>6.04</td>
<td>10.00</td>
</tr>
</tbody>
</table>
Table B.2: Preset velocity $U_R$ for the single inclined hot-wire calibration.

<table>
<thead>
<tr>
<th>25.4 mm plate</th>
<th>38.1 mm plate</th>
<th>50.8 mm plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta p$ (mm of H$_2$O)</td>
<td>$U_R$ (m/s)</td>
<td>$\Delta p$ (mm of H$_2$O)</td>
</tr>
<tr>
<td>13.20</td>
<td>14.78</td>
<td>5.79</td>
</tr>
</tbody>
</table>

Table B.3: Preset position of the single inclined hot-wire probe.

<table>
<thead>
<tr>
<th>No.</th>
<th>$\alpha$ (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>49</td>
</tr>
<tr>
<td>3</td>
<td>53</td>
</tr>
<tr>
<td>4</td>
<td>57</td>
</tr>
<tr>
<td>5</td>
<td>61</td>
</tr>
<tr>
<td>6</td>
<td>65</td>
</tr>
<tr>
<td>7</td>
<td>41</td>
</tr>
<tr>
<td>8</td>
<td>37</td>
</tr>
<tr>
<td>9</td>
<td>33</td>
</tr>
<tr>
<td>10</td>
<td>29</td>
</tr>
<tr>
<td>11</td>
<td>25</td>
</tr>
</tbody>
</table>
Figure B.1 Option window of the hot-wire calibration program.

Figure B.2 Hot-wire Calibration window for the hot-wire calibration program.
Figure B.3 Typical calibration results for the test of the 25.4 mm (1 in.) hole diameter 50% solidity plate.

Figure B.4 K calculation template which is a Microsoft Excel workbook file.
Figure B.5 Yaw angle $\alpha$ used in the yaw coefficient calibration.

Input:
1. Calibration coefficients $A, \dot{B}, C$ from the velocity calibration
2. Voltage data $E_{\alpha}$ taken at different angles $\alpha$ with velocity $U$ set at a constant value. $\alpha$ is the angle as illustrated in Figure A.5

1. Calculate $E_{\theta} = \left( \frac{E_{\alpha}^2 - A}{E_{\theta}^2 - A} \right)^{1/C}$
2. Calculate $x = E_{\theta}^2 \sin^2 \alpha - \sin^2 \alpha$
3. Calculate $r = E_{\theta}^2 - 1$
4. Fit pairs of $x$ & $r$ values to linear function $r = \omega x$ and obtain $\omega$ value as the slope of the line.
5. Calculate $K$ as $K = \sqrt{1 - \omega}$

Figure B.6 Flow chart for K calculation.
Appendix C. Test Procedure Instructions

1) Fix the perforated plate at the entrance to the test section. Make sure there is no leakage of air at the sides of the plate.

2) Follow steps 1)-7) in section B.1 of Appendix B to connect the hardware.

3) Put the probe holder at the second last slot in the bottom panel of the test section. Adjust the hot-wire probe to the center of the cross section. Make sure the stem of the probe support is aligned with the mean flow direction.

4) Following the “Sample Project II” section in Chapter 6 of the StreamLine, Installation and User’s Guide, set the experiment layout that will be used in the subsequent test. In the “A/D Board Setup (Analog Input)” window, change the sample frequency and sample number to 10 kHz and 262144 respectively without changing the other settings.

5) Set the vane of the blower to a position which is expected to correspond to a Reynolds number of 15000 for the specific plate.

6) Turn on the blower.

7) Conduct the “Run Experiment” command of the StreamWare® software to start the data acquisition process. This process takes about 50 seconds.

8) Turn off the blower.

9) Do the “Basic statistic routines” in the “Run → Extended processing” submenu of the StreamWare® software.

10) Repeat steps 5) - 9) until the resultant mean velocity in step 9) is the one that corresponds to a Reynolds number of 15 000.

11) Mark the position of the vane on the vane-handle.

12) Repeat steps 5) – 11) for a Reynolds number of 22 000 and 29 000 respectively.

13) Move the probe holder to the location corresponding to one the three downstream distances listed in Table 3.2.

14) Turn on the blower.

15) Adjust the hot-wire probe to the center of the cross section.

16) Adjust the vane of the blower to the position corresponding to a Reynolds number of 15000.

17) Conduct the “Run Experiment” command of the StreamWare® software to start a data acquisition process.
18) Repeat steps 16) – 17) for a Reynolds number of 22 000 and 29 000 respectively.
19) Repeat steps 15) – 18) with the hot-wire probe positioned at each of the other 80 points over the cross section.

For a test that is conducted using the single inclined hot-wire probe, step 17) will be carried out twice, one for the positive 45° probe position and the other for the negative 45° probe position. It should be noted that the hot-wire anemometer needs to be set to “stand by” whenever the probe needs to be moved.
Appendix D. Uncertainty Analysis

The uncertainty in the current study comes mainly from the process of calibrating the hot-wire probes and the process of acquiring the instantaneous velocity data. Details of each source of uncertainty will be considered in the following sections. The uncertainty in the following dimensionless turbulence parameters will be specified.

- The normalized turbulence intensity $u'/U$ and $v'/U$.
- The normalized turbulence length scale $L/D$.
- The homogeneity factor defined by $H = \frac{1}{u'} \sqrt{\sum_{i=1}^{n} (u_i - \overline{u_i})^2 / 80}$.
- The isotropy factor $I = \overline{u^2}/\nu^2$.
- Flatness factor $F = \overline{u^4}/(u')^4$.

D.1 Calibration uncertainty

The calibration uncertainty resulted mainly from three sources, namely, the uncertainty in the velocity, $U_R$, used as the calibration standard, the uncertainty in voltage reading, $E_R$, corresponding to the $U_R$, and uncertainty from curve-fitting pairs of $U_R$ and $E_R$ values to calibration equation $E^2 = A + BU_{\text{eff}}^C$. To simplify the following analysis, it is assumed that the uncertainties in the calibration velocity, $U_R$, and the measured voltage reading, $E_R$, are negligible. Following the work of Yavuzkurt [1984], the curve-fitting uncertainty is found to be:

$$\Delta(U_{\text{eff}}) = \beta U_{\text{eff}},$$ (D-1)

where $U_{\text{eff}}$ is the instantaneous effective velocity calculated from the calibration equation and $\beta$ can be calculated from the curve fitted data as:

$$\beta = \sqrt{\frac{1}{N} \sum_{i=1}^{n} \left( \frac{U_{\text{eff}} - U_R}{U_{\text{eff}}} \right)^2},$$ (D-2)
D.2 Data acquisition uncertainty

The data acquisition uncertainty resulted from four sources, namely, the digitization uncertainty from digitizing the analog signal from the hot-wire anemometer, the probe spatial uncertainty from resetting the probe position, the uncertainty from resetting the incoming mean flow velocity via adjusting the vane position of the blower and the uncertainty from the signal conditioner’s setting of gain of offset.

D.2.1 Digitization uncertainty

The uncertainty in the digitized hot-wire anemometer output voltage is $\pm 0.5$ of the least significant bit, which, for the 12 bits A/D with a input range set as 0 to 10V, is:

$$\Delta E = 0.5 \times 10^{\frac{1}{2^{12}}} = 0.0012V.$$  \hspace{1cm} (D-3)

The digitization uncertainty in the effective velocity is:

$$\Delta \left( U_{eff} \right) = \frac{dU_{eff}}{dE} \Delta E = \frac{2\sqrt{A+BU_{eff}^c}}{CB} U_{eff}^{1-c} = \gamma U_{eff},$$  \hspace{1cm} (D-4)

where

$$\gamma = \frac{2\sqrt{A+BU_{eff}^c}}{CB} U_{eff}^{-c}. \hspace{1cm} (D-5)$$

D.2.2 Probe spatial uncertainty

The probe spatial uncertainty was estimated by resetting the hot-wire probe to a typical measurement position for 20 times with all the other test conditions remaining the same. Each time, a set of instantaneous velocity data was obtained. The standard deviation of the effective turbulence intensity $\overline{u_{eff}^2}$ and that of the mean velocity $U$ are computed. The probe spatial uncertainties in $\overline{u_{eff}^2}$ and $U$ are estimated as 2 times their standard deviations and are expressed as:

$$\Delta \left( \overline{u_{eff}^2} \right) = 0.027 \overline{u_{eff}^2},$$  \hspace{1cm} (D-6)

and

$$\Delta (U)_1 = 0.008 U.$$  \hspace{1cm} (D-7)
D.2.3 Incoming velocity uncertainty

The incoming velocity uncertainty was estimated by resetting the vane on the blower to a typical position which corresponded to a specific mean velocity 20 times with all other conditions remaining the same. Each time a batch of instantaneous velocity data was obtained. The standard deviation of the effective turbulence intensity $u_{\text{eff}}^2$ and that of the mean velocity are computed. The incoming velocity uncertainties in $u_{\text{eff}}^2$ and $U$ are estimated as 2 times their standard deviations and are expressed as:

$$\Delta(u_{\text{eff}}^2)_2 = 0.034u_{\text{eff}}^2,$$

(D-8)

and

$$\Delta(U)_2 = 0.007U.$$

(D-9)

D.2.4 Uncertainty from the signal conditioner gain and offset settings

All of the raw data in this study were acquired with the signal conditioner offset and gain set to zero and one respectively. This was expected to render some uncertainties in the final results. A secondary test was conducted over the test plane that was closest to exit of the test section with plate 3 put at the entrance of the test section. The test was first conducted with the gain and offset set to 16 and 1.6 respectively, which were the highest values that were achievable. The same test was repeated with the gain and offset set to 1 and 0 respectively. The effective turbulence intensities $u_{\text{eff}}^2$ and mean velocity $U$ were obtained from the data of both tests. The uncertainties were found to be:

$$\Delta(u_{\text{eff}}^2)_3 = \zeta u_{\text{eff}}^2 = 0.07u_{\text{eff}}^2,$$

(D-10)

and

$$\Delta(U)_3 = \xi U = 0.053U,$$

(D-11)

where

$$\zeta = \frac{1}{181} \sum_{i=1}^{81} \left( \frac{u_{\text{eff}}^2}{u_{\text{eff}}^2 \text{ gain=16,offset=1.6}} \right) - \left( \frac{u_{\text{eff}}^2}{u_{\text{eff}}^2 \text{ gain=1,offset=0}} \right),$$

(D-12)
\[ \xi = \sqrt{\frac{1}{81} \sum_{i=1}^{81} \left( \frac{\left( U \right)_{\text{gain}=1.6, \text{offset}=1.6} - \left( U \right)_{\text{gain}=1, \text{offset}=0}}{U} \right)^2}. \]  

(D-13)

D.3 Uncertainty in mean velocity \( U \) and non-normalized turbulence intensities \( \overline{u^2} \) and \( \overline{v^2} \)

In this section, the uncertainty propagation from calibration uncertainty and digitization uncertainty will be first considered. The results will then be combined with the probe spatial uncertainty, incoming velocity uncertainty and the signal conditioner uncertainty to obtain the total uncertainty in the mean velocity, \( U \), and non-normalized turbulence intensity, \( \overline{u^2} \). The uncertainty in \( \overline{v^2} \) will also be specified.

D.3.1 Uncertainty propagation from the calibration and digitization uncertainty

Following the work of Yavuzkurt [1984], the uncertainty in \( \overline{u^2_{\text{ef}}} \) can be expressed as:

\[ \Delta \overline{u^2_{\text{ef}}} = 2(\beta^2 + \gamma^2) \overline{u^2_{\text{ef}}}, \]  

(D-14)

and the uncertainty in \( U \) is:

\[ \Delta (U) = (\beta^2 + \gamma^2) U. \]  

(D-15)

D.3.2 Total uncertainty in \( U \) and \( \overline{u^2_{\text{ef}}} \)

The total uncertainty in \( \overline{u^2_{\text{ef}}} \) is obtained by combining equations (D-6), (D-8), (D-10) and (D-14) to give:

\[ \Delta \overline{u^2_{\text{ef}}} = \sqrt{\left( \Delta \overline{u^2_{\text{ef}}} \right)_1^2 + \left( \Delta \overline{u^2_{\text{ef}}} \right)_2^2 + \left( \Delta \overline{u^2_{\text{ef}}} \right)_3^2 + \left( \Delta \overline{u^2_{\text{ef}}} \right)_4^2}, \]  

(D-16)

\[ = \overline{u^2_{\text{ef}}} \sqrt{0.007 + 4(\beta^2 + \gamma^2)^2}. \]

Similarly, by combing equations (D-7), (D-9), (D-11) and (D-15), one gets:
\[ \Delta U = \sqrt{ \left( \Delta U_1 \right)^2 + \left( \Delta U_2 \right)^2 + \left( \Delta U_3 \right)^2 + \left( \Delta U_4 \right)^2 } \]

\[ = U \sqrt{0.003 + \left( \beta^2 + \gamma^2 \right)^2}. \] (D-17)

A typical value of \( \beta \) is found to be approximately 0.003. After checking with the calibration results, it is found that typical values of the calibration coefficients are:

\[ A \equiv 1.6, \]
\[ B \equiv 0.9, \] (D-18)
\[ C \equiv 0.45. \]

Substituting (D-18) into (D-16) and (D-17) one gets:

\[ \Delta u_{\text{eff}}^2 = u_{\text{eff}}^2 \sqrt{0.007 + 4(\beta^2 + \gamma^2)^2} = 0.08 u_{\text{eff}}^2, \] (D-19)

and

\[ \Delta U = U \sqrt{0.003 + \left( \beta^2 + \gamma^2 \right)^2} = 0.06 U. \] (D-20)

D.3.3 Uncertainty in turbulence normal intensity \( \overline{u^2} \)

One generally takes:

\[ \overline{u^2} = u_{\text{eff}}^2 \] (D-21)

by neglecting the truncation error in obtaining \( \overline{u^2} \) from \( u_{\text{eff}}^2 \). The uncertainty in \( \overline{u^2} \) is, therefore, estimated as:

\[ \Delta \overline{u^2} = \Delta u_{\text{eff}}^2 = u_{\text{eff}}^2 \sqrt{0.007 + 4(\beta^2 + \gamma^2)^2} \approx 0.08 u_{\text{eff}}^2. \] (D-22)

Accordingly, the uncertainty in \( u' = \left( \overline{u^2} \right)^{1/2} \) is:

\[ \frac{\Delta u'}{u'} = \frac{1}{2} \frac{\Delta u_{\text{eff}}^2}{u_{\text{eff}}^2} = 0.04. \] (D-23)

D.3.4 Uncertainty in turbulence lateral intensity \( \overline{v^2} \)

The turbulence lateral intensity, \( \overline{v^2} \), is obtained from the following relationship:
\[
\overline{v'^2} = \frac{u_{\text{eff}, \alpha=45'}^2 + u_{\text{eff}, \alpha=-45'}^2 - 2f^2 u^2}{2f^2 l^2},
\]  
(D-24)

where \(u_{\text{eff}, \alpha=45'}^2\) and \(u_{\text{eff}, \alpha=-45'}^2\) are the effective turbulence velocities obtained with the normal of the single inclined hot-wire probe at \(+45'\) and \(-45'\) to the mean flow direction respectively. \(f\) and \(l\) are defined as:

\[
f = (\cos^2 45' + K^2 \sin^2 45')^{1/2}
\]  
(D-25)

and

\[
l = \frac{(1-K^2)\cos^2 45'}{\cos^2 45' + K^2 \sin^2 45'}\tan 45'.
\]  
(D-26)

By assuming that there is no uncertainty in the yaw coefficient, \(K = 0.2\), the uncertainty in \(\overline{v'^2}\) is estimated as:

\[
\Delta \overline{v'^2} = \sqrt{\left(\frac{\partial \overline{v'^2}}{\partial \overline{u'^2}} \Delta \overline{u'^2}\right)^2 + \left(\frac{\partial \overline{v'^2}}{\partial \overline{u_{\text{eff}, \alpha=45'}^2}} \Delta \overline{u_{\text{eff}, \alpha=45'}^2}\right)^2 + \left(\frac{\partial \overline{v'^2}}{\partial \overline{u_{\text{eff}, \alpha=-45'}^2}} \Delta \overline{u_{\text{eff}, \alpha=-45'}^2}\right)^2}.
\]  
(D-27)

Substituting equations (D-19) and (D-22) into (D-27), one gets

\[
\Delta \overline{v'^2} \approx \sqrt{\left(\frac{0.08\overline{u'^2}}{l^4}\right)^2 + \left(\frac{0.08\overline{u_{\text{eff}, \alpha=45'}^2}}{4f^4 l^4}\right)^2 + \left(\frac{0.08\overline{u_{\text{eff}, \alpha=-45'}^2}}{4f^4 l^4}\right)^2}.
\]  
(D-28)

By assuming that \(u_{\text{eff}, \alpha=45'}^2 \approx u_{\text{eff}, \alpha=-45'}^2 \approx 2\overline{u'^2}\) and \(\overline{u^2} = 1.4\overline{v'^2}\), (D-28) is approximated as:

\[
\Delta \overline{v'^2} \approx 0.27\overline{u'^2} \approx 0.38\overline{v'^2}.
\]  
(D-29)

Correspondingly, the uncertainty in \(v'\) is:

\[
\frac{\Delta v'}{v'} = \frac{1}{2} \frac{\Delta \overline{v'^2}}{\overline{v'^2}} = 0.2.
\]  
(D-30)
D.4 Uncertainty in the dimensionless turbulence parameters

In this section, the uncertainty in the dimensionless turbulence parameters will be considered.

D.4.1 Uncertainty in normalized turbulence intensity \( u'/U \) and \( v'/U \)

The uncertainties in the two normalized intensities are:

\[
\frac{\Delta(u'/U)}{(u'/U)} = \sqrt{\left(\frac{\Delta U}{U}\right)^2 + \left(\frac{\Delta u'}{u'}\right)^2} \tag{D-31}
\]

and

\[
\frac{\Delta(v'/U)}{(v'/U)} = \sqrt{\left(\frac{\Delta U}{U}\right)^2 + \left(\frac{\Delta v'}{v'}\right)^2}. \tag{D-32}
\]

Substituting equations (D-20), (D-23) and (D-30) into equations (D-31) and (D-32), one gets:

\[
\frac{\Delta(u'/U)}{(u'/U)} = \sqrt{\left(\frac{\Delta U}{U}\right)^2 + \left(\frac{\Delta u'}{u'}\right)^2} = 0.07 \tag{D-33}
\]

and

\[
\frac{\Delta(v'/U)}{(v'/U)} = \sqrt{\left(\frac{\Delta U}{U}\right)^2 + \left(\frac{\Delta v'}{v'}\right)^2} = 0.2. \tag{D-34}
\]

D.4.2 Uncertainty in the normalized integral length scale \( L/D \)

The non-normalized length scale, \( L \), is calculated using the following formula:

\[
L = U \int \rho(t) dt = U \int \frac{\mu(t)+t+\tau}{u^2} dt. \tag{D-35}
\]

For the purpose of this uncertainty analysis, equation (D-35) can be approximated as:

\[
L = U \int \rho(t) dt = U \int \frac{\mu(t)+t+\tau}{u^2} dt \propto U \frac{u_{\text{eff}}^2}{u^2}. \tag{D-36}
\]

Using equation (D-36) and assuming that there is no uncertainty in \( D \), the uncertainty in \( L/D \) can be estimated as:
\[ \frac{\Delta(L/D)}{L/D} = \sqrt{\left( \frac{\Delta u_{\text{eff}}^2}{u_{\text{eff}}^2} \right)^2 + \left( \frac{\Delta u}{u} \right)^2} = 0.13. \tag{D-37} \]

### D.4.3 Uncertainty in homogeneity factor \( H \)

The homogeneity factor \( H \) is defined as:

\[ H = \frac{1}{u'} \sqrt{\sum_i \frac{(u_i - \bar{u})}{u'}}/80, \tag{D-38} \]

where \( \bar{u}' \) is the mean value of the turbulence rms velocity over a test plane. A further definition comes as:

\[ M = \sqrt{\sum_i (u_i - \bar{u})^2}/80. \tag{D-39} \]

Following the work of Yavuzkurt [1984], the uncertainties in \( M \) and \( u' \) can estimated as:

\[ \frac{\Delta M}{M} = \frac{\Delta u'}{u'} = 0.06 \tag{D-40} \]

and

\[ \frac{\Delta \bar{u}'}{u'} = \frac{\Delta u'}{u'} = 0.06. \tag{D-41} \]

The uncertainty in factor \( H \) is, therefore, estimated as:

\[ \frac{\Delta H}{H} = \sqrt{\left( \frac{\Delta M}{M} \right)^2 + \left( \frac{\Delta \bar{u}'}{u'} \right)^2} = 0.09. \tag{D-42} \]

### D.4.4 Uncertainty in isotropy factor \( I \)

The isotropy factor, \( I \), is defined as:

\[ I = \bar{u}^2 / \bar{v}^2. \tag{D-43} \]

The uncertainty in \( I \) is estimated as:

\[ \frac{\Delta I}{I} = \sqrt{\left( \frac{\Delta u^2}{u^2} \right)^2 + \left( \frac{\Delta v^2}{v^2} \right)^2} = 0.39. \tag{D-44} \]
D.4.4 Uncertainty in flatness factor $F$

The flatness factor, $F$, is defined as:

$$F = \frac{\overline{u^2}}{\langle u' \rangle^4}.$$  \hfill (D-45)

The uncertainty in $F$ is estimated as:

$$\frac{\Delta F}{F} = \sqrt{2^2 \left( \frac{\Delta u^2_{\text{eff}}}{u^2_{\text{eff}}} \right)^2 + 4^2 \left( \frac{\Delta u'}{u'} \right)^2} = \sqrt{4 \times 0.08^2 + 16 \times 0.04^2} \approx 0.2. $$  \hfill (D-46)
Vita Auctoris

1974    Born in Mudanjiang, China on April 10.
1988    Completed high school at Mudanjiang No.1 High School, Mudanjiang, China in July.
1995    Received Bachelor of Engineering at Tianjin Institute of Commerce, Tianjin, China in July.
2002    Currently a candidate for the degree of Master of Applied Science in Mechanical Engineering at the University of Windsor, Windsor, Ontario, Canada.