An experimental investigation of three-dimensional curved wall jets.

Uday M. Patankar

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AN EXPERIMENTAL INVESTIGATION OF
THREE-DIMENSIONAL CURVED WALL JETS

A Thesis
Submitted to the Faculty of Graduate Studies Through
the Department of Mechanical Engineering in Partial
Fulfillment of the Requirements for the Degree of
Master of Applied Science at the
University of Windsor

by

Uday M. Patankar

Windsor, Ontario
July, 1970
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ABSTRACT

This thesis presents an experimental investigation of mean velocities of turbulent, three-dimensional, incompressible air jets from various rectangular orifices issuing tangentially to and flowing along the surface of a curved wall into quiescent ambient air. An experimental study of the jet separation is also presented.

The three-dimensional curved wall jet is found to be drastically different in its mean-property behaviour from its so-called two-dimensional counterpart.

Velocity contour plots show the resultant effect on the jet flow of two opposing tendencies - the freejet flow and the coanda flow. This effect is found to occur earlier with smaller aspect-ratio orifices.

The three-dimensional curved wall jet may be characterized by three regions of maximum velocity decay. The rate of maximum velocity decay is dependent on orifice aspect ratio, except in the potential core region.
ACKNOWLEDGEMENTS

The author is grateful to Professor W.G. Colborne, Head of the Department of Mechanical Engineering, for having offered him the opportunity to pursue this investigation.

The author is indebted to Dr. K. Sridhar for his guidance, generous aid and encouragement throughout this work.

The help of Mr. O. Brudy, The Central Research Workshop technical staff and Mr. R. Meyers is gratefully acknowledged.

The work was financially supported by the National Research Council of Canada (Grant No. A-2190).
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NOTATION

AR  jet orifice aspect ratio, \(/

\ell  jet orifice length (L)

n  exponent describing the decay of maximum velocity: \(u_m \sim x^{-n}\)

\(P_a\)  atmospheric pressure \((\text{ML}^{-1}\text{T}^{-2})\)

\(P_t\)  exit total pressure of jet \((\text{ML}^{-1}\text{T}^{-2})\)

R  radius of curved wall (L)

\(\text{Re}_j\)  jet Reynolds number, \(\left[\frac{(P_t - P_a) R (\ell/t)^0.5}{\rho v^2}\right]^{0.5}\)

t  jet orifice width (L)

u  velocity component in x-direction \((\text{LT}^{-1})\)

\(u_m\)  maximum velocity along the jet \((\text{LT}^{-1})\)

\(u_o\)  jet velocity at the orifice exit \((\text{LT}^{-1})\)

\(\bar{u}\)  non-dimensional velocity, \(u/u_m\)

x  streamwise coordinate, \(R \theta\) (L)

\(\bar{x}\)  non-dimensional streamwise distance, \(x/t\)

y  normal (radial) coordinate (L)

\(y_m\)  value of y at \(u = u_m\) (L)

\(y_{m/2}\)  larger value of y for which \(u = (u_m)/2\) (L)

\(\bar{y}_{m/2}\)  non-dimensional distance, \((y_{m/2})/t\)

\(\bar{y}\)  non-dimensional distance, \(y/(y_{m/2})\)

z  spanwise coordinate (L)
\( z_{m/2} \) mean value of \( z \) for which \( u = \left( u_m \right)/2 \) (L)

\( \overline{z}_{m/2} \) non-dimensional distance, \( (z_{m/2})/t \)

\( \overline{z} \) non-dimensional distance, \( z/(z_{m/2}) \)

\( \theta \) angular position measured from the orifice exit

\( \theta_{sep} \) angular position of jet separation at centreline

\( \nu \) kinematic viscosity of air (L^2 T^{-1})

\( \rho \) density of air (ML^{-3})

**ABBREVIATIONS**

PC Potential Core

CD Characteristic Decay

CD-I Characteristic Decay - I

CD-II Characteristic Decay - II
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CHAPTER I

INTRODUCTION

An experimental investigation of the mean velocities of turbulent, three-dimensional, incompressible jets flowing around the surface of a circular cylinder, the surrounding being stationary and the fluid in the jet being the same as that in the surroundings, is presented.

The flowfields were generated by a rectangular orifice in the present investigation. Each orifice possessed a different aspect ratio, defined as the ratio of the length to the width of the orifice, but all orifices were of equal area. Hence all the flows were observed under conditions of equal initial momentum flux.

The study of wall jets is of interest for boundary-layer control to prevent separation, and basic information about bounded ("two-dimensional") curved wall jets is important in fluidic design. A knowledge of three-dimensional wall-jet behaviour is important in the field of film-cooling of blades in turbomachinery.

A schematic representation of the flowfield of the three-dimensional curved wall jet is shown in Fig. 1.1.
CHAPTER II

LITERATURE SURVEY

A great number of papers concerning various aspects of wall jets have been written. Glauert (Ref. 1) presented a theoretical analysis of the plane and radial wall jets. Bakke (Ref. 2) compared the results of his experimental observations with Glauert's theoretical predictions of a radial wall jet.

The Coanda effect - the phenomenon of jets adhering to and flowing round nearby solid boundaries - has also been studied extensively in literature on wall jets. Borque and Newman (Ref. 3) studied the reattachment of a "two-dimensional" jet to an inclined flat plate. Fekete (Ref. 4), Nakaguchi (Ref. 5) and Sridhar and Tu (Ref. 6) made comprehensive theoretical and experimental investigations of "two-dimensional", curved wall jets.

Many of these studies showed an approximate similarity in the jet flowfield in non-dimensional velocity profiles normal to the wall. Almost all of the investigations were made with nozzles of finite aspect ratio and with endplates to prevent spanwise growth of the jets, and since the velocity profiles agreed very well with the Glauert (Ref. 1) profile, this flow geometry was assumed to give rise to two-dimensional or very nearly two-dimensional flows.
Several investigators have observed departures from two-dimensionality in rectangular jets (Refs. 7,8 and 9). Isotach patterns and static pressure contours in a bounded jet with an aspect ratio of 6 suggested the presence of a secondary flow structure to Foss and Jones (Ref. 10). They concluded that the three-dimensional effects are highly significant in bounded jets of modest aspect ratio, even in the midplane between bounding walls.

Sforza and coworkers (Refs. 9,11,12 and 13) have been concerned primarily with three-dimensional effects in freejets, wall jets and wall wakes. Their investigations into the mean properties of three-dimensional free jets (Ref. 11) showed three distinct regions based on maximum velocity decay.

A) Potential Core Region, characterized by a uniform maximum velocity close to the jet exit velocity.

B) Characteristic Decay Region, in which the maximum velocity decay is dependent upon orifice configuration, and velocity profiles in the plane of the minor axis of the orifice are found to be "similar", whereas those in the plane of the major axis are "nonsimilar".
C) Axisymmetric Decay Region, wherein the maximum velocity decay resembles the decay of an axisymmetric jet, i.e., $u_m \sim x^{-1}$, and velocity profiles in both symmetry planes are similar.

The streamwise locations of these three regions were found to depend on orifice aspect ratio.

The streamwise variation of half-widths in the two principal planes were also studied, and it was found that, whereas the half-width parallel to the minor axis of the orifice increased continuously with streamwise distance, the half-width parallel to the major axis showed an initial decrease.

Velocity irregularities - the occurrence of a maximum velocity away from the planes of symmetry, saddle-shaped spanwise velocity profiles and asymmetry in the velocity profiles - were observed in the three-dimensional freejets.

The three-dimensional, turbulent, plane wall jet was observed to have three regions of maximum velocity decay as in the freejet flowfield. The decay in region C is independent of orifice aspect ratio and is of the radial wall jet type (Ref. 12), i.e., $u_m \sim x^{-1.15}$. 

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Similarity in velocity profiles was observed in regions B and C. For the square orifice (AR ≈ 1.0) a direct transition to the radial wall jet decay was observed.

Transverse (spanwise) spread of the jet was found to be more rapid than its spread normal to the wall.

Nonuniformities in velocity distributions were also observed for the three-dimensional plane wall jet. The validity of the characterization of the wall jet flowfield generated by a finite, although slender slot as quasi-two-dimensional might be questionable, Sforza and Herbst (Ref. 12) concluded.

Studies of the angle of separation, \( \theta_{sep} \), of the "two-dimensional" curved wall jet by Fekete (Ref. 4) indicate that \( \theta_{sep} \) increases with jet Reynolds number defined as

\[
Re = \left[ \frac{(P_t - P_a) R_t}{\rho v^2} \right]^{0.5}
\]

and levels off at approximately 210 degrees beyond \( Re \approx 4 \times 10^4 \). Separation was found to occur earlier for rougher walls.
CHAPTER III
TEST FACILITIES

A schematic diagram of the test facilities is shown in Fig. 3.1. Reference to the letter code used in Fig. 3.1 is made in the description of the test facilities.

3.1 AIR SUPPLY AND GUIDING DUCT

Air is supplied by a type HS, size 200 American standard centrifugal fan (A) with static pressure of five inches of water. This fan is driven by a 5 hp, 1745 rpm General Electric induction motor. A 30-in. long wooden guiding duct (B) with a 16 in. by 21 in. crosssection is attached to the fan exit. A honeycomb flow straightener is placed in the guiding duct to reduce the turbulence level induced in the flow.

3.2 CONTRACTION DUCT AND ORIFICE PLATE

A wooden contraction duct (C) 30 inches long is placed after the guiding duct. A rectangular channel (D) made of plexiglass with uniform crosssection of 2in. x 9 in. is fixed on the contraction duct exit by bolts. The orifice plate (E), made of aluminium, is attached to the plexiglass channel. The area contraction ratio for the contraction duct is 19.4. A Keil probe with a 0.125 in. diameter shroud is placed in the contraction duct to measure the air supply pressure.
3.3 ORIFICE CAPS

Individually machined and interchangeable orifice caps, mounted on the orifice plate, formed the five orifice configurations used (Fig. 3.2). Each cap has an orifice of different aspect ratio but is carefully machined to have an orifice area of $0.400 \pm 0.008$ sq. in. The orifice plate-to-orifice area ratio is 45.0. The surface of each cap is machine finished.

No leaks were detected at the various junctions in the above apparatus.

3.4 CYLINDER AND PROBE TRAVERSE

As shown in Fig. 3.2, a vertical rod holds the plexiglass cylinders. The rod is rigidly mounted at the centre of a heavy table. The height and level of the table can be adjusted to a desired position by means of its adjustable legs. Each of the three cylinders is machined so that the curved wall is flush with the orifice plate when in position. The three cylinders used in the present study have radii of 6.0, 4.5 and 3.0 inches and a length of 14 inches.

The probe traverse (Fig. 3.3) consists of two aluminium arms parallel to each other, supported on the vertical rod along the axis of the cylinder. A rod with 20 threads per inch is mounted on to the two arms on the
outside, and completes the rigid probe traverse frame.

The probe holder is capable of being moved in a direction radial to the cylinder axis in the horizontal plane. The radial position is gauged by means of a dial vernier with a least count of 0.001 inch, and a range of 13 inches. The spanwise (vertical) position of the probe is controlled by a micrometer attached to the threaded rod. The probe holder mounting is supported on two additional guide rods, which run parallel to the threaded rod, on bearings to ensure motion parallel to the cylinder axis. The micrometer has a least count of 0.001 inch and a range of 12 inches. The angular position of the traverse frame is gauged by a dial-and-pointer arrangement, with a least count of 1 degree and a range of 220 degrees.

3.5 **TOTAL PRESSURE PROBE**

A round stainless steel hypodermic tube with an internal diameter of 0.014 in. and an outer diameter of 0.030 in. is used to measure the total pressure in the jet (Fig. 3.4). The probe is used in conjunction with a Lambrecht inclined manometer with n-butyl alcohol as the manometric fluid. The pressure measuring unit has a response time of approximately 4 minutes.
CHAPTER IV

EXPERIMENTS

The principal objectives of the experiments were to study the behaviour of the three-dimensional curved wall jet in terms of mean velocities, and to study the phenomenon of jet separation.

Velocity-profile studies were made using the 6-inch radius curved wall, and three orifices of aspect ratios 15.6, 5.0 and 1.0 were employed during these studies. Information obtained through these studies was used to interpret the jet flow in terms of velocity-profile variations, maximum velocity decay and jet-growth.

In order to study velocity irregularities and deviations from conventional bounded curved wall jet flow, entire flowfields of jets with aspect ratios of 15.6 and 1.0 were mapped at various streamwise locations. Isotach patterns were generated through this data.

Three curved walls of 6.0, 4.5 and 3.0 in. radii and five orifices with aspect ratios of 15.6, 10.0, 5.0, 2.5 and 1.0 were used in separation-angle studies.

The jet Reynolds number was maintained constant at $13.3 \times 10^4$ throughout the experiments.
4.1 CALIBRATION OF JET AT ORIFICE EXIT

The jet was tested for uniformity of orifice exit velocity for all aspect ratios. The orifice wall entrance radii were modified until satisfactory uniformity of velocity was obtained at the orifice exit. Figures 4.1 (a) and (b) show typical velocity profiles obtained at the exits of two orifices (AR = 15.6 and 1.0 respectively). The probing was done along the two axes of symmetry of the orifice area.

The exit velocity profile was taken intermittently during the course of experimentation and was found to be "flat" (i.e., $u_0$ sensibly constant).

The above calibration was made with the curved wall away from the orifice plate.

4.2 TEST PROCEDURE

4.2.1 Velocity Profiles

After the orifice plate and the curved-wall assembly were aligned, a minimal gap of approximately a paper thickness was kept between the two to prevent the transmission of blower vibrations to the probe. No significant amount of air could be sucked in through this gap (Ref. 14).
The jet, with a particular aspect ratio was then probed at several different stations along the wall $(0 \leq \theta < \theta_{\text{sep}})$. At each station, the flow was probed in a direction normal to the wall, and in the plane of symmetry $(z = 0)$; the flow was also probed in the span-wise direction at $y = y_m$, having known the value of $y_m$ from the previous probing.

During these studies one end of the inclined manometer was connected to the total pressure probe, the other end being open to atmosphere. No attempt was made to take into account the static pressure variation within the jet in computing the mean velocity (Ref. 12).

4.2.2. Isotach Patterns

For each $y-z$ plane $(\theta = \text{constant})$ studied for isotach patterns, over two hundred points forming a rectangular grid were probed for velocity. The grid spacing was based on the two velocity profiles previously obtained at that plane.

4.2.3 Visualization of Flow Separation

Centreline separation angles were determined for each of the three cylinders using the five orifices. The determination of $\theta_{\text{sep}}$ was done by letting small droplets of a suspension of lampblack in kerosene run down the dry
wall by gravity. The trace of droplets running down the wall at $\theta < \theta_{\text{sep}}$ would be kinked in the direction of flow. The angular position where the kink just disappeared was defined as $\theta_{\text{sep}}$ at centreline. Numerous independent determinations of $\theta_{\text{sep}}$ gave values within $\pm 2$ degrees.
CHAPTER V
EXPERIMENTAL RESULTS

5.1 DATA REDUCTION

For the purpose of this study, air was treated as incompressible because the maximum velocity encountered in the jet was only 140 ft/sec. Density of air was determined from readings of barometric pressure and room temperature monitored many times during a particular run.

Experimental data was reduced with the help of an IBM 1620 computer and results were plotted on a CALCOMP 565 plotter. Input data were room temperature, barometric pressure, orifice aspect ratio, radius of wall, the three coordinate values (θ, y, z) of the probing locations and manometer readings from jet probing.

Isotach patterns were obtained on the plotter from the experimental data by a programme using linear interpolation.

5.2 PRESENTATION AND DISCUSSION OF RESULTS

5.2.1. Maximum Velocity Decay

The decay of maximum velocity with streamwise distance (θ or x) is of interest in this study. The maximum velocity does not necessarily occur in the plane of symmetry (z = 0) due to the presence of velocity
irregularities in three-dimensional jet flows (Refs. 8, 11, 12). Following the method adopted by Sforza and Herbst (Ref. 12) the term "maximum velocity" here denotes the maximum value of velocity as found in the velocity distribution in the radial (y) direction at z = 0.

As shown in Fig. 5.1 the three-dimensional curved wall jets issuing from rectangular "slender" (AR>1.0) orifices are characterized by three distinct regions described by the different rates of streamwise decay of the maximum velocity:

Region A, Potential Core Region (PC): It is the region close to the jet orifice where the maximum velocity is constant and approximately equal to the jet exit velocity, \( u_o \).

Region B, Characteristic Decay Region I (CD-I): In this region the maximum velocity decays as a constant power of streamwise distance \( (u_m \sim x^{-n}) \). The value of the exponent \( n \) is dependent on orifice AR.

Region C, Characteristic Decay Region II (CD-II): This region extends downstream of Region B, and velocity decay in this region is faster than in Region B. The value of \( n \) is again dependent on orifice AR.
An examination of Fig. 5.1 shows that the nondimensional length of PC region increases with AR. For AR = 15.6 its value is about 6, which is close to the value found in the case of "two-dimensional" curved wall jet (Ref. 6).

For the square orifice, Regions B and C cannot be distinguished from each other, resulting in a single value of the decay exponent $n = 0.96$. This value is very close to the observed value of unity for the three-dimensional square freejet and the axisymmetric jet (Ref. 11).

Values of $n$ in Region B are plotted against AR in Fig. 5.2 for various three-dimensional jets. The present investigation gives results comparable with those of other three-dimensional flows. There is a dependence on AR, but the variation of $n$ with AR is not monotonic. This indicates that, for the three-dimensional curved wall jet, there is a geometrical configuration leading to a "slowest" rate of maximum velocity decay.

Sforza and his coworkers (Refs. 11, 12) found that, for three-dimensional freejets and wall jets, $n$ was independent of AR in Region C. However, for the three-dimensional curved wall jet $n$ is found to be dependent on aspect ratio, $n$ increasing with AR. It is interesting to note that the values of $n$ encountered here are by far the
largest occurring in jet decays. Table I summarizes the values of n for various types of jets studied to date.

5.2.2 Half-Width Boundaries

In previous investigations of two-coordinate flows, the streamwise growth of the normal (y) coordinate at which the velocity has half its local maximum value has been used for studying the flow growth (Refs. 6, 15). In three-dimensional flows, the boundaries defined as above in both the normal (y) and the spanwise (z) directions, have been used (Refs. 11, 12, 13).

Streamwise variation of $\bar{y}_{m/2}$ and $\bar{z}_{m/2}$ for AR = 1.0, 5.0 and 15.6 are shown in Figs. 5.3, 5.4 and 5.5 respectively. These results indicate that for AR > 1.0 the spanwise half-width ($\bar{z}_{m/2}$) initially decreases considerably and then increases, whereas the normal half-width ($\bar{y}_{m/2}$) grows. A similar behaviour has been noticed in other three-dimensional jet flows (Refs. 11, 12), where the growth of $\bar{y}_{m/2}$ was not as large as that observed in this study.

For the square-orifice jet, Fig. 5.3 shows a monotonic streamwise increase in both $\bar{y}_{m/2}$ and $\bar{z}_{m/2}$, the growth rate of $\bar{y}_{m/2}$ being larger.
5.2.3 **Velocity Profiles**

The streamwise variations in both normal and spanwise velocity profiles in the three curved wall jets tested are discussed in this section. All normal profiles are in the plane of symmetry \((z = 0)\); all spanwise profiles are at \(y = y_m\).

Dimensional velocity distributions in the normal direction are shown in Figs. 5.6, 5.7 and 5.8 for \(AR = 1.0\), 5.0 and 15.6 respectively. For \(AR = 1.0\), an "aberration" is noticed near the wall in the distribution at \(\theta = 15^\circ\) (Fig. 5.6). This aberration becomes more pronounced as \(\theta\) increases. For larger \(AR\), the aberration is noticed farther downstream (Figs. 5.7, 5.8).

Non-dimensional normal velocity profiles, using \(u_m\) and \(y_m/2\) as scales are plotted for \(AR = 1.0\) (Fig. 5.9), \(AR = 5.0\) (Fig. 5.10 for CD-I region, Fig. 5.11 for CD-II region) and \(AR = 15.6\) (Fig. 5.12 for CD-I region, Fig. 5.13 for CD-II region).

Examination of Figs. 5.9 through 5.13 reveals that conditions of approximate similarity hold in the outer layer \((y > y_m)\) of the jets. Overall similarity in normal velocity profiles is obtained in the CD-II regions of jets with \(AR = 5.0\) (Fig. 5.11) and \(AR = 15.6\) (Fig. 5.13), and in the far – CD region of the square jet (Fig. 5.9).
The maximum velocity position occurs farther away from the wall than in the case of other wall jets. Values of $y/y_m/2$ are in the range of 0.4 to 0.7 for the three-dimensional curved wall jet as against typical values of 0.14 for the Glauert profile and 0.2 for the "two-dimensional" curved wall jet profile (Ref. 4).

Non-dimensional spanwise velocity profiles, using $u_m$ and $z_m/2$ as scales, show a fair symmetry about the midplane (Figs. 5.14, 5.15, 5.16). Approximate similarity is found to exist in these profiles after an initial distance from the jet exit.

5.2.4 Velocity Irregularities

Sforza and his coworkers (Refs. 11, 12) observed certain irregularities in the velocity profiles parallel to the major axis of the orifice in three-dimensional jets. These irregularities were at first attributed to experimental error - a magnified propagation of indiscernable irregularities in the jet-exit velocity profile, but were later confirmed as a flow phenomenon after the irregularities were found to be present in jets issuing from carefully, independently machined orifices.

For the three-dimensional curved wall jet, the velocity irregularities appear in the CD-I region (Figs. 5.15, 5.16), getting less pronounced with an increase in $\theta$. In
the CD-II region the spanwise velocity profiles become approximately similar without any noticeable irregularities. The irregularities are observed only in the outer layer \((y > y_m)\). Saddle-shaped spanwise profiles at \(y > y_m\) (Figs. 5.17, 5.18) show these irregularities strikingly.

An explanation of the above phenomenon is given by Sforza and Herbst (Ref. 12) in terms of induced vortices surrounding the outer region of three-dimensional jet flows.

No trace of this irregular behaviour was observed for the square jet.

5.2.5 **Isotach Patterns**

Isotach patterns (equal-velocity contours) were obtained for jets with \(AR = 1.0\) and 15.6 in various planes of \(\theta = \text{constant}\) (Figs. 5.19 and 5.20 respectively).

The "distortion" observed in the pattern in the near-wall region of the flow appears to be stronger for the square jet than for the slender jet. It also becomes more prominent in the streamwise direction. The aberration observed in the normal velocity profiles is a one-dimensional representation of this distortion.

The conventional wall jet flowfield consists of two parts as one proceeds in a direction normal to the wall: the inner portion exhibits the characteristics of boundary-layer flow over a surface, and an outer portion which exhibits the characteristics of a freejet type flowfield.
(Ref. 12). In jets over flat walls there is a smooth transition between the two portions of flow because there is no eventual separation of the jet.

In "two-dimensional" curved wall jets, the flow is deflected round the wall by the Coanda effect. Borque and Newman (Ref. 2) explained that the establishment of Coanda flow depends on the maintenance of approximately two-dimensional conditions, in particular the prevention of spanwise flow and entrainment parallel to the major axis of the orifice. In practice such flow is prevented by the use of endplates.

In the three-dimensional curved wall jet, spanwise flow and entrainment from the two ends are considerable. These characteristics become more prominent as the jet becomes less slender (AR→1.0). They result in a general weakening of the Coanda effect, which acts primarily on the inner portion. The outer, or the freejet portion, which has a higher momentum flux than the inner portion, has a relatively higher proneness to maintain its direction of flow. The two portions thus diverge, resulting in the distortion observed in the isotach patterns.

The isotach patterns for AR = 15.6 also indicate the presence of velocity irregularities in the outer layer of the flowfield, which become less noticeable
in the streamwise direction.

The square jet has approximately circular isotach patterns throughout its flow. The slender wall jet starts with its major axis in the z-direction and as it proceeds downstream, transfigures into a shape having its major axis in the y-direction.

5.2.6 The Separation Phenomenon

Flow visualization studies of three-dimensional curved wall jets have shown an approximately triangular separation profile on the wall, with its base at $\theta = 0$ and its apex downstream on the centreline. This indicates that separation of the jet proceeds in the spanwise direction toward the centreline as $\theta$ increases. Wilson (Ref. 16) also observed the above behaviour.

Variations of the centreline separation angle, $\theta_{\text{sep}}$ with AR for the three radii of curvature are plotted in Fig. 5.21. The effect of $R$ on $\theta_{\text{sep}}$ is found to be less pronounced than the effect of AR, possibly due to the fact that operating Reynolds numbers were high ($Re > 9.5 \times 10^4$).

Even with $AR = 15.6$, the separation angles found were of the order of $85^\circ$, much less than the value $210^\circ$ associated with "two-dimensional" curved wall jets.
CHAPTER VI

CONCLUSIONS

An experimental study of the mean velocities of turbulent, three-dimensional, incompressible curved wall jets issuing into stationary ambient air has been presented. The results obtained indicate some characteristics of such flowfields.

The more striking results may be listed as follows:

1. Isotach patterns show a flowfield resulting from two diverging tendencies - the freejet flow and the Coanda effect.
2. These flows may be characterized by three regions defined by the maximum velocity decay rate.
3. The maximum velocity decay rate has a strong dependence on orifice geometry.
4. The values of decay exponent n in the CD-II region are by far the largest occurring in jet flows.
5. The half-width growth in the normal direction is more rapid than in the spanwise direction.
6. Irregularities in spanwise velocity distribution exist in the nearfield of jets emanating from slender orifices.
7. Separation of the flow from the wall occurs earlier than in the case of bounded curved wall jets. The separation angle increases with aspect ratio and radius of curvature.
## REFERENCES


<table>
<thead>
<tr>
<th>Type of flowfield</th>
<th>Exponent ( n ) of streamwise velocity decay ( (u_m \sim x^{-n}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. &quot;Two-dimensional&quot; wall jet</td>
<td>0.53</td>
</tr>
<tr>
<td>2. Radial wall jet</td>
<td>1.11</td>
</tr>
<tr>
<td>3. Axisymmetric freejet</td>
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</tr>
<tr>
<td>4. Three-dimensional freejet</td>
<td>( AR = 1.0 ) (square) : 1.0</td>
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<tr>
<td></td>
<td>Region B</td>
</tr>
<tr>
<td></td>
<td>( AR = 20.0 ) : 0.45</td>
</tr>
<tr>
<td></td>
<td>( AR = 10.0 ) : 0.35</td>
</tr>
<tr>
<td></td>
<td>( AR = 5.0 ) : 0.46</td>
</tr>
<tr>
<td></td>
<td>Region C</td>
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<tr>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>(for all jets)</td>
</tr>
<tr>
<td>5. Three-dimensional wall jet</td>
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<tr>
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<td>( AR = 40 ) : 0.41</td>
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<tr>
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<td>( AR = 20 ) : 0.43</td>
</tr>
<tr>
<td></td>
<td>( AR = 10 ) : 0.16</td>
</tr>
<tr>
<td></td>
<td>Region C</td>
</tr>
<tr>
<td></td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td>(for all jets)</td>
</tr>
<tr>
<td>6. Three-dimensional curved wall jet</td>
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<td>( AR = 15.6 ) : 0.37</td>
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<td></td>
<td>( AR = 5.0 ) : 0.33</td>
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<td>Region C</td>
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<tr>
<td></td>
<td>( AR = 15.6 ) : 2.99</td>
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<tr>
<td></td>
<td>( AR = 5.0 ) : 1.49</td>
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FIGURE 1.1 Schematic Representation of Three-Dimensional Curved Wall Jet Flowfield

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FIGURE 3.1 Schematic Diagram of Test Facility
FIGURE 3.2 ORIFICE ASSEMBLY
FIGURE 3.3 Curved Wall and Probe Traverse
FIGURE 3.4 Total Pressure Probe
FIGURE 4.1 Jet Orifice Exit Profiles

(a) AR = 15.6

(b) AR = 1.0

\[ \frac{u}{u_0} \text{ vs. } \frac{z}{l} \text{ (ALONG MAJOR AXIS)} \]

\[ \frac{u}{u_0} \text{ vs. } \frac{y}{t} \text{ (ALONG MINOR AXIS)} \]

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FIGURE 5.2 Exponent $n$ of Maximum Velocity Decay for Various Three-Dimensional Jets in Region B
FIGURE 5.3 Streamwise Variation of Half-Width Boundaries, AR = 1.0
FIGURE 5.4 Streamwise Variation of Half-Width Boundaries, AR = 5.0

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FIGURE 5.5 Streamwise Variation of Half-Width Boundaries, AR = 15.6

R = 6 in.
FIGURE 5.6 Dimensional Normal Velocity Profiles

AR = 1.0
FIGURE 5.7 Dimensional Normal Velocity Profiles

AR = 5.0
FIGURE 5.9 Non-Dimensional Normal Velocity Profiles

AR = 1.0

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FIGURE 5.10 Non-Dimensional Normal Velocity Profiles

AR = 5.0, CD-I Region

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FIGURE 5.11 Non-Dimensional Normal Velocity Profiles

$AR = 5.0, CD-II$ Region

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FIGURE 5.12 Non-Dimensional Normal Velocity Profiles

AR = 15.6, CD-I Region
FIGURE 5.13 Non-Dimensional Normal Velocity Profiles

AR = 15.6, CD-II Region
FIGURE 5.14 Non-Dimensional Spanwise Velocity Profiles
FIGURE 5.16 Non-Dimensional Spanwise Velocity Profiles

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FIGURE 5.19a Isotach Patterns for AR = 1.0

$\theta = 15^\circ$
FIGURE 5.19b  Isotach Patterns for AR = 1.0

$\theta = 25^\circ$
APPENDIX

ERRORS

The errors involved in the measurement and correlation of variables involved in the present investigation are listed below.

a) Measurement of velocity, u

\[ u = c \sqrt{h} \]  \hspace{1cm} (eq. A.1),

where c is a constant

and h is the reading of the sloping manometer

From eq. A.1,

\[ d(u) = \frac{c}{2} \cdot \frac{d(h)}{u} \]  \hspace{1cm} (eq. A.2).

With the manometer accuracy of \( d(h) = \pm 0.5 \) mm, \( d(u) \) varies from \( \pm 0.018 \) to \( \pm 0.028 \) ft/sec in the region of u from 165 to 25 ft/sec, depending upon the slope used on the manometer.

Theoretically this error tends to \( \pm \infty \) as u approaches 0.

In addition, the intermittent nature of turbulent flow, the finite diameter of the total pressure probe and the presence of velocity gradients in the flowfield will cause an error in the velocity measured.

b) Measurement of \( \theta \) and \( x \)

The probe traverse can be positioned to within \( d(\theta) = \pm 0.5 \) deg. in the \( \theta \)-direction. For a cylinder of
radius $R = 6$ in., $d(x) = \pm 0.052$ in.

$$x = x/t$$

$$d(x) = \pm 0.32 \text{ for } AR = 15.6$$
$$\quad = \pm 0.19 \text{ for } AR = 5.0$$
$$\quad = \pm 0.08 \text{ for } AR = 1.0$$

c) Measurement of $y, z$

$$d(y) = d(z) = \pm 0.0005 \text{ in.}$$

d) Measurement of $\theta_{sep}$

$$d(\theta_{sep}) = \pm 2 \text{ deg.}$$
VITA AUCTORIS

1946 Born at Khamgaon, India on June 4.

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