CHARACTERISTICS OF FLOW THROUGH AN ABRUPT TWO DIMENSIONAL EXPANSION

by

Dennis Michael Duffy

A Thesis Submitted to the Faculty of the
DEPARTMENT OF CIVIL ENGINEERING
In Partial Fulfillment of the Requirements
For the Degree of
MASTER OF SCIENCE
In the Graduate College
THE UNIVERSITY OF ARIZONA

1970
STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: Dennis Michael Duffy

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

Thomas Carmody
Associate Professor of
Civil Engineering

August 25, 1969
ACKNOWLEDGMENTS

I wish to thank my thesis Director Dr. Thomas Carmody for the direction and assistance provided throughout this master's program. I am especially grateful for his assistance during the summer of 1969, at the expense of his personal vacation.

I also wish to thank my wife, Kathleen, for her understanding and encouragement which made this degree possible.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OBJECTIVES</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>TEST EQUIPMENT</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>TEST SEQUENCE</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>DISCUSSION OF DATA ACCURACY</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>ANALYSIS AND DISCUSSION OF RESULTS</td>
<td>21</td>
</tr>
<tr>
<td>6</td>
<td>CONCLUSIONS</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>REFERENCES</td>
<td>57</td>
</tr>
</tbody>
</table>

LIST OF ILLUSTRATIONS: v
LIST OF TABLE: vii
ABSTRACT: viii
<table>
<thead>
<tr>
<th>Figure</th>
<th>Illustration Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Entrance Slot Details</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>Apparatus</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>Instruments Used in Experiment</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>Definition Sketch in Region of Expanded Flow</td>
<td>13</td>
</tr>
<tr>
<td>5</td>
<td>Typical Jet $\frac{u'^2}{U_0}$ Distribution</td>
<td>17</td>
</tr>
<tr>
<td>6</td>
<td>Zones of Jet Flow After Sawyer (1963)</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>Turbulence Measurements</td>
<td>20</td>
</tr>
<tr>
<td>8</td>
<td>Horizontal Streamlines at Centerline of Conduit for Expansion Ratio 2</td>
<td>22</td>
</tr>
<tr>
<td>9</td>
<td>Vertical Streamlines at Centerline of Conduit for Expansion Ratio 2</td>
<td>23</td>
</tr>
<tr>
<td>10</td>
<td>Horizontal Streamlines at Centerline of Conduit for Expansion Ratio 3+2</td>
<td>24</td>
</tr>
<tr>
<td>11</td>
<td>Vertical Streamlines at Centerline of Conduit for Expansion Ratio 3+2</td>
<td>25</td>
</tr>
<tr>
<td>12</td>
<td>Horizontal Streamlines at Centerline of Conduit for Expansion Ratio 3</td>
<td>26</td>
</tr>
<tr>
<td>13</td>
<td>Vertical Streamlines at Centerline of Conduit for Expansion Ratio 3</td>
<td>27</td>
</tr>
<tr>
<td>14</td>
<td>Horizontal Streamlines at Centerline of Conduit for Expansion Ratio 4</td>
<td>28</td>
</tr>
<tr>
<td>15</td>
<td>Vertical Streamlines at Centerline of Conduit for Expansion Ratio 4</td>
<td>29</td>
</tr>
<tr>
<td>16</td>
<td>Horizontal Streamlines at Centerline of Conduit for Expansion Ratio 5</td>
<td>30</td>
</tr>
<tr>
<td>17</td>
<td>Vertical Streamlines at Centerline of Conduit for Expansion Ratio 5</td>
<td>31</td>
</tr>
<tr>
<td>Figure</td>
<td>Illustration Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>18</td>
<td>Horizontal Streamlines at Centerline of Conduit for Expansion Ratio 7.</td>
<td>32</td>
</tr>
<tr>
<td>19</td>
<td>Vertical Streamlines at Centerline of Conduit for Expansion Ratio 7.</td>
<td>33</td>
</tr>
<tr>
<td>20</td>
<td>Horizontal Velocity Distributions for Expansion Ratio 2.</td>
<td>34</td>
</tr>
<tr>
<td>21</td>
<td>Horizontal Velocity Distributions for Expansion Ratio 3×2.</td>
<td>35</td>
</tr>
<tr>
<td>22</td>
<td>Horizontal Velocity Distributions for Expansion Ratio 3.</td>
<td>36</td>
</tr>
<tr>
<td>23</td>
<td>Horizontal Velocity Distributions for Expansion Ratio 4.</td>
<td>37</td>
</tr>
<tr>
<td>24</td>
<td>Horizontal Velocity Distributions for Expansion Ratio 5.</td>
<td>38</td>
</tr>
<tr>
<td>25</td>
<td>Horizontal Velocity Distributions for Expansion Ratio 5.</td>
<td>39</td>
</tr>
<tr>
<td>26</td>
<td>Horizontal Velocity Distributions for Expansion Ratio 7.</td>
<td>40</td>
</tr>
<tr>
<td>27</td>
<td>Horizontal Velocity Distributions for Expansion Ratio 7.</td>
<td>41</td>
</tr>
<tr>
<td>28</td>
<td>Continuity Quantities.</td>
<td>44</td>
</tr>
<tr>
<td>29</td>
<td>Velocity Profile</td>
<td>46</td>
</tr>
<tr>
<td>30</td>
<td>Momentum Quantities.</td>
<td>47</td>
</tr>
<tr>
<td>31</td>
<td>Energy Quantities.</td>
<td>48</td>
</tr>
<tr>
<td>32</td>
<td>Ambient Pressure of Side Panels When Flow is Along Left Side for B/b = 2.</td>
<td>50</td>
</tr>
<tr>
<td>33</td>
<td>Ambient Pressure of Side Panels When Flow is Along Left Side for B/b = 3.</td>
<td>51</td>
</tr>
<tr>
<td>34</td>
<td>Ambient Pressure of Side Panels When Flow is Along Left Side for B/b = 3×2.</td>
<td>52</td>
</tr>
<tr>
<td>35</td>
<td>Ambient Pressure of Side Panels When Flow is Along Right Side for B/b = 4.</td>
<td>53</td>
</tr>
<tr>
<td>36</td>
<td>Ambient Pressure of Side Panels When Flow is Along Right Side for B/b = 5.</td>
<td>54</td>
</tr>
<tr>
<td>37</td>
<td>Ambient Pressure of Side Panels When Flow is Along Left Side for B/b = 7.</td>
<td>55</td>
</tr>
</tbody>
</table>
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Nomenclature</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nomenclature</td>
<td>4</td>
</tr>
</tbody>
</table>
ABSTRACT

Low-turbulence, uniform, steady flow through an abrupt 1 1/2 x 7 1/2 inch slot into a rectangular expansion was investigated. Average, uniform velocity of the air through the slot was 110 ft/sec, with a Reynolds number of $7 \times 10^4$. Velocity and pressure distributions were obtained and continuity, momentum, and energy relationships were evaluated. The ratio of conduit-to-entrance-slot width was varied from 2 to 7 while the vertical distance was held constant. Mean streamlines, eddy pockets, and the stability of flow were examined for each ratio.

The analysis performed on a section of unit height across the conduit at the mid point of the expansion indicated the eddy-pocket size, streamline development, and possible flow separation. The analysis indicates that the flow is three dimensional for the slot and conduit widths tested.

Stable-jet wall attachments were found to exist at expansion ratios less than three, and neutrally stable wall attachments at ratios between three and seven. Slight irregularities in symmetry of the conduit influenced the wall attachment of the jet. The attachment occurs first on the wall closer to the entrance slot.
CHAPTER 1

OBJECTIVES

Flow through an infinite slot and through rectangular conduits has been previously examined by Albertson et al. (1950) and Hindall (1966). The purpose of the author's work is to provide additional information on the flow through abrupt, rectangular expansions. This information was obtained by examining flow through a 1 1/2 x 7 1/2 inch slot into a rectangular conduit without a transition section. The conduit's height was constant while the width varied.

Among the objectives of the project was the determination of mean streamlines of flow through the various expansion ratios. In about 1781 Lagrange presented what is known today as the concept of streamlines: a continuous line drawn through a fluid such that it is tangent to the velocity vector at each point is a streamline. There is no flow across a streamline, thus a particle of fluid moves in the direction of the streamline at any instant. Its displacement is $\delta s$ with components in the $x$, $y$, $z$ directions. Then $\frac{\delta x}{u} = \frac{\delta y}{v} = \frac{\delta z}{w}$ states that the corresponding components are proportional and thus $\delta s$ and $q$ lie in the same direction where $q$ has components $u$, $v$, $w$. Now expressing the displacements in differential form to produce the differential equations of a streamline yields:

$$\frac{dx}{u} = \frac{dy}{v} = \frac{dz}{w}$$

Equation (1) is actually two independent equations for which any line
that satisfies them is a streamline. For the purpose of this experiment where turbulent, steady flow is used, the streamlines represented are the average positions of the instantaneous streamlines, thus they do not change with time.

Determination of zones of flow separation due to adverse pressure gradients was also within the scope of the project. Hindall (1966) found large zones of separation on the top and bottom of the rectangular conduits he examined, therefore the author was especially interested in the possibility of their occurrence in this work.

In conjunction with evaluation of flow separation, the location and size of eddy pockets created by the geometry of the expansions was to be evaluated. The sizes and shapes of these pockets are important factors governing the amount of energy dissipated as flow passes through the eddy-pocket region.

Jet stability within the conduit is connected to eddy-pocket development and stability. Therefore the stability of the jet with respect to external forces and expansion ratios was examined. It has been established that a jet issuing from a slot parallel to a flat plate will attach itself such that it flows along the plate, Sawyer (1960) and (1963). Hindall (1966) also found in an abrupt expansion this same condition. The jet stability and attachment condition was evaluated for each expansion ratio.

While evaluating the flow characteristics of each expansion it became necessary to determine the continuity, momentum, and energy relationships. Rouse (1959) presents the Reynolds equation which
governs turbulent flow on a unit volume basis as: (see Table 1)

\[ \rho u_j \frac{\partial u_i}{\partial x_j} = \rho x_i - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} - \rho u_i u_j' \right) \]  

(2)

in the x direction this is expanded to:

\[ \rho \left( \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial w} \right) = \rho x - \frac{\partial p}{\partial x} + \frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} - \rho u v' \right) 
+ \frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} - \rho u' v' \right) + \frac{\partial}{\partial z} \left( \mu \frac{\partial u}{\partial z} - \rho u' w' \right) \]  

(3)

The left side is momentum flux, the first right term is the body forces. The second right-side term represents pressure forces, while the third, forth, and fifth are viscous and Reynolds-stress terms.

For momentum analysis the general equation as found in Rouse (1959) is:

\[ \rho \int_s n_j u_i \overline{u}_j \, dS + \rho \int_s n_j u_i u_j' \, dS = \]

\[ \rho \int_V x_i \, dV - \int_s n_i p \, dS + \mu \int_s n_j \frac{\partial u_i}{\partial x_j} \, dS \]  

(4)

In the x direction this equation may be reduced to:

\[ \rho \int_s (\overline{x} u_i^2 + \overline{mu} v + \overline{nu} w) \, dS + \rho \int_s (\overline{x} u' v + \overline{mu} v' + \overline{nu} w') \, dS \]

\[ \rho \int_V x_dV - \mu \int_s \overline{u} p \, dS + \mu \int_s (\overline{\partial u}{\partial x} + m \overline{u}{\partial y} + n \overline{u}{\partial z}) \, dS \]  

(5)
TABLE 1

Nomenclature

\( \rho = \) Mass density of fluid  
\( \Re = \) Reynolds number  
\( \mu = \) Dynamic viscosity  
\( q = \) Flow rate per unit width  
\( R = \) Hydraulic radius  
\( A = \) Area of fluid at cross-section  
\( P = \) Wetted perimeter of conduit  
\( B = \) Width of expansion conduit  
\( b = \) Width of expansion conduit  
\( \delta = \) Boundary layer thickness  
\( P_t = \) Mean total pressure  
\( P_a = \) Mean ambient pressure  
\( P_o = \) Free stream dynamic pressure; \( P_o = \frac{\rho U^2}{2} \)  
\( U = \) Free stream velocity  
\( U_o = \) Entrance slot velocity  
\( u,v,w = \) Instantaneous velocity components  
\( \bar{u},\bar{v},\bar{w} = \) Temporal - mean velocity components  
\( u',v',w' = \) Instantaneous deviations from temporal mean velocity components  
\( \bar{V} = \) Total mean velocity; \( \bar{V}^2 = \bar{u}^2 + \bar{v}^2 + \bar{w}^2 \)  
\( V' = \) Total turbulence velocity; \( V'^2 = u'^2 + \bar{u}^2 + \bar{w}^2 \)  
\( i = \) Free index in tensor notation  
\( j = \) Dummy index in tensor notation
By neglecting the body forces (air in air), viscous stresses, and mean transverse velocity components \( \overline{v} \) and \( \overline{w} \), equation (5) reduces to a two-dimensional momentum-flux equation

\[
\int_{y_1}^{y_2} \rho u^2 \, dy + \int_{y_1}^{y_2} p_y \, dy = 0
\]  
\( (6) \)

Rouse also obtains the work-energy equation where the fluctuating, mean velocity and pressure components are substituted for instantaneous values in (2). By averaging the terms the result will be:

\[
\bar{u}_j \frac{\partial}{\partial x_i} \left( \rho \frac{\overline{v}^2}{2} + \frac{\overline{v'}^2}{2} \right) + u' \frac{\partial (\overline{v'}^2)}{\partial x_j} + \overline{a(u_i u'_i u'_j)}
\]

\[
= \rho \bar{u}_i x_i - \bar{u}_i \frac{\partial \bar{P}}{\partial x_i} + \mu \bar{u}_i \frac{\partial^2 \overline{u_i}}{\partial x_j \partial x_j} + \mu u' \frac{\partial^2 u'_i}{\partial x_j \partial x_j} - u' \frac{\partial \bar{P}}{\partial x_i}
\]  
\( (7) \)

which is the differential equation of work and energy. Upon integration of (7) over a given region and after the volume integrals have been changed by the Gaussian theorem to surface integrals, the following equation results:

\[
\int_s \frac{\overline{v}^2}{2} - \bar{u}_i \frac{\partial x_i}{\partial n} \, dS + \int_s \bar{u}_i \rho u'_i u'_j \frac{\partial x_i}{\partial n} \, dS - \int_v \rho u'_i u'_j \frac{\partial \bar{u}_i}{\partial x_j} \, dV
\]

\[
= \int_v \rho \bar{u}_i x_i \, dV - \int_s \bar{P} - \bar{u}_i \frac{\partial \bar{u}_i}{\partial n} \, dS + \int_s \mu \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_i}{\partial x_i} \right) \bar{u}_i \frac{\partial x_i}{\partial n} \, dS
\]

\[
- \int_v \mu \left( \frac{\partial \bar{u}_i}{\partial x_j} \right) \frac{\partial x_i}{\partial x_j} \, dV
\]  
\( (8) \)
The far left term represents net flux of kinetic energy out of the region, the second represents the rate of work done by the Reynolds stresses over the surface, and the third term is the Reynolds-stresses work done throughout the interior of the region. On the right side of the first and second terms are the rates at which work is done by the external pressures, and by the body forces. And the third and fourth terms are the rates at which work is being done by the viscous stresses.

By applying the same assumptions used in the momentum analysis the following is obtained:

\[
\int_S \rho \frac{V^2}{2} \bar{u} dS - \int_V \rho \bar{u}_i \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} dV = -\int_S P_A \bar{u} dS \tag{9}
\]

for turbulent flow \( V \sim \bar{u} \) and \( \frac{\rho u^2}{2} + P_A = P_T \), by setting

\[
E_T = \int_V \rho \bar{u}_i \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} dV
\]

then the rate of turbulent-energy production may be expressed as:

\[
E_T = \int_S \rho \frac{\bar{u}^3}{2} dy + \int_S P_A \bar{u} dy = \int_S P_T \bar{u} dy \tag{10}
\]

Using the above relationships momentum and energy analysis were performed for the various expansions. The dissipation or conservation of energy through the expansion will aid in determining the relative efficacy of a similar structure. Current hydraulic structures are using abrupt expansions to dissipate energy down stream of turbines. An example is Mica dam on the Columbia river where circular expansions are used for this purpose, Russell and Ball (1967).
After determining the flow characteristics it was necessary to evaluate the effectiveness of the analysis. Data was gathered over a horizontal section across the conduit taken at the vertical mid point. It was realized that because flow is entering and leaving the upper and lower boundaries of the section this movement must be considered in the analysis of flow conditions.
CHAPTER 2

TEST EQUIPMENT

Once the objectives were decided upon, it became necessary to assemble the equipment required for the project. The major concern of the author was the selection of fluid to be used and the method of setting the fluid in motion. The problems associated with the use of water as the fluid are such that air was considered for this experiment. Rouse (1947) listed several advantages of the low velocity air tunnel in hydraulics research. They are:

1. Due to low density of the air ($\frac{1}{800}$ that of water), structural requirements of the equipment are kept to a minimum.
2. For the same reason power requirements are low.
3. Absolute tightness of the system is not as critical with air as with water.
4. Reservoirs and catch basins are eliminated.
5. Many phases of instrumentation, especially the hot-wire anemometer, become greatly simplified when air is used instead of water.

There are problems associated with the use of air for hydraulic research. They occur when the effects of compressibility, cavitation, or gravitational attraction of water are not duplicated by air under the same flow conditions. Air may, however, undergo velocities of over
one hundred feet per second while closely matching the flow characteristics of water. Because of the range of Reynolds numbers encountered in flow in and around common hydraulic structures the geometry of the structure dominates the properties or flow characteristics instead of velocity, scale, and viscous influences, Rouse (1949). Thus when considering the current, flow velocities, viscosities, and size of hydraulic structures in use today, the shape of the structure controls the flow characteristics.

Schlichting (1955) mentions that flows of gases can be treated as incompressible with a good degree of approximation if the dynamic head is small compared to the modulus of elasticity of the fluid. Thus from Bernoulli's equation $p + \frac{\rho v^2}{2} = \text{constant}$ and where $v =$ velocity of flow, the change in pressure $p$ caused by flow is the order of the dynamic head $q = \frac{\rho v^2}{2}$ so that $\frac{\Delta p}{\rho_o} \propto \frac{q}{E}$. Assuming a maximum velocity of 150 ft/sec the $\frac{q}{E}$ ratio is 0.014. Schlichting also states that the outside value acceptable of $\frac{q}{E}$ is 0.05 for the flow to be considered incompressible. Therefore the velocity of 150 ft/sec is well within the range of incompressible flow.

On the basis of the acceptability of air, equipment was assembled. The fluid mechanics laboratory had on hand a two-horsepower centrifugal ventilation blower with a rubber coupling on the discharge duct to reduce vibration. The blower was attached to a plywood tunnel 6 x 19 inches and 28 inches long. Several layers of screen were placed within the tunnel to break up blower disturbances in the flow. In addition to the screens 1/2 inch tubing placed horizontal within the tunnel also reduced the
effects of the blower and insured uniform flow. The inside of the tunnel was free of burrs or obstructions immediately upstream of the slot.

To the end of the tunnel a 1/4-inch plywood end plate with a 7 1/2 x 1 1/2 inch smooth slot was attached, see Figures 1, 2, 3, and 4. To the face of the entrance a 1/4-inch plexiglass rectangular conduit with moveable sides was mounted. The top and bottom panels of the conduit was flush with the slot. The conduit was 30 times as long as the entrance slot was wide. A maximum expansion of the conduit to seven times the slot width was possible.

Along the left and top sides of the conduit ambient-pressure taps were installed on a spacing of 1 1/2 inches. On the right and bottom sections taps were also installed to determine ambient pressures along these walls. All ambient taps were drilled 1/16 inch in diameter. On the right panel 3/8 inch holes were drilled at stations 2b, 10b, 18b, 26b, 34b, and 44b, on the center line of the panel. The purpose of these holes is to allow determinations of the pressures and velocities within the conduit by probes. All holes were drilled normal to the surface, and were free of burrs. The ambient-pressure taps were sealed with surgical tubing and clamps. The probe holes were sealed with tape.

After the critical expansion ratio was found (i.e., where the jet could not be switched from wall to wall) additional 3/8 inch holes were drilled to allow more complete study of the fluid stream. Every joint of the conduit was sealed with tape to prevent flow leakage.
Figure 1 Entrance Slot Details
Figure 2 Apparatus

Figure 3 Instruments Used in Experiment
Figure 4 Definition Sketch in Region of Expanded Flow
Three types of pressure probes were used. All probes were fabricated from 1/16-inch O.D. brass tubing with an inside-to-outside diameter ratio of 0.577. The stagnation pressure, ambient pressure, and reverse-flow stagnation-pressure probes had openings at least 18 times the diameter of the probe holder upstream of the holder. The tip of the ambient-pressure probe extended 5/8 inch beyond the two 0.01-inch-diameter sensing holes in the probe. The end of the probe is ellipsoidally shaped to allow minimum flow separation around the tip.

To measure velocities a hot-wire anemometer, Old Gold Model type 4-2, with a mean-product computer type 2, and a Hewlett-Packard model 130B dual-trace oscilloscope was used. The anemometer wire is 0.00015 inch in diameter made of tungsten, and spread between two prongs approximately 1/8 inch apart.

For the determination of eddy-pocket size and for confirming possible zones of flow separation, a 1/8-inch brass rod with thread on one end was used. The thread provided a visual indication of the presence of flow turbulence as well as indicating direction of flow.

Tolerances in construction and alignment of the apparatus was within 1/64 and 1/16 of an inch respectively. A stagnation-pressure survey was conducted over the entrance slot without the plexiglas attached, to verify uniform flow at the entrance. The variation in velocity was less than one percent of the maximum velocity.
CHAPTER 3

TEST SEQUENCE

The complete apparatus was assembled with the conduit walls at the maximum width. With all joints sealed with tape the alignment of the conduit was checked and the blower started. The tunnel is centrally located in a laboratory room with the approximate dimensions of 20 ft x 40 ft x 12 ft high. The blower draws air from one end of the room and forces it through the expansion and into the room again. With all room doors closed a smooth circulation of the room air takes place. The room temperature varied within two degrees centigrade during the longest test period, and with a closed system the pressure was constant.

At the start of each test the initial temperature and pressure were recorded. The initial flow condition was observed by inserting a stagnation-pressure probe into the discharge end of the conduit. Typical observations noted at that time were: direction of flow within the conduit, and any variation of velocity or pressure occurring along the conduit relative location and extent of eddy pockets or separation zones, and an estimation of the vertical variation in pressure gradients.

After a "feel" for the type of flow occurring within the system was obtained, the alcohol manometer was attached to the ambient-pressure taps and the wall pressures recorded. The jet was then deflected and the location of the deflecting device at the time of deflection noted. If the deflected jet stayed in its new orientation, it was termed
neutrally stable. If it did not stay in the new position but immediately returned to the original flow condition, it was considered stable.

To define the flow parameters within the conduit, stagnation-pressure and velocity traverses were made, by proceeding in 1/2-inch increments across the conduit at the stations previously listed. In determining the net, jet area the turbulence channel on the Old Gold Computer was used to detect the zones of shear, Figure 6, and thus define the net area of the jet, Figure 5.

Following the compilation of the pressure and velocity data, a thread survey was undertaken. As previously mentioned this technique was used to define the areas of flow separation.

At the end of each test run the room temperature and pressure were checked, and the mean value of each was used in any calculations. Data which appeared to be in error were checked at this time.
Figure 5 Typical Jet $\frac{\bar{u}^2}{U_0}$ Distribution

Figure 6 Zones of Jet Flow After Sawyer (1963)
CHAPTER 4

DISCUSSION OF DATA ACCURACY

In attempting to obtain meaningful data the data itself must be examined and a decision made on its authenticity. In restricting the data to a unit slice across the conduit at the center, several advantages occur. First the size of the apparatus could be to a scale commensurate with the monies available for this research. Secondly, the space required for correct orientation of the probes to obtain accurate readings is reduced, and the disturbance of flow due to sampling is also reduced.

The problems associated with probe orientation with respect to mean flow is worthy of concern. Due to confined working areas, within the conduit, it was almost impossible to set the probe parallel to the local velocity. The problems became complex when using the ambient probe. The flow would often be parallel to the tip while at the sensing holes crossflow was occurring. Though the lack of perfect probe stationing is sure to have caused some error in the data the author believes it to be slight.

Hot-wire anemometers, developed around 1914 and refined continuously since, are subject to considerably less errors than the pressure probes as far as orientation is concerned. The sensing wire was always set in the vertical position, and thus the flow was always normal to the wire. Except for the case of flow approaching the wire from along the probe arm, errors in velocity determination due to positioning of the probe are slight.
Hubbard (1957) developed a calibration procedure which when followed allows the investigator to determine velocities and to check the functioning of the complete system. By performing this calibration before and after each run, equipment accuracy was assured. The single largest source of error is believed to be caused by the human element. There is considerable fluctuation of the computer monitor in some flow regions. This necessitates the operator estimating the mean dial reading and thus introducing a probable error. Figure 7 shows a typical series of turbulence measurements.

Emmett and Wallace (1964) discuss errors in piezometric measurements in hydraulic research. They found that errors increase with hole diameter as flow separation occurs across the hole. Boundary roughness will also affect tap pressures. For a smooth channel with a 0.05-inch diameter hole the pressure was less than three percent in error. The test taps used in this project were 0.062 inches in diameter so the error anticipated should have been in the five-percent range.

Another source of possible error is the alignment of the test equipment. The alignment was held to 1/16 inch variation to insure accurate data. There is undoubtedly some error due to this tolerance, however, it should not be detectable in light of the flow velocities used.

Though the author was aware of the many possibilities of error present, no corrections of raw data were made. If the results of a survey were obviously in error the survey was re-run and the new data used in the analysis.
Figure 7 Turbulence Measurements

\[ \sqrt{\frac{u'^2}{U_0}} \]
variation with distance from entrance slot at expansion ratio 7.
CHAPTER 5

ANALYSIS AND DISCUSSION OF RESULTS

The streamlines depicted on Figures 8 through 19 were determined by dividing the net flow area (defined as that flow at any cross-section which ultimately leaves the conduit without undergoing a reversal of direction in an eddy or separation pocket) into equal areas. The boundaries of the equal q areas were then used as mean streamlines.

Due to a difficulty in determining the location of the boundary between net flow and the fluid entrained by the jet, the streamlines are subject to some variation. Sawyer (1963) breaks the jet into three separate zones, Figure 6. The middle zone is potential flow, and is bounded by two turbulent mixing layers. The third zone is where the jet is self-preserving. The author found the zone of turbulent mixing or the shear zone difficult to detect with any accuracy in lateral extent. Figure 5 as previously referred to was the author's basis of distinguishing between the zones. To ensure the most accurate representation of the mean streamlines it became necessary to make slight variations so that agreement was reached between all data available.

With some expansion ratios the velocities were slightly greater at station 4b than at the entrance slot, Figures 20 through 27. This indicated that the flow was separating on the top and bottom panels of the conduit. The most likely cause of this separation was the existence of an adverse pressure gradient, Streeter (1962) and Schlichting (1955).
Figure 8  Horizontal Streamlines at Centerline of Conduit for Expansion Ratio 2
Figure 9  Vertical Streamlines at Centerline of Conduit for Expansion Ratio 2
Figure 10. Horizontal Streamlines at Centerline of Conduit for Expansion Ratio 3+2
Figure 11  Vertical Streamlines at Counterline of Conduit for Expansion Ratio 3+2
Figure 12 Horizontal streamlines at Centerline of Conduit for Expansion Ratio 3
Figure 13  Vertical Streamlines at Centerline of Conduit for Expansion Ratio 3
Figure 14: Horizontal Streamlines at Centerline of Conduit for Expansion Ratio 4
Figure 15  Vertical Streamlines at Centerline of Conduit for Expansion Ratio 4
Figure 16  Horizontal Streamlines at Centerline of Conduit for Expansion Ratio 5
Figure 17  Vertical Streamlines at Centerline of Conduit for Expansion Ratio 5
Figure 18  Horizontal Streamlines at Centerline of Conduit for Expansion Ratio 7
Figure 19  Vertical Streamlines at Centerline of Conduit for Expansion Ratio 7
Figure 20 Horizontal Velocity Distributions for Expansion Ratio 2
Figure 21 Horizontal Velocity Distributions for Expansion Ratio 3+2
Figure 22 Horizontal Velocity Distributions for Expansion Ratio 3
Figure 23 Horizontal Velocity Distributions for Expansion Ratio 4
Figure 24 Horizontal Velocity Distributions for Expansion Ratio 5
Figure 25 Horizontal Velocity Distributions for Expansion Ratio 5
Figure 26 Horizontal Velocity Distributions for Expansion Ratio 7
Figure 27 Horizontal Velocity Distributions for Expansion Ratio 7
However, the author was unable to confirm the occurrence of the separation zones by the use of thread surveys. The possible separation zones on the top and bottom panels most likely do exist despite lack of visual conformation.

The eddy pockets were clearly defined, Figures 8 through 19. As shown on these sheets the eddy-pocket size increases with expansion ratio. Sawyer (1960) found in his studies of a jet issuing parallel to a flat plate, that when the entrance slot of width $b$ was 5.62 times this width from the parallel plate, the point of reverse flow was $11b$ downstream of the slot. For this project when the expansion ratio is five the reverse flow occurs at a distance of $14b$. This appears to be in general agreement with Sawyer's work. However, without knowing the velocities with which he worked further correlation is impossible.

Not only should the lengths of the eddy pockets increase in size with expansion ratio, but they should also increase with increasing slot velocities. As the initial particle momentum through the slot increases, the point of jet attachment moves farther from the slot. Also as the Reynolds number goes to infinity the length or the eddy-pocket goes to infinity.

An additional item of importance was found to be the mirror-image existence of the eddy pockets as the neutrally stable flow was forced from one wall to another. Relatively identical reproduction of the pockets was obtained respective to the wall attachment condition. For the stable jet attachment there was only one possible combination of eddy pockets for each expansion.
The method of analysis was partially successful. Development of the streamlines and eddy pockets was possible through the analysis. However, the continuity, momentum, and energy relationships, for the 1:5 rectangular slot are affected by the accelerated flow through the area analyzed. This flow condition in the area analyzed necessitated additional evaluation of the data before the above relationships could be obtained.

By analyzing the continuity, momentum, and energy relationships, not only can the conservation of energy be evaluated, but selections of an expansions to conserve or dissipate energy can be made. Integration of the velocity over the section area normal to the mean flow will determine the mean rate of flow. For continuity requirements to be met the flow rate past one section must be the same as past all sections within the test conduit. Figure 28 illustrates the results of the continuity analysis for each expansion ratio. Possible flow separation and the growth of the boundary layer have produced the indicated increasing flow along the channel. Because the flow parameters are obtained and analyzed at a segment of unit height across the conduit the increasing velocities at the center line of the conduit indicate a greater flow rate than actually exists. Schlichting (1955) for turbulent boundary layer thickness develops the thickness equation:

$$\frac{\delta}{L} = 0.37(R_L)^{-0.20}$$

For a rectangular conduit the Reynolds number $R_L$ is a function of the hydraulic radius $R$, where $R = \frac{A}{P}$. Then the Reynolds number $R = \frac{4RU}{u}$, Rouse (1949). This means that the greater the expansion ratio and thus the $R$, the smaller will be the boundary layer thickness. A thicker boundary layer will require a faster centerline velocity along
Figure 28 Continuity Quantities
the conduit which is verified by Figures 20 through 27. For the expansions smaller than B = 4b the boundary layer appears to have been completely developed beyond station 30b. The velocity distribution has at this station assumed the shape as shown on Figure 29.

Figures 30 and 31 show the effect of separation due to adverse pressure gradients and the effect of boundary layer growth on the momentum and energy relationships. Figure 31 also indicates that as the expansion ratio increases the tendency is for increasing energy dissipation. In the vicinity of $\frac{x}{b} = 5$ the apparent flow separation on the top and bottom panels has a marked effect upon the velocity distribution and thus the energy relationship.

At expansion ratios 4, 5, and 7 the flow existed in neutral stability. Neutral stability is defined as that condition of flow where the jet when attached to one side of the conduit can be deflected to the opposite side where it remains until again deflected. Sawyer (1960) describes the tendency for a jet to remain along a wall. Fluid entrained by the jet causes the initial curvature of the jet towards the wall as the entrainment produces a pressure difference. The final jet configuration results when the mean volume flow entrained from the eddy cavity by the inner edge of the jet is balanced by the mean flow back into the eddy pocket. At the expansion ratio of approximately 3 a movement of 1/16 inch in either wall produced a jet attachment along the wall closer to the entrance slot. The significance of this occurrence is that under similar conditions not only can the orientation
Figure 29 Velocity Profile
Figure 30 Momentum Quantities
Figure 31 Energy Quantities
of the flow be predicted, but to an extent it can be controlled. Figures 32 through 37 show the effect of jet attachment on the ambient wall pressures.
Figure 32 Ambient Pressure at Side Panels When Flow is Along Left Side for $B/b = 2$
Figure 33 Ambient Pressure at Side Panels When Flow is Along Left Side for B/b = 3
Figure 34 Ambient Pressure at Side Panels When Flow is Along Left Side

for $b/b = 3+2$
Figure 35 Ambient Pressure at Side Panels When Flow is Along Right Side for $B/b = 4$
Figure 36 Ambient Pressure at Side Panels When Flow is Along Right Side for $B/b = 5$
Figure 37 Ambient Pressure at Side Panels When Flow is Along Left Side for $B/b = 7$
CHAPTER 6

CONCLUSIONS

The following conclusions are presented as the important findings of this research.

1. The jet is neutrally stable for the 1:5 entrance slot at expansion ratios between 3 and 7.
2. The jet attaches itself to the closer wall at expansion ratios less than 3.
3. The greater the expansion ratio, the greater the rate of energy dissipation.
4. The smaller the expansion ratio, the smaller is the momentum increase. Separation on the top and bottom of the conduit due to adverse pressure gradients becomes less possible as the expansion ratio decreases.
5. Eddy-pockets increase in length as the expansion ratio increases.
6. For the expansions with B less than 4b the boundary layer was apparently fully developed by station 30. And for the expansions greater than 4 the conduit length did not allow full development of the boundary layer on all sides of the conduit.
REFERENCES


