A FLOW VISUALIZATION STUDY OF THE 
INLET VORTEX PHENOMENON

by

Francesca De Siervi

GT & PDL Report No. 159 July 1981

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This research was supported by the Air Force Office of Scientific Research under Contract No. F49620-78-C00084, Dr. J.D. Wilson, Program Manager.
ABSTRACT

The inlet vortex phenomenon was experimentally investigated in a water tunnel, using hydrogen bubble flow visualization techniques. Several inlet-ambient flow combinations were studied, including an inlet and ground plane configuration in a known shear as well as an irrotational flow, and a double (twin) inlet configuration in an irrotational flow. This latter situation created a boundary layer free analogue of the ground plane and enabled investigation of inlet vortex formation in flow essentially free of ambient vorticity. The three dimensional inlet flow field and the vortex formation mechanisms were determined by marking material lines and observing their path and deformation as they are convected from a far upstream location into the inlet.

Two basic mechanisms of inlet vortex generation were found. For flows possessing a vertical component of ambient vorticity, the amplification of this vorticity as the vortex lines are stretched and drawn into the inlet results in the formation of an inlet vortex. However, an inlet vortex does not require the presence of ambient vorticity to form. It can also be created in an irrotational flow, with an inlet in crosswind. In this situation, it is accompanied by a variation in circulation along the axial length of the inlet. The ratio of inlet velocity to upstream velocity is an important parameter in determining the generation of an inlet vortex for both mechanisms.
ACKNOWLEDGEMENTS

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The author is also grateful to all the members of the Gas Turbine Laboratory and to all her friends at M.I.T. for making the last two years an enjoyable experience that she well remember and treasure always.

Finally, the author would like to dedicate this thesis to her family, especially her parents, whose love and unending support were constantly felt across the miles.

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<tr>
<td>CW</td>
<td>Clockwise</td>
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<tr>
<td>CCW</td>
<td>Counterclockwise</td>
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<td>D</td>
<td>Inlet Inside Diameter</td>
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<tr>
<td>Dn</td>
<td>Hydraulic Diameter of Honeycomb</td>
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<td>d</td>
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<td>f</td>
<td>Friction Factor of Honeycomb</td>
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<td>g</td>
<td>Gravity</td>
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<td>H</td>
<td>Height of Inlet Centerline Above the Ground Plane</td>
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<td>h</td>
<td>Height of Cylindrical Control Volume in Appendix 4</td>
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<td>K_o</td>
<td>Flow Pressure Drop Coefficient</td>
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<td>L</td>
<td>Length of Honeycomb</td>
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<td>ℓ</td>
<td>Tunnel Height</td>
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<td>n</td>
<td>Unit Normal to a Surface</td>
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<td>p</td>
<td>Pressure</td>
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<td>p_D</td>
<td>Pressure Downstream of Honeycomb</td>
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<td>p_∞</td>
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<td>p(o,z)</td>
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<td>Re</td>
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<td>s</td>
<td>Surface Bounding the Volume, τ</td>
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<tr>
<td>s'</td>
<td>Surface Bounding the Volume, τ', Moving with the Fluid</td>
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<td>t</td>
<td>Time</td>
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<tr>
<td>U_i</td>
<td>Inlet Velocity</td>
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<td>U_∞</td>
<td>Free Stream Velocity</td>
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<td>U(Z)</td>
<td>Velocity Profile</td>
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<td>Symbol</td>
<td>Description</td>
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<tr>
<td>( \bar{V} )</td>
<td>Velocity Vector</td>
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<td>( V_x )</td>
<td>Velocity Component in the x Direction</td>
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<td>( V_y )</td>
<td>Velocity Component in the y Direction</td>
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<tr>
<td>( V_z )</td>
<td>Velocity Component in the z Direction</td>
</tr>
<tr>
<td>( V_{\theta} )</td>
<td>Velocity Component in the ( \theta ) Direction</td>
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<tr>
<td>( V_r )</td>
<td>Velocity Component in the r Direction</td>
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<td>( x )</td>
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<td>( y )</td>
<td>Transverse (Horizontal) Coordinate</td>
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The inlet vortex phenomenon has been of interest for some time in connection with gas turbine engine operation near a ground plane. In this situation, a strong vortex can form and be ingested into the engine inlet. The flow is often made visible "naturally" by water vapor condensing in the high-velocity and low-temperature center of the swirling region. In the past the phenomenon's notoriety was mainly due to its ability to lift and ingest foreign matter into the engine. Although the damage thus incurred can be significant, a more serious potential threat is that the vortex creates a compressor inlet velocity distortion that can induce compressor surge. Recently, the formation of inlet vortices has become of more concern due to the advent of wide-body aircraft with high bypass ratio engines, which possess larger diameter engines at a closer proximity to the ground. In these engines, the inlet vortex also can encompass a larger proportion of the primary air stream; therefore, its impact on the core compressor is more severe.

The inlet vortex produces a swirling flow which has a large amplitude, large extent, flow angle and velocity distortion, but often a small extent total pressure defect. Thus it cannot be predicted by present distortion analyses which are aimed at roughly uni-directional flow with total pressure defects which extend over a significant part of the circumference of the compressor. Previous studies have dealt with this phenomenon qualitatively. In particular, a basic explanation has not been given either for the mechanisms that generate the inlet vortex or for the predominant characteristics of the flow field. A detailed examination of this three-dimensional,
rotational flow field, especially in the region of the engine inlet, would therefore be useful in clarifying its salient features.

This thesis summarizes an experimental investigation of the fluid mechanics of the ground vortex. The experiments were conducted in a large water tunnel using hydrogen bubble flow visualization. Both steady flow and transient studies were carried out with a single inlet configuration (similar to the actual physical geometry of the situation), as well as with a double (twin) inlet configuration. The tests provided an understanding of the overall three dimensional inlet velocity field and of two basic mechanisms associated with the generation of an inlet vortex.

The single inlet was examined in a known shear flow as well as in an irrotational flow, the former being created by honeycomb of non-uniform length. For the shear flow, the convection downstream and ingestion of the vortex lines, which are material lines in the flows studied, could be observed using hydrogen bubbles, since a line of hydrogen bubbles is a good approximation to a material line. Two types of vortex lines were thus studied in detail: those initially parallel to the ground (i.e., horizontal) and normal to the mean flow far upstream, and those vertical and normal to the flow far upstream. For each case, the inlet was positioned at zero and ninety degrees of yaw and relative to the mean upstream flow; the latter case modelling a crosswind condition. In addition, the inlet was investigated at yaw angles of zero, ninety, and two hundred seventy degrees in an irrotational flow.

The double inlet configuration was examined in irrotational flow with inlet orientations to the mean flow of zero degrees, ninety degrees, and two hundred and seventy degrees. In this case, the ground plane was replaced by an
(inviscid) plane of symmetry between the two inlets. Although we will discuss the results in detail subsequently, we can note that the vortices that were obtained with this configuration preclude speculation that the ingestion of a ground boundary layer is necessary for their formation. In addition, these tests enabled the examination of inlet vortex generation with completely irrotational flow upstream of the inlet.

During the investigation, a previously undetected feature of the flow field around an inlet at ninety degrees to the mean upstream flow was revealed. This was a large vortex that trailed from the downstream side of the inlet. Associated with this trailing vortex was a marked change in the location of the separation points on the inlet as one moved from near the lip to regions far from the lip. This new feature was examined under both transient and steady flow conditions, and its relation to the inlet vortex formation was described.
CHAPTER 2

BACKGROUND

Many studies of the inlet vortex phenomenon have been conducted in the past. A detailed summary of the previous investigations can be found in reference (1), however, and we will therefore only discuss the main conclusions shown by these studies. There are several dominant characteristics of this phenomenon that are described. First, it is assumed that an inlet vortex can form only if ambient vorticity exists in the fluid drawn into the engine. (Ambient vorticity is defined here as vorticity existing at a far upstream location, where the flow is essentially unaffected by the presence of the inlet). Second, a stagnation point on the ground appears to be necessary. Third, the existence of the (thin) boundary layer due to the sink-like flow caused by the inlet is not believed to be vital. Fourth, the basic parameters that have been used to describe this phenomenon are $U_i/U_\infty$, the inlet velocity to wind velocity ratio, $H/D$, the center-line height to the inlet diameter ratio, the inlet velocity to the product of the wind velocity gradient and inlet diameter ratio (which is a rough measure of the ambient vorticity), and the wind direction. Fifth, a stagnation region forms on the ground plane under the inlet in near-static conditions; however, if the wind velocity is too high, this will be "blown away" and a vortex will not form.

In spite of the work that has been done on this topic, the basic features of the inlet flow and the mechanisms that generate it are still not completely understood. For example, if we accept the hypothesis that the formation of the inlet vortex is due to the intensification of ambient vorticity as it is
ingested into the inlet, the evolution of far upstream vortex lines into the inlet might appear as in Figure 1. This shows a sketch of an initially horizontal vortex line at three instants of time. Since vortex lines cannot end in the fluid, the two legs that are ingested should each possess equal and opposite circulation. However, only one vortex generally appears to have been observed in practice.

Some insight into the solution of this basic question is rendered by Viguier in reference (1). In this report, a secondary flow approach is used to study the phenomenon. The flow is assumed to consist of a weak shear flow and a mean irrotational primary flow, with the vortex lines associated with the former being regarded as convected by the latter. The amplification of the vorticity can be found by computing the stretching of the vortex lines. This is done by "tracking" two particles between a far upstream location, where the vorticity is known, and the engine inlet. For vortex lines initially (i.e. far upstream) vertical and perpendicular to the mean flow, Viguier found that the upper legs of the vortex lines are "fanned out" over the upper part of the inlet, while the lower legs are "squeezed" around the forward stagnation line. Thus, there is a region in the lower half of the inlet in which the circulation per unit area can become very high, which could be taken as an indication of possible vortex formation. The central concept is shown in Figure 2 which is taken from (1) and is for an engine with a headwind; i.e., oriented at zero degrees to the mean flow. The verification of these results and the location of the second vortex "leg" in crosswind are two prospective goals of the present investigation.

A second fundamental question deals with the possibility of an inlet vortex forming in irrotational flow; i.e., in the absence of ambient vorticity.
In anticipation of the experimental results to be subsequently discussed, we can mention that an inlet vortex can form in a uniform (far upstream) flow, contrary to what has been supposed. The mechanism of its formation, which appears not to have been recognized previously, is also explored in this study.
CHAPTER 3

DESCRIPTION OF THE FLOW FIELDS STUDIED

3.1 THE ACTUAL FLOW

The three dimensional flow field actually produced by a jet engine run near the ground is very complex. To investigate the overall phenomenon, this flow field is modelled in the experimental investigation as incompressible and steady, with negligible body forces. In addition, it is expected that viscous effects will not be significant over the major part of the volume of the flow field. Typically, the Reynolds number based on center-line height and approaching wind velocity is of the order of $10^6$, so the inviscid assumption is valid, at least in the flow upstream of the inlet. In order to assume incompressibility, the Mach number squared must be much less than one. This criterion is fulfilled in all regions of the actual ("real life") flow except near the inlet tip where the Mach number is near one. However, compressibility effects are still considered to be insignificant in the examination of this phenomenon, since the locally high Mach number would be expected to have little influence on the overall phenomenon.

Since both the actual flow and the investigated flow (see below) possess the above specifications, it is valid to use the experimental results to infer information about the actual flow. In addition, the details of the mechanism which produces the inflow through the inlet should not be critical to the process of vortex formation; therefore it is justifiable to carry out the investigation independent of the turbomachinery components.
3.2 THE INVESTIGATED FLOW

In this investigation, the ambient vorticity typically present in the vicinity of an outdoor engine test stand or airfield (i.e., the wind shear) is simulated in the water tunnel by using non-uniform honeycomb to create several shear profiles. The profile can have either vertical or horizontal components of vorticity. Normally, the vorticity found in wind shear is small in magnitude; therefore, it must be substantially amplified in the region of the engine for an inlet vortex to form. It is one objective of this study to obtain the three dimensional inlet flow field and the vortex formation mechanisms by determining the variation of this vorticity between a far upstream location and the engine inlet. Since material lines are vortex lines, the amplification or reduction of the vorticity is discerned by marking a material line with hydrogen bubbles and observing its path and deformation as it is convected downstream and ingested into the inlet. The path followed by the material lines gives insight into the inlet velocity field and its deformation indicates the strength of the vortex, since the magnitude of the vorticity is directly proportional to the length of the vortex line. The mechanisms of formation are deduced by comparing the above observations.

To determine the necessity of ambient vorticity in the formation of an inlet vortex, irrotational flow was investigated. In this case, there is no ambient vorticity present and there are no upstream vortex lines. However, material lines (time lines) can still be used to study the flow field around and inside the inlet.
CHAPTER 4

EXPERIMENTAL APPARATUS

4.1 WATER TUNNEL CONFIGURATIONS

4.1.1 G.T. & P.D. L. Small Water Channel

The M.I.T. Ocean Engineering Water Tunnel was used to carry out the main part of this experimental investigation. However, this facility is in high demand, so a smaller water channel was first constructed to facilitate the development of an appropriate flow visualization technique and shear profile generator. The principal design objectives of this small channel were the delivery of uniform flow at velocities up to 0.15 m/sec and a minimal construction time. This latter requirement was particularly responsible for the unorthodox design shown in Figure 3. The 3.2 mm hexagonal cell honeycomb, the 80 pores per inch polyurethane foam and the 33, 6.4 mm diameter, holes per inch stainless steel screen were all necessary to straighten the flow and suppress turbulence. Kraft paper treated with plastic was used for the honeycomb profile generator. The channel was constructed using 19 mm plexiglass and the piping is all Gauge 40 Polyvinyl Chloride (PVC). The flow in the channel is driven by a one and a half horsepower centrifugal pump and measured by a vertical flowmeter. More detailed information about the equipment can be found in Appendix 1.

It should be mentioned that prior to using honeycomb, the ability of stainless steel mesh screens, perforated plates, porous foam and straws to produce shear flows was investigated in the small channel. They were all found to be unsuitable, because they either failed to create the appropriate shear or induced turbulence and local flow non-uniformities in the downstream flow.
4.1.2 M.I.T. Ocean Engineering Water Tunnel

All of the flow visualization studies were carried out in the 6,000 gallon capacity M.I.T. Ocean Engineering Water Tunnel. A schematic of this facility is shown in Figure 4. The 1.5 m long, 0.5 m square test section is equipped with four interchangeable 0.038 m thick plexiglass windows. In this investigation, it was run with a free surface. The test section is preceded by a settling chamber and a contraction to reduce velocity non-uniformities and turbulence level in the tunnel. A honeycomb structure fabricated from 1,944 acrylic tubes, each with a diameter of 0.03 m and a length of 0.30 m is contained in the settling chamber. This structure is followed by three wire screens with 0.43 m diameter wires spaced 3.18 mm apart. The overall contraction ratio is 4.92:1.

Following the test section, there is a diffuser and a turning vane section; above this vaned section, a vacuum chamber is positioned. The large storage tank on the lower level of the tunnel permits the draining of the test section; it can be refilled in 3 to 4 minutes using a 350 gallon per minute pump. A 0.77 m I.D. impeller (located at the bottom right corner of the sketch of the tunnel shown in Figure 4) is connected through pulleys to the motor drive: a digital frequency counter connected to this impeller indirectly measures the tunnel velocity. More detailed information can be found in reference (2).

Additional piping was necessary to adapt this facility to the present investigation; however, the pump, flow meter, and flow filter are basically the same units used in the small water channel. A 0.05 m brass gate valve downstream of the flow meter is used to regulate the inlet flow. A 0.08 m high plexiglass "false bottom" was also inserted into the test section to
facilitate the observations of the vortex between the ground plane and the inlet.

4.2 INLET GEOMETRIES

The engine inlet is modeled in this investigation by a plexiglass pipe, with the suction provided by the centrifugal pump. Four different inlet configurations were studied in some detail: an inlet at zero degrees to the mean flow far upstream; an inlet at ninety degrees to the mean flow far upstream \(^{(3)}\), an inlet at two hundred seventy degrees to the mean flow far upstream and a double inlet configuration at ninety degrees to the mean flow. Thelets had inside diameters of 0.045 m, 0.051 m and 0.025 m, respectively. The convention followed in this is that if one looks from (far) upstream to downstream in the tunnel, zero degrees denotes an inlet pointing upstream. Ninety degrees indicates an inlet facing to the right and two hundred seventy degrees designates an inlet facing to the left. All the inlets are (platinum) wired for hydrogen bubble flow visualization, in order to determine the location of the vortex in the inlet. The wire is located 0.03 m downstream of the lip and is situated normal to the inlet axis. The rear of the zero degree inlet was constructed out of plexiglass, and the positioning of a mirror downstream of the inlet thus enabled the location and the sense of rotation of the vortex in the inlet to be detected. A sketch of the water tunnel test section with a zero degree inlet configuration in a boundary layer type shear is shown in Figure 5. Figure 5 also indicates the coordinate system that we will use to describe the results. The x coordinate is in the direction of the mean flow, the y coordinate is normal to mean flow and in the ground plane; i.e., the ground plane is the x-y plane, and the z coordinate is normal to the ground plane.
The ratio of the inlet centerline height from the ground plane, or symmetry plane, to the inlet diameter was held constant at approximately 1.4 for all four configurations. This is a number typical of the actual centerline height to diameter ratio of several high-bypass ratio gas turbine engines which are used on current wide body aircraft.

4.3 GENERATION OF SHEAR PROFILES

The generation of the shear flows used in the experiments was accomplished by using honeycomb of non-uniform lengths. These were designed according to the calculation procedures developed by Kotansky in (3). Details of this method are given in Appendix 2. Four different shear profiles were created; a boundary layer type flow, a jet type flow, a right to left windshear and a left to right windshear. The first profile was generated from 3.18 mm hexagonal cell honeycomb, while the remaining three shear profiles employed 4.76 mm hexagonal cell honeycomb. The velocity profiles can be seen in Figures 6a to d, respectively. In this Figure, the velocities are shown in dimensional form to indicate the representative actual range of velocities at which the hydrogen bubble technique was used. The vertical axis in the figures is the non-dimensional transverse (y) coordinate or the non-dimensional height above the ground plane (z) coordinate. It should be mentioned that the precise shapes of the velocity profiles were dependent on Reynolds number (based on honeycomb cell size and mean velocity); however, over the range of flows studied, this difference was not large and does not affect the general conclusions concerning mechanism that are given herein.

The first two velocity profiles have vortex lines that are parallel to the ground plane and normal to the mean flow, i.e., along the y axis, far upstream of the inlet. For the "boundary layer type" profile, the circulation
is clockwise when viewed from the ninety degree position (looking along the $y$ axis from negative to positive). For the jet type profile, therefore, the circulation is counterclockwise when viewed from the same vantage point. A further note on the jet profile is that since the flow satisfies the no slip condition, there was a thin viscous region with clockwise circulation below the region with counterclockwise circulation. However, the thickness of the former was approximately an order of magnitude smaller than the thickness of the latter.

The two velocity profiles shown in Figure 6c and 6d have vortex lines which are along the $z$ axis; i.e., perpendicular to the ground plane and to the mean flow direction.* These represent velocity gradients that might result from a wind which varied in magnitude from one location to another in the same horizontal plane. They will thus be referred to as the left-to-right and right-to-left shear, respectively. The circulation around the former is counterclockwise when viewed looking down on the tunnel (in the negative $z$ direction) and the latter has a clockwise circulation.

4.4 FLOW VISUALIZATION

Hydrogen bubble flow generation was determined to be the most appropriate flow visualization method for this application. In this investigation, a thin platinum wire was employed as the cathode of a DC circuit used to electrolyze the water. The current travelled from the wire through the water to an anode plate far downstream in the tunnel. Hydrogen ions are formed at the cathode.

* As previously mentioned, this cannot be true in the thin viscous groundplane boundary layer (4). However, we will use this nomenclature in discussing these particular velocity profiles.
These hydrogen ions combine to form hydrogen gas which is swept off the wire by hydrodynamic forces in the form of hydrogen bubbles. The diameter of these bubbles and their number are proportional to the diameter of the wire and the current, respectively. Since the flow around the bubbles is slow moving and steady, it can be described as a Stokes flow; therefore, a small diameter wire insures that the drag force on the bubbles is greater than the buoyancy force. Consequently, the majority of the hydrogen bubbles follow the flow and are good indicators of the local water velocity. A detailed discussion of this technique is presented in Appendix 3 with information provided by the following references: (5), (6), and (7).

The variable DC power supply was constructed using a variac, a transducer, an AC to DC rectifier, and electric circuit elements, as described in Appendix 3. It has the capability of delivering up to 300 volts either as a continuous voltage, or a pulsed voltage for a wide range of frequencies. Aside from the wires embedded in the inlet, three different wire probes were used to examine the flow: a 0.30 m high vertical probe normal to the upstream mean flow, a 0.23 m long horizontal probe parallel to the ground plane and normal to the upstream flow, and a smaller probe which could be inserted at various positions in the flow field. These all used 0.025 mm wire. Since the inlet velocity was much higher than the tunnel velocity, the wires used in the inlet were thicker and the bubbles consequently larger. However, no evidence was seen of any significant effects of buoyancy. The struts supporting the wires were formed from plexiglass and plastic. In the first two probes, the struts were streamlined to minimize their disturbance to the surrounding flow field.
The proper illumination of hydrogen bubbles is **critical** in observing and photographing them. In this experiment, suitable lighting was achieved by using two 0.28 m square Fresnel lenses, with 0.24 m focal length, and a tungsten halogen lamp. The two lenses were situated parallel to each other with the first lens directly above the area to be illuminated and the second lens a few centimeters above it. The lamp was located a focal length above the second lens.

The hydrogen bubble data was photographed and videotaped. The instantaneous photographs were taken using a Calumet 4 x 5 View Camera using Polaroid Type 57 film. The videotaped data required a videocamera, a videorecorder, a videoprojector, and a power source.
Prior to starting a series of runs, the M.I.T. Ocean Engineering Water Tunnel was deaerated for several hours. Then the tunnel velocity and the inlet velocity were set to the desired reading. Since each honeycomb shape had a different resistance, the velocity was calibrated separately for each screen. This was accomplished by taking photographs of streamlines pulsed at a selected frequency for a wide range of tunnel frequency counter readings. Photographing a known length relates the image distance to the actual distance by a constant; therefore, the velocity can easily be deduced from the photographs, since the time is given by the pulsing rate.

The flow around the single inlet was investigated with all three probes for each of the four shear profiles at zero degrees and ninety degrees of yaw. In addition to the above two orientations, the single inlet and double inlet were also studied at two hundred seventy degrees of yaw in irrotational flow. The transient conditions involved in the inlet vortex start up and cessation, for the single inlet and double inlet configurations oriented at ninety degrees to the mean upstream flow, were examined by decreasing the tunnel velocity while keeping the inlet velocity constant at 1.2m/s, as well as by keeping the tunnel velocity constant at 0.08m/s and decreasing the inlet velocity until the vortex disappeared.
CHAPTER 6

EXPERIMENTAL OBSERVATIONS

As stated, flow visualization experiments were conducted with several inlet-ambient flow combinations. In this section, we will merely describe the experimental observations. The next section will then present a discussion and interpretation of these observations. It should be stressed that this investigation was not a parametric study. The objective was to examine a vortex typical of those actually observed at the (representative) centerline height to diameter ratio of approximately 1.4 and to determine the important features of the flow and the vortex generating mechanisms.

The tests included both steady flow and (start-up and stop) transient studies with an inlet-ground plane configuration, similar to the geometry of the actual situation, as well as with a double inlet configuration. This latter was located in the center of the water tunnel far from the ground plane. In the double inlet tests, there was a plane of symmetry between the inlets; i.e., one inlet could be viewed as the "image" of the other. Essentially, an inviscid (boundary layer free) analogue of the ground plane was established. This enabled us to investigate the inlet vortex formation with (nominally) no ambient vorticity upstream of the inlet. The double inlet studies were conducted with irrotational flow only; however, the single inlet studies were carried out with a known shear, as well as with irrotational flow. The upstream velocity profiles that were used included cases with horizontal vortex as well as vertical vortex lines.
The overall matrix of experiments that were conducted was as follows:

**Single Inlet:**

<table>
<thead>
<tr>
<th>Yaw</th>
<th>Flow</th>
<th>Time Dependence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero degrees</td>
<td>Irrotational flow</td>
<td>steady</td>
</tr>
<tr>
<td></td>
<td>horizontal vortex lines</td>
<td>steady</td>
</tr>
<tr>
<td></td>
<td>(boundary layer - CW*)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>vertical vortex lines</td>
<td>steady</td>
</tr>
<tr>
<td></td>
<td>(right-left windshear-CW**)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>vertical vortex lines</td>
<td>steady</td>
</tr>
<tr>
<td></td>
<td>(left-right windshear-CCW**)</td>
<td></td>
</tr>
</tbody>
</table>

| Ninety degrees       | irrotational flow                         | steady & transient |
|                      | horizontal vortex lines                   | steady          |
|                      | (boundary layer-CW*)                      |                 |
|                      | horizontal vortex lines                   | steady          |
|                      | (jet-CCW*)                                |                 |
|                      | vertical vortex lines                     | steady          |
|                      | (right-left windshear-CW**)               |                 |
|                      | vertical vortex lines                     | steady          |
|                      | (left-right windshear-CCW**)              |                 |

| Two Hundred Seventy degrees | irrotational flow | steady |

**Double Inlet:**

| Ninety degrees       | Irrotational flow | steady & transient |
|                      |                  |                   |

| Two Hundred Seventy degrees | Irrotational flow | steady |

---

* Sense of circulation as observed looking at ninety degrees to x-z plane (along y-axis from negative to positive).

** Sense of circulation as observed looking down on the tunnel (along z-axis from positive to negative).
Although it may seem to be in reverse order, we will describe the results with the shear first, since the mechanism of vortex formation in this situation is most readily understood based on the calculations reported in Reference (1). The results from the examination of a single inlet in irrotational flow will then be discussed. It is in this situation that the new mechanism referred to earlier was made apparent. Finally, the results with the double inlet will be mentioned since they are helpful in understanding this latter mechanism of inlet vortex formation.

6.1 SINGLE INLET IN SHEAR FLOW AT ZERO DEGREES OF YAW

6.1.1 Boundary Layer Type Profile

In this case and the other cases with a known shear flow, the ingestion of ambient vorticity can be directly studied since (outside of the viscous vortex core and the thin ground plane and inlet boundary layers) vortex lines are material lines. A line of hydrogen bubbles is to a very good approximation a material line; thus, the hydrogen bubble lines give the position of vortex lines as they are convected into the inlet. One is therefore able to speak with a reasonable degree of confidence about the kinematics of the vortex lines associated with the ambient vorticity.

A vortex filament in a ground plane boundary layer type velocity profile is initially horizontal, parallel to the ground plane, perpendicular to the mean flow, and possesses clockwise rotation when viewed at ninety degrees from the x-z plane (looking along y axis from negative to positive). Its ingestion by an inlet at zero degrees to the mean flow is illustrated in Figure 7. This is a drawing of the actual phenomenon from videotapes and observations of the hydrogen bubble marked material lines. There is a symmetrical pattern formed by the vortex lines about the vertical centerline
of the inlet; the central portion of this line is ingested prior to the two "ends" which enter the inlet for the line chosen at roughly 0.9 inlet centerline heights. In the front view, only one solid line is shown because at this location there was very little vertical movement. Photographs of this behavior for three successive time intervals are presented in Figure 8a, 8b, and 8c, respectively.

Figure 9 is a view of the above flow as observed in a mirror located downstream of the inlet for a vortex line originating at roughly 0.9 inlet centerline heights. The sense of the vortex rotation is in the direction that one would observe looking into the inlet from an upstream location; i.e., viewed along x-axis from negative to positive. This occurs because there are two left-right inversions, one due to the photograph being taken from the downstream end of the inlet and the second due to the mirror. The position of a vortex in the inlet can be described conveniently by referring to the inlet area perpendicular to the flow in terms of a clock face. Thus, using this nomenclature, the two vortices visible in Figure 9 are located at 5:30 and 6:30; the rotation exhibited by the two vortices appears equal and opposite, with the former turning clockwise and the latter counterclockwise when viewed looking into the inlet. At the ratio of inlet velocity to free stream velocity (~8) pictured, this behavior is true for vortex lines approximately 0.5 inlet centerline heights or lower; if they originate at a greater height, the vortex lines proceed straight into the inlet without any appreciable rotation. The velocity ratios used in this study were selected by examining the inlet vortex over a wide range of velocity ratios and selecting one that resulted in a strong steady vortex for geometric configurations typical of current wide body aircraft; i.e., H/D ~ 1.4.
6.1.2 "Left-to-Right Windshear" Profile

The vortex lines associated with the shear in this case are initially vertical, perpendicular to the ground plane, normal to the mean flow and possess a counterclockwise rotation when viewed looking down on the tunnel (along the z axis from positive to negative). Figure 10 shows the inlet vortex location for the zero degree inlet configuration. It indicates that a single vortex is present in the inlet at approximately 6:00 and at 0.8 inlet centerline heights. When looking down on the tunnel, the vortex leg directly in front of the inlet reveals a large counterclockwise spiraling vortex extending between the ground plane and the inlet with the diameter of the spiral diminishing as it moves toward the inlet; a photograph of this flow is shown in Figure 11. In the center of the spiral, a hydrogen bubble marked thread of fluid particles moves vertically up and into the inlet. The sense of the rotation of the vortex is clockwise when viewed looking into the inlet from upstream.

Further investigation of the flow indicated that at the velocity ratio studied, the inlet's influence was felt at roughly 2.5 inlet centerline heights above the ground plane, 1.5 inlet centerline heights to either side of the vertical centerline, and 1 inlet centerline height in front of the inlet face. In this examination, the inlet was situated directly in the center of the tunnel; however, shifting the inlet's position while keeping its alignment constant did not produce any distinguishable deviation in the vortex position or rotation.

6.1.3 'Right-to-Left Windshear' Profile

The circulation around the vertical vortex lines associated with this shear profile was clockwise when viewed from the top of the tunnel. The features detected for the zero degree inlet configuration were very similar
to those observed in the previous case, except, of course, for the sense of the vortex rotation. Both profiles possessed a single strong vortex as the same inlet position and centerline height. However, the rotation perceived in the present case was counterclockwise looking into the inlet from upstream.

6.2 SINGLE INLET IN SHEAR FLOW WITH NINETY DEGREES OF YAW

6.2.1 Boundary Layer Type Flow

Some of the features described for a boundary layer type flow drawn into an inlet at zero degrees to the mean upstream flow are also observed for the ingestion of the same type of flow into an inlet oriented at ninety degrees to the upstream flow. The behavior of the latter is depicted in Figure 12 for a horizontal vortex line originating at roughly 0.9 inlet centerline heights above the ground plane. A central section is again drawn into the inlet first with the two "ends" entering at a later time, and the vortices enter the inlet at the same height and position with a consistent sense of rotation. However, the flow pattern is asymmetrical and the two vortices do not appear to be equal in strength. The clockwise vortex, as viewed looking into the inlet, encompasses a larger proportion of the inlet area and appears to rotate faster; the clockwise leg of the vortex line also swings out in front of the inlet prior to being ingested while the counterclockwise leg follows the outside contour of the cylinder until it is drawn into the inlet. As vortex lines from different initial heights are examined, additional insight concerning the flow beneath and in front of the inlet can be discerned. Figure 13 illustrates the path taken by a horizontal vortex line initially at 0.1 inlet heights above the ground plane. The counterclockwise leg appears to stem from the separation region located underneath the inlet.
and 0.8 to 0.9 inlet centerline heights from the inlet lip. It remains at the same height and moves horizontally towards the inlet lip where it is drawn vertically up and into the inlet at the 6:30 location. Simultaneously, the clockwise vortex leg reveals a large clockwise spiraling flow extending between the ground plane and the inlet. At the velocity ratio investigated (~ 8) the clockwise spiral encircles the counterclockwise vortex leg if the vortex line originates at .6 inlet centerline heights above the ground plane or lower.

6.2.2 Jet Type Profile

The jet profile consisted of a strong shear layer. It required substantially higher ratios of inlet velocity to free stream velocity (~ 40) for a vortex to form than with the boundary layer type profile. Consequently, the usefulness of the flow visualization probes was limited, and only a small amount of data was obtained. The vortex lines in the jet type flow are horizontal, with the circulation around a vortex line in the counterclockwise direction when viewed at ninety degrees from the x-z plane. In actuality, a thin ground plane boundary layer also existed with the jet shear. However, the height of the former was negligible (roughly 5%) relative to the thickness of the latter.

6.2.3 'Left-to-Right Windshear'

Changing the inlet orientation from zero to ninety degrees with the mean flow for this shear profile did not alter the position or rotation of the vortex in the inlet; therefore, the observations for both inlet orientations were quite similar.
6.2.4 'Right-to-Left Windshear' Profile

When the ninety degree inlet configuration was investigated in a shear profile with vertical vortex lines possessing clockwise rotation when viewed looking down on the tunnel, a clockwise (looking into the inlet) rotating vortex was observed, as shown in Figure 14. It was located in the inlet at approximately 6:00 and roughly 0.7 centerline heights above the ground plane.

6.3 SINGLE INLET IN IRROTATIONAL FLOW

The presence of the clockwise rotation bias exhibited in the ninety degree inlet configuration motivated investigating the inlets in an irrotational flow.* There is no ambient vorticity present and consequently there are no upstream vortex lines. The investigation is thus confined to studying the flow field around and inside the inlet.

6.3.1 Single Inlet in Irrotational Flow at Zero Degrees of Yaw

For an inlet at zero degrees to the uniform upstream flow, two small equal symmetric and counterrotating vortices are observed looking into the inlet. This showed that the flow in the tunnel was quite symmetric with negligible vertical vorticity.

6.3.2 Single Inlet in Steady Irrotational Flow at Ninety Degrees of Yaw

A strong steady inlet vortex at 6:00 was observed for an inlet oriented at ninety degrees to the mean flow. The vortex exhibited a clockwise rotation when viewed looking into the inlet. Further investigation of this configuration revealed a previously undetected feature of the flow field surround-

*Except, of course, for the thin boundary layers on tunnel and inlet walls.
ing the inlet. This was a trailing vortex which was shed from the downstream side of the inlet as illustrated in Figure 15. Relative to the small and concentrated inlet vortex, the trailing vortex was much larger with a diameter of the vortical part of the swirl of approximately 0.9 inlet diameters. It had a clockwise rotation when viewed from the upstream section of the tunnel (along the x axis from negative to positive). The vortex lines and the material lines associated with this flow are depicted in Figures 16 and 17, respectively. The dashed lines on Figure 17 indicate the part of the trailing vortex not directly visible. This trailing vorticity was associated with a movement in the separation points of the flow from the inlet's surface. Figure 18 illustrates this variation of the separation points along the length of the inlet. In the rear of the inlet; i.e., far from the lip along the inlet axis, the flow separated at approximately 12:00 and 6:00 from the inlet. This rough symmetric separation implies near zero circulation as expected for two-dimensional flow over a cylinder near a ground plane at the present H/D value (8). Proceeding along the inlet axis towards the inlet lip revealed the development of assymmetric flow separation. In addition, the velocities appeared to be substantially higher at the lip than in the rear. Both of these conditions thus indicate a significant circulation round the inlet near the lip. At this location, the hydrogen bubbles show the flow separation occurring at 4:00 and 6:00 as illustrated in the sketch of the material lines for the ninety degree inlet configuration in irrotational flow, Figure 17.

6.3.3 Single Inlet in Steady Irrotational Flow at Two Hundred Seventy Degrees of Yaw

The inlet was also oriented at two hundred seventy degrees to the mean flow. A steady strong vortex, exhibiting counterclockwise rotation when
viewed looking into the inlet was found at approximately 6:00. This was similar to the ninety degree case.

6.3.4 Single Inlet in Transient Irrotational Flow at Ninety Degrees of Yaw

Presumably, the asymmetric separation of the flow is due to an interaction between the ground plane and the inlet lip which creates the inherently three-dimensional flow over the inlet. To understand the development of this feature, the inlet vortex and trailing vortex formation were examined during a (slow) transient test of the ninety degree inlet configuration in irrotational flow. Initially, the tunnel velocity was very high; therefore, there was no stagnation point on the ground and the flow symmetrically separated from the inlet lip at roughly 2:30 and 3:30. Consequently, a vortex did not form. Holding the inlet velocity constant and decreasing the tunnel speed resulted in the flow separation points shifting to 4:00 and 6:00. This clockwise shifting of the separation points as the tunnel velocity decreased was accompanied by the formation of a trailing vortex. Figures 19a to 19d photographically represent this successive shifting in position of the separation point at the inlet lip during the transient response. The flow beneath the inlet cannot be seen in the above figures due to the difficulty in simultaneously lighting the regions above and below the inlet; however, the inlet vortex position is revealed by the inlet flow visualization wires and is shown in Figure 20. The above succession of events was also observed during the transient response of the system to a change in pump speed while holding the tunnel velocity constant.
The transient response of the system therefore displayed the movement of the inlet lip separation points, as well as the formation of the inlet vortex and the trailing vortex.

6.4 DOUBLE INLET CONFIGURATION IN IRROTATIONAL FLOW

In this arrangement, the ground plane was "replaced" by a symmetry plane between the two inlets with a centerline height to diameter ratio for each of the two inlets of approximately 1.4. The absence of the viscous ground plane boundary layer allows us to study the inlet vortex formation with no ambient vorticity upstream of the inlet.

6.4.1 Double Inlet Configuration in Steady Irrotational Flow at Ninety Degrees of Yaw

The investigation of this flow field revealed a steady strong vortex core stretching between the two inlets with a clockwise rotation as viewed looking down on the tunnel. A trailing vortex was also shed from each of the inlets. The configuration is thus drawn in Figure 21, which shows the streamlines for this case. Figure 22 depicts the location of the vortex lines associated with this inlet arrangement which when taken as a unit resembles a horseshoe vortex. The material lines connected with this inlet configuration are sketched in Figure 23 and photographed in Figure 24. The inlet vortex enters the top and bottom inlets at approximately 6:00 and 12:00 with clockwise and counterclockwise rotation when viewed looking into the inlets, respectively. The center of the core was often apparent due to cavitation along its length.
6.4.2 Double Inlet Configuration in Steady Irrotational Flow at Two Hundred Seventy Degrees of Yaw

As in the single inlet configuration, this orientation was again used to check for the presence of any asymmetry. The flow examination yielded the same features observed in the previous arrangement, but the sense of rotation of the vortices was again reversed, indicating the absence of any significant asymmetry; for example, any appreciable component of ambient vertical vorticity.

6.4.3 Double Inlet Configuration in Transient Irrotational Flow at Ninety Degrees of Yaw

A fundamental question still remains unanswered for the (inviscid) double inlet orientation. Namely, where does the vorticity in the core come from? The transient case was investigated to resolve this question.

It was found that the inlet vortex initially formed during the transient process associated with start-up of the pump; i.e., with a sudden increase in $U_1/U_\infty$ from zero to the large value associated with inlet vortex formation. It originated in between and slightly downstream of the two inlets; therefore, it is initially fed by the fluid in that region. As the vortex formed and became stable it moved to the location in front of the inlets illustrated in Figure 25. Once formed, the vortex was no longer fed by the downstream flow. In contrast to the single inlet case, a time delay on the order of ten convection length time scales; i.e., $\sim 0(10H/U_\infty)$, was associated with its formation. When the inlet flow (the pump) was stopped, the vortex detached from the inlets and burst in the region immediately downstream of the inlet.
CHAPTER 7

RESULTS

The central results of the flow visualization studies are summarized in Table 1. Although this table cannot include all the information about the various cases, it will provide a convenient framework from which to discuss them. As in the previous section, we will discuss the results with ambient shear first, and then compare these with the theoretical calculations of Viguier.

7.1 SINGLE INLET IN SHEAR FLOW AT ZERO DEGREES OF YAW

7.1.1 Boundary Layer Type Profile

As noted previously, a horizontal vortex line initially exhibiting clockwise rotation gave rise to two symmetrically located counterrotating vortices when ingested into an inlet oriented at zero degrees to the far upstream flow. This is readily understood from considerations of flow symmetry and solenoidality of the vorticity field and will not be further discussed, except to again note that it gives a good indication of the overall symmetry of the tunnel flow.

7.1.2 'Left to Right' Windshear

The behavior of vertical vortex lines ingested into an inlet at zero degrees to the far upstream flow was computed by Viguier in reference (1), and his method is summarized in the background section of this report. Since vortex lines cannot be cut, the ingestion of a central section of a vortex line indicates that two vortex legs must extend out of the inlet. Viguier (1)
found that the upper legs of these vortex lines that were ingested into the inlet were "fanned out" over the upper part of the inlet while the lower legs were squeezed around the streamline which ran from the ground plane stagnation point into the front of the inlet. This implies a locally high level of circulation per unit area in the latter region which strongly suggests the formation of an inlet vortex. As denoted in Table 1, the experimental observation for this case is in agreement with Viguier's calculation for the lower leg. The vertical vortex lines are convected downstream, and they form a localized vorticity concentration in the lower half of the engine face plane, due to the flow field associated with this inlet. Note that when looking down on the tunnel, the vortex lines exhibit counterclockwise rotation; however, the vertical vortex lines are bent ninety degrees to enter the lower half of the inlet. Hence, the sense of their rotation is clockwise when one looks into the inlet. Similarly, vertical vortex lines possessing clockwise circulation when viewed looking down on the tunnel will give rise to a counterclockwise rotating vortex, as seen looking into the inlet from upstream. The "fanning out" of the upper region of the vortex leg could not be observed within the constraints of the present experimental program. This amplification of the upstream ambient vorticity as the vertical vertical vortex lines are stretched is one basic method of vortex formation.

7.1.3 'Right to Left' Windshear

As in the previous case, the ingestion of the vertical vortex lines associated with this profile produced an inlet vortex exhibiting the opposite sense of rotation when viewed looking into the inlet as the vortex lines when observed looking down on the tunnel; i.e., the rotation was reversed from
case 7.1.2. This result therefore also supports Viguier's conclusion and gives added justification to considering the amplification of the upstream ambient vertical vorticity as one mechanism of vortex formation.

7.2 SINGLE INLET IN SHEAR FLOW WITH NINETY DEGREES OF YAW

7.2.1 Boundary Layer Type Flow

Based on Viguier's calculations, it would be expected that the ingestion of horizontal vortex lines into a ninety degree oriented inlet would result in two asymmetrically placed counterrotating vortices. Therefore, in contrast to the results discussed in 7.1.2 and 7.1.3, no predominant single concentration of vorticity was predicted. Within the context of this secondary flow analysis, the circulation around the two legs will be of the same magnitude even though the vorticity is not necessarily equal. The vortices observed were in fact not equal in strength; the clockwise vortex encompassed a larger area and had a faster rotation rate. In addition, the overall flow field outside the inlet was dominated by this vortex. Consequently, it is clear that the qualitative picture provided by Viguier does not fully describe the flow. There are features other than just the stretching of ambient vorticity which must be explained.

7.2.2 Jet Type Profile

The investigation of horizontal vortex lines initially possessing counterclockwise rotation revealed a single strong clockwise rotating vortex, as observed looking into the inlet. As mentioned previously, the second vortex can be quite hard to find. However, if the only mechanism were the amplification of ambient vorticity, one might expect a counterclockwise rotation. This is therefore an indication that a clockwise "bias" is
associated with this phenomenon when the inlet is oriented at ninety degrees to the mean flow.

7.2.3 'Left to Right' Windshear

For an inlet oriented at ninety degrees to the mean upstream flow, the flow with vertical vortex lines initially exhibiting counterclockwise rotation (when viewed looking down on the tunnel) resulted in a single clockwise vortex inside the inlet. This observation was expected, as per the discussion in section 7.1.2.

7.2.4 'Right to Left' Windshear

With far upstream vertical vortex lines having clockwise rotation (when viewed looking on the tunnel), a single clockwise vortex formed inside the inlet. The rotation sense of the vortex is opposite to the sense of the ambient vorticity since the vortex lines must bend ninety degrees to enter the inlet, and they should therefore exhibit counterclockwise rotation. This is another indication of a strong clockwise bias in the phenomenon, which dominates the mechanism associated with stretching and intensification of far upstream vorticity. (It was possible that there are smaller and weaker vortices in the inlet of opposite sign; however, with the present experiment we could not detect them.)

7.3 SINGLE INLET IN IRROTATIONAL FLOW

The clockwise rotational bias seen in the investigation of the ninety degree inlet configuration prompted the examination of the inlet flow field with initially uniform flow far upstream. This irrotational flow study was undertaken to see whether the clockwise inclination was created by either the tunnel flow or the geometry and was carried out by running the tunnel
with no added resistances. The upstream flow was thus uniform aside from the thin (displacement thickness estimated to be approximately 5mm) boundary layers on the walls of the tunnel. The flow outside of the boundary layers was quite uniform and did not possess a detectable swirl.

7.3.1 Single Inlet at Zero Degrees of Yaw

A rotational upstream flow resulted in an inlet vortex rotating in a direction opposite to that predicted from basic ambient vortex stretching arguments (7.2.4). Thus, another mechanism independent of ambient shear, and therefore observable in a uniform flow, must be operating. To dispel any supposition that this 'other mechanism' is due to some gross asymmetry in the flow, a test was run with a single inlet at zero degrees of yaw in irrotational flow. When the above configuration was examined, two small equal and counterrotating vortices were found in the inlet. The ambient shear used in the previous cases was reasonably strong; hence, a large readily visible departure from uniformity is essential to obtain the strong bias that was experimentally observed. In other words, we were not looking for a small effect and this test indicates that the clockwise bias is not due to any geometric asymmetry of the tunnel. Consequently, an inherent asymmetry must be present in the flow around the inlet.

7.3.2 Single Inlet at Ninety Degrees of Yaw

For inlet to free stream velocity ratios greater than 10, a strong steady clockwise vortex was observed when viewed looking into the inlet. This indicates the presence of vorticity in the flow, at least in the vortex core. However, no conclusions concerning the mechanism of the formation of this vortex can be formulated without additional information.
A further investigation of the flow for this configuration was therefore conducted. It revealed the presence of a trailing vortex downstream of the inlet in addition to the inlet vortex. This should be expected since there is no mechanism in the flow to create an appreciable circulation round the inlet at a location far from the inlet lip. At this 'far field' location, the flow may be approximated by a two dimensional flow about a cylinder-ground plane configuration with the cylinder axis positioned perpendicular to the free stream velocity. In this case, as described by Bearman and Zdravkovich (8), the pressure distributions around the cylinder are fairly symmetric at the H/D investigated, and hence the net circulation is small. Thus, the circulation around the inlet at an axial location far from the inlet is also expected to be small. If only a single vortex were associated with the inlet, however, a large net circulation would exist at any axial station along the length of the inlet. This condition is thus incompatible with the preceding description of the flow around the inlet at locations far from the lip; consequently, an inlet with only a single vortex is not possible. The circulation must therefore increase as one examines stations closer to the lip, as shown in Figure 26. In this figure, the circulation 'far away' from the inlet lip is near zero. The circulation round a contour outside the lip which includes the inlet vortex is not zero; it is probably close to the circulation around the inlet vortex. Therefore, there must be trailing vorticity between these contours as indicated in the Figure. An analogous (converse) example of circulation changing with spanwise position is the finite wing problem. In the present case, however, the circulation has a large value around the "tip" of the inlet and is approximately zero away from the tip.
This change in circulation was observed using the flow visualization technique to examine the separation points of the flow from the inlet surface. A symmetric (top and bottom) separation and streamline pattern indicates a near zero circulation. The observed circulation was small at axial distances more than a diameter from the inlet lip; however, a pronounced clockwise circulation was evident at the inlet lip, as illustrated in Figures 19a and 19b, respectively. Presumably, the asymmetric flow separation and thus the clockwise circulation, is due to the non-symmetric pressure field resulting from the ground plane and cylinder interaction when there is a large ratio of inlet to far upstream velocity. However, whatever the detailed mechanism, it is clear that the variation of circulation with axial distance along the inlet length is directly linked to the generation of the trailing vortex system, and is a heretofore undescribed method of inlet vortex formation.

7.3.5 Single Inlet in Transient Irrotational Flow at Ninety Degrees of Yaw

In order to obtain further insight into the overall mechanism, it was suggested by Marble (9) that the successive states encountered during a transient; i.e., a change in \( U_1/U_\infty \), be investigated. The response of the ninety degree inlet configuration in irrotational flow to a transient variation in \( U_1/U_\infty \) displayed a movement of the separation point at the inlet tip and the formation of the trailing vortex system. At low values of \( U_1/U_\infty \), the flow at the inlet lip does not "feel" the presence of the ground; i.e., the capture streamlines do not hit the ground. The flow around the inlet is roughly symmetrical and the circulation is essentially zero. Consequently, no vortices form. As \( U_1/U_\infty \) is increased, an interaction between the ground plane and the inlet occurs which results in an asymmetric pressure field. Thus, a
non-symmetric flow separation at the inlet lip and a consequent circulation round the inlet are created. The transient response of the system displayed the movement of the inlet lip's separation point, as well as the formation of the inlet vortex and the trailing vortex. These three features are all interrelated and are regulated by the inlet velocity to tunnel velocity ratio, $U_1/U_\infty$. For low $U_1/U_\infty$ there were no vortices but as this velocity ratio increased the vortices appeared and became stronger.

7.4 DOUBLE INLET CONFIGURATION IN IRROTATIONAL FLOW

Once the inlet vortex in the preceding cases is formed, it is fed by the vorticity in the ground plane boundary layer. (In other words, vorticity is continuously convected along the axis of the vortex into the inlet, and one "source" for this vorticity can be the ground plane boundary layer (11). The major part of the flow field does not seem however to be significantly influenced by any viscous effects. In order to investigate the dependence of the vortex formation on the existence of a viscous boundary layer, a double inlet configuration was examined.

7.4.1 Double Inlet Configuration in Steady Irrotational Flow at Ninety Degrees of Yaw

The presence of the inlet vortex (and consequent trailing vortex systems) shown in Figures 21 to 24 for this essentially vorticity free upstream flow indicates that neither the ground plane nor ambient vorticity are essential for vortex formation. As in the single inlet situation, the hydrogen bubbles observation again show the circulation around the inlet varying with axial distance from the inlet lip. Note that the vortex core stretched between the two inlets and there was no feeding of this core (with vortical fluid) from the
region downstream of it. However, since there is a continuous convection of vorticity into the inlets, a question of interest is: what is the source of the vorticity in the core; i.e., how is the vortex maintained?

7.4.2 Double Inlet Configuration in Transient Irrotational Flow at Ninety Degrees of Yaw

In order to better understand the new mechanism and to determine the source of the vorticity present in the core, the double inlet configuration was investigated under transient conditions. This consisted of simply turning the pump on or off. In both these cases the final value of pump flow was established in approximately a second which is comparable with but somewhat longer than $H/U_\infty$, the time scale for convection past the neighborhood of the inlet with the free stream velocity of $U_\infty$. For the double inlets, $H/U_\infty$ is approximately $1/2 - 1$ second depending on the precise conditions.

Studies showed that the vortex was in fact formed during the (pump) start-up process and that it reached a steady-state in a time on the order of ten $H/U_\infty$. In this configuration there is no ambient vorticity and no ground boundary layer. Since the vorticity must be generated by viscous effects, and the only region in which viscous effects are important are in the boundary layers on the inlet surface, the vorticity must come from this area during the start-up process. The large time needed to form the vortex is probably due to the time required for the slow moving fluid in the inlet surface boundary layer to be shed into the cylinder wake and then convected back upstream.

It is important to note that once formed there is no further flux of vorticity into the core from the surrounding fluid. The convection of vorticity out of the region between the inlets (and into the inlets) must therefore be balanced by a production of vorticity in this region. This production can
only be due to the straining of the vortex filaments in the core.

This process can be looked at in several ways. From a local standpoint, it can be regarded as a balance between the effects of viscosity which tends to diffuse the vorticity and the convective effects which tend to inhibit the growth of the regions of rotational flow. For a steady state to exist the two must be in balance. It is also useful to examine the process from a more global viewpoint. Consider a cylindrical control volume, $\tau$, surrounding the inlet vortex as shown in Figure 27. An expression for the rate of change of vorticity within this fixed control volume, $\tau$, is given in Appendix 4 (10). This is

$$\frac{\partial}{\partial t} \int_{\tau} \vec{\omega} \, dt = \int_{\tau} (\vec{\omega} \cdot \nabla) \vec{V} \, dt - \int_{S} (\hat{n} \cdot \vec{V}) \omega ds - \nu \int_{S} \hat{n} x (\nabla \times \omega) ds$$

where $s$ is the surface bounding $\tau$ and $\hat{n}$ is the normal to $s$. The three terms on the right hand side represent (I) the production of vorticity within the fixed volume, (II) the convection of vorticity out of the volume, and (III) the diffusion of vorticity out of the volume. If we take the radius of the control volume to be large enough so that viscous effects are negligible on the curved sides, there is a balance between the convection out through the top and bottom surfaces, the diffusion across these surfaces and the production within the volume for a steady state. This balance is made more explicit in the Appendix where this expression is applied to the case of an infinite vortex strained along its axis (which is an exact solution of the Navier-Stokes solution) and the different terms can easily be written down.
To summarize the content of the preceding several paragraphs: the vorticity in the core of the vortices is produced initially by the action of viscosity which has its source in the boundary layers on the outer surfaces of the inlet. Once the vortex is formed, however, there is no longer any vorticity convected into it; the vorticity needed to maintain it is produced by the extension of the (already existing) vortex filaments in the core. These experiments thus show clearly that ambient vorticity is not necessary for the formation of an inlet vortex.
In the preceding we have presented two different mechanisms for inlet vortex formation. The first of these, the intensification of ambient (vertical) vorticity is essentially an inviscid phenomenon, with the role of viscosity being primarily to limit the vorticity amplification to the high rates of stretching. It thus appears that many of the features of this type of flow can be predicted using an inviscid calculation procedure, perhaps coupled with an approximate description of the effects of viscosity.

In the second mechanism the appearance of an inlet vortex is linked directly to the variation in circulation along the length of the inlet. Viscous effects are much more central in creating this type of flow since the circulation distribution round the inlet is determined by the separation of the three-dimensional boundary layers on the outer surface of the inlet.

In most practical inlets there are no salient edges which set these separation points (as there are in flow past a wing, flat plate, etc., at an angle of attack). Finding the circulation thus involves a calculation of the three-dimensional pressure field round the inlet, as well as of the locations of the boundary layer separation lines. This is complicated since, in the situation of interest there will be a strong interaction between the viscous and inviscid parts of the flow field.

Although carrying out this type of calculation is beyond the scope of this study, some general comments can be made which address the questions raised in the section on experiment design. First, the experiments were carried out as cylinder Reynolds numbers, based on mean tunnel velocity and inlet outer dia-
meter, of 6000 or less. Consequently, the flow round the inlets can be taken to be subcritical (this is also indicated by the location of the separation points near 12:00 and 6:00 in regions far from the lip). For an actual wide-bodied aircraft engine inlet in cross wind the Reynolds number, based on a wind velocity of 4m/s and an inlet outer diameter of 3m, is $8 \times 10^5$, which puts it above the value for transition to the supercritical regime (based on a two-dimensional single cylinder). In this regime the upper and lower separation points are closer together than in the subcritical regime. The potential for movement of these points, and hence changes in circulation may thus be less for the actual inlets than in our experiments.

Second, based on the ideas about the two mechanisms, we can attempt to reconcile the various observations that have been made. It should be clear that for the inlets at zero yaw it is the first mechanism, the amplification of ambient vertical vorticity, that is responsible for the inlet vortex. For the inlets in an irrotational cross wind; i.e., at ninety or two hundred seventy degrees in irrotational flow on the other hand, it is only the second mechanism, the axial variation of circulation round the inlets, which is relevant. For those cross wind experiments with a shear, however, both mechanisms are interacting. It is an oversimplification to say that the two effects are additive. One might expect, however, that when the two mechanisms are "competing" there would be less tendency to form a vortex than when the two are complementing each other. Experiments to examine this interaction between the two mechanisms could not readily be carried out with the facility used, and we will only comment that in the particular cross wind cases studied the second mechanism was the dominant one, although it should be true that there will be other combinations of shear and yaw angle at which the first mechanism is the
more important. We hope to study this further in the coming year on a larger scale model in a wind tunnel.

Finally, there are thus several areas yet unresolved. The foremost is the quantification of the fluid dynamic process that set the circulation round the inlet and hence that determine the strength of the vortex generated by the second mechanism. If this can be done, one is then in a position to state which of the two mechanisms is important in a given situation, as well as how serious the vortex problem will be in a given practical situation.
Two basic mechanisms of inlet vortex formation have been found. The first is associated with the production of a vortex in a flow possessing ambient vertical vorticity. It is the amplification of this ambient vorticity as the vertical vortex lines are stretched and drawn into the inlet that is responsible for the formation of an inlet vortex. However, ambient vorticity is not essential for the generation of a vortex. In the second mechanism, which has not been previously recognized, an inlet vortex can be created with an inlet in crosswind in flow that is irrotational far upstream. Associated with the vortex is a variation in circulation along the axial length of the inlet and thus a trailing vortex system. The circulation around the inlet at sections far from the lip is therefore quite small.

A relevant parameter in determining the appearance of a vortex is the inlet velocity to upstream velocity ratio. In the first mechanism, this ratio determines the amount of stretching incurred by a vertical vortex line and therefore the vorticity increase. For the second mechanism, this ratio has a strong effect on the separation points on the inlet; consequently, it directly controls the inherent three dimensionality of the flow, in particular the circulation distribution along the inlet.

The experiments were carried out with an inlet and ground plane, as well as with a double inlet configuration. The latter series of tests present a situation in which an examination of the transient start up process is extremely useful in understanding the fluid mechanics of the eventual steady state that is produced. In addition they provide a clear illustration of the balance which occurs between the vorticity production (by straining) within
a fixed volume and the convection and diffusion of vorticity out of the volume.
To gain more insight into the inlet vortex phenomenon, additional work is required in the computational analysis as well as in experimental research.

The computational method used to predict the potential flow field must be improved so that it suppresses recirculation and adequately describes the flow at the engine face plane. Detailed recommendations concerning these improvements can be found in Viguier (1).

In addition, the quantification of the vortex formation mechanisms would be very desirable. In rotational flow, this can be achieved by experimentally measuring the circulation during wind tunnel tests. However, deducing the magnitude of the circulation present in the newly discovered mechanism of vortex generation is more complicated. The determination of the criteria which set the magnitude of this circulation should thus be a key part of any further study.
APPENDIX 1

EQUIPMENT INFORMATION

Additional Equipment Information:


2) Vertical Flow Meter, Brooks Instrument Division, Penn., Model # 1114.


4) 20 MHz Function Generator, Waveteck, Mass., Model # 143.


6) Platinum Wire, Omega Inc., Conn., Order # SPPL-001.

7) Fresnel Lens, Edmund Scientific Co., N.J., 0.28 m square, 0.24 m focal length, St # 72246.
APPENDIX 2
GENERATION OF SHEAR PROFILES

The four artificial shear flows utilized in this investigation were generated using honeycomb of non-uniform lengths designed according to the two-dimensional calculation procedure developed by Kotansky in (3). The pressure drop across the honeycomb is defined as follows:

\[ p(0,z) - p_D = \frac{4f(z)L(z)}{D_h} \left( \frac{L}{2} \rho U^2(z) \right) \] (2-1)

where \( p_D \) is the pressure downstream of the honeycomb, \( p(0,z) \) is pressure just upstream of the honeycomb, \( f \) is the friction factor, \( L \) is the length of the honeycomb, \( D_h \) is the hydraulic diameter of the honeycomb, \( \rho \) is the density of the water, \( U \) is the velocity, and for a given axial tunnel distance \( z \) is the direction in which the velocity profile varies. Upstream of the honeycomb the flow field is considered to be irrotational with parallel flow at a far upstream location, no flow normal to the channel walls and a prescribed axial component of velocity at the honeycomb. The flow downstream of the honeycomb is also parallel, although rotational, with a constant static pressure.

In the potential flow region upstream of the honeycomb, we can use a two-dimensional stream function \( \psi \) which satisfies Laplace's equation. The solution for \( \psi \) satisfying the wall and far upstream boundary conditions is

\[ \psi(x,z) = U_\infty z + \sum_{n=1}^{N} a_n \sin \left( \frac{n \pi z}{L} \right) \exp \left( \frac{n \pi z}{L} \right) \] (2-2)
where

\[ a_n = \frac{2}{n\pi} \int_0^L \cos \frac{n\pi z}{L} [U(z) - U_\infty] dz \]  \hspace{1cm} (2-3)

In this, \( L \) is the height of the tunnel. The velocity components \( v_x \) and \( v_z \) in the \( x \) and \( z \) direction, respectively, can be found from:

\[ v_x = \frac{\partial \psi}{\partial z} \quad v_z = \frac{\partial \psi}{\partial x} \]  \hspace{1cm} (2-4)

In the irrotational flow region, we can write

\[ p(o,z) - p_\infty = \frac{1}{2}\rho U^2(z) - \frac{1}{2}\rho v^2(z,0,y) + \frac{1}{2}\rho U^2_\infty \]  \hspace{1cm} (2-5)

Using 2-1, 2-2, and 2-4 we can derive an equation for the honeycomb length, \( L(z) \):

\[ L(z) = \frac{D_h}{4f(z)} \left[ \frac{U_\infty^2}{U^2(z)} + K_0 \frac{U^2_\infty}{U^2(z)} - 1 - \frac{v_z^2(0,z)}{U^2(z)} \right] \]  \hspace{1cm} (2-6)

where

\[ K_0 = \frac{p_\infty - p_D}{1/2\rho U^2_\infty} \]  \hspace{1cm} (2-7)

which is a parameter to be chosen. The friction factor, \( f(z) \), is determined from

\[ f(z) = \frac{16}{Re(z)} \]  \hspace{1cm} (2-8)

where

\[ Re(z) = \frac{U(z)D_h}{\nu \beta} \]  \hspace{1cm} (2-9)

and \( \nu \) is the kinematic viscosity of water and \( \beta \) is the open area to total area ratio of the honeycomb.
By selecting $U(z)$ and $K_0$, $v_z(o,z)$ and $f(z)$ can be obtained. Thus, the length of the honeycomb is obtainable from Eq. (2-6).
APPENDIX 3

HYDROGEN BUBBLE FLOW VISUALIZATION

3.1 GENERAL DESCRIPTION

There are many different kinds of flow visualization, but hydrogen bubble flow generation was determined to be the most appropriate for this application. This method utilizes a fine wire as the cathode of a DC circuit used to electrolyze the water, with the second electrode being either part of the tunnel or an inserted piece of corrosion resistant metal. Hydrodynamic forces sweep the hydrogen bubbles off the wire and downstream following the path of the flow, and they are made visible by specially arranged lighting. As pointed out by Schraub, et al. in (5), this method offers a great deal of flexibility to the experimenter. For instance, probes of different arrangements can be used to illustrate particular characteristics of the flow, or the voltage to the cathode wire can be pulsed creating time lines which provide a qualitative picture of the velocity profile. In addition, hydrogen bubbles do not contaminate flow or require special ducting as dye and other tracing materials do. Many of the other advantages associated with this technique are discussed by Clutter in (6).

3.2 DETAILS OF THE METHOD

Figure 28 displays the circuit used in this investigation; it was adapted from the one employed by Clutter in (6). As shown, AC line voltage comes into the circuit and is raised above ground level by an isolation transformer. A variable resistor in the form of a variac is then used to set the voltage that will eventually appear across the cathode-anode arrangement. The second transformer boosts the AC line voltage to the desired voltage level, and the
rectifier transforms the system from an AC voltage source to a DC voltage source. The remaining circuitry establishes the sharp on-off voltage characteristics required for good bubble formation. This circuit can either operate as a pulsed voltage source using the pulse generator to power the relay coil or as a continuous voltage source. It has been found that wires which were operating satisfactorily sometimes suddenly begin to function sporadically. Clutter (6) recommended inverting the polarity across the wire for a few minutes when this occurs; therefore, a polarity reversing switch was put into the circuit.

As mentioned previously, a fine wire* is used as the cathode in the circuit. Many different types of materials have been used very effectively for hydrogen bubble generation, but we chose to use platinum because it does not corrode and it has been reported to accumulate dirt less rapidly than other materials. The fine diameter wire is used to minimize flow disturbances and to keep the size of the bubbles small. Mattingly in (7) suggested keeping the Reynolds number, dependent on wire diameter, at a value less than forty to avoid shedding vortices from the wire and therefore flow disturbances. The size of the bubbles produced by the wire is proportional to the wire diameter; hence, it is also necessary to use a thin wire since only small diameter bubbles follow the actual path of the local velocity field.

*3x10^{-5} m platinum in the present set of experiments.
A gas bubble moving at a slow steady speed can be approximated as a Stokes Flow with the ratio of forces described by:

\[
\frac{\text{Buoyancy Force}}{\text{Drag Force}} = \frac{gd^2}{18\nu U(z)}
\]  

(3-1)

where g is the gravity. It is apparent from the above equation that if the diameter is small, the drag force predominates and the bubble path will accurately exhibit the flow path. To maintain good bubble quality, it is also advisable to keep the wire voltage uniform, and this was achieved in the experiment by connecting two leads to the wire whenever possible.

The circuit utilized is capable of delivering up to three hundred volts; however, one hundred volts was the maximum amount required during the experimentation.
APPENDIX 4 *

CHANGES OF VORTICITY IN A VOLUME OF FIXED IDENTITY

To find the changes of vorticity for a constant density fluid in a volume of fixed identity, one can start by taking the curl of the momentum equation. In the absence of non-conservative body forces, this yields

\[
\frac{\partial \vec{\omega}}{\partial t} - \nabla \times (\nabla \times \vec{\omega}) = \nu \nabla^2 \vec{\omega}, \tag{4-1}
\]

where \( \vec{\omega} \) is the vorticity, \( \nabla \) is the velocity and \( \nu \) is the kinematic viscosity. Integrating Eq. (4-1) over a fixed volume, \( \tau \), bounded by a surface, \( s \), gives

\[
\int_\tau \frac{\partial \vec{\omega}}{\partial t} \ dt = \int_\tau \nabla \times (\nabla \times \vec{\omega}) \ dt + \nu \int_\tau \nabla^2 \vec{\omega} \ dt. \tag{4-2}
\]

Now the last term of the above equation can be rewritten as

\[
\nabla^2 \vec{\omega} = \nabla (\nabla \cdot \vec{\omega}) - \nabla \times (\nabla \times \vec{\omega}) = -\nabla \times (\nabla \times \vec{\omega}) \tag{4-3}
\]

Using this in the following vector integration formula,

\[
\int_\tau \nabla \times \vec{F} \ dt = \int_s \hat{n} \times \vec{F} \ ds, \tag{4-4}
\]

where \( \vec{F} \) is a vector and \( \hat{n} \) is the unit normal to the surface, \( s \), and employing the expression for vector triple product, permits Eq. (4-2) to be stated in the following manner:

\[
\frac{\partial}{\partial t} \int_\tau \vec{\omega} \ dt = \int_s (\hat{n} \cdot \vec{\omega}) \ \nabla \ ds - \int_s (\hat{n} \cdot \nabla) \vec{\omega} \ ds - \nu \int_s \hat{n} \times (\nabla \times \vec{\omega}). \tag{4-5}
\]

I  II  III

This Appendix was written by E. M. Greitzer
The first of the terms on the right hand side can be put in a more recognizable form by noting that

\[(\hat{\mathbf{n}} \cdot \vec{\omega}) \vec{V} = \hat{i} [\hat{\mathbf{n}} \cdot (\vec{\omega} \ V_x)] + \hat{j} [\hat{\mathbf{n}} \cdot (\vec{\omega} \ V_y)] + \hat{k} [\hat{\mathbf{n}} \cdot (\vec{\omega} \ V_z)] \]  

(4-6)

where \(\hat{i}, \hat{j}\) and \(\hat{k}\) are constant unit vectors in the x, y, z directions.

By applying the Divergence Theorem, term I of Eq. (4-5) can be expressed as

\[
\int_s (\hat{\mathbf{n}} \cdot \vec{\omega}) \vec{V} \ ds = \hat{i} \int \nabla \cdot (\vec{\omega} \ V_x) \ d\tau + \hat{j} \int \nabla \cdot (\vec{\omega} \ V_y) \ d\tau + \hat{k} \int \nabla \cdot (\vec{\omega} \ V_z) \ d\tau
\]

(4-7)

But

\[
\nabla \cdot (\vec{\omega} \ V_x) = (\vec{\omega} \cdot \nabla) v_x,
\]

(4-8)

and the remaining two components can be similarly written. Adding up the components we thus find

\[
\int_s (\hat{\mathbf{n}} \cdot \vec{\omega}) \vec{V} \ ds = \int_\tau (\vec{\omega} \cdot \nabla) \vec{V} \ d\tau
\]

(4-9)

Substituting Eq. (4-9) into Eq. (4-5) gives the desired expression for the rate of change of vorticity in a fixed volume, \(\tau\)

\[
\frac{\partial}{\partial \tau} \int_\tau \vec{\omega} \ d\tau = \int_\tau (\vec{\omega} \cdot \nabla) \vec{V} \ d\tau - \int_s (\hat{\mathbf{n}} \cdot \vec{V}) \vec{\omega} \ ds - \nabla \int_s \hat{n} \times (\nabla \times \vec{\omega}) \ ds.
\]

(I) \hspace{1cm} (II) \hspace{1cm} (III)  

(4-10)

The three terms show: (I) - the production of vorticity inside the fixed volume by the stretching and "tipping" of existing vortex lines, (II) - the convection of vorticity out of the fixed volume through the surface, s, and (III) - the diffusion of vorticity by viscous effects at the surface.
Although not of direct application in the present investigation, Reynolds' transport theorem can be used to convert Eq. (4-10) to an expression for the change of vorticity in a volume (τ') moving with the fluid as follows

\[ \frac{D}{Dt} \int_{\tau'} \overline{\omega} \, d\tau = \int_{\tau'} (\overline{\omega} \cdot \nabla) \overline{V} \, d\tau - \nu \int_{s'} n \times (\nabla \times \overline{\omega}) \, ds \quad (4-11) \]

where \( s' \) is the surface bounding \( \tau' \), which is also moving with the fluid. This equation shows that changes in vorticity, for a given collection of fluid particles, are due to production and diffusion of vorticity.

In the context of the present problem, it is of interest to apply Eq. (4-10) to the case of a vortex stretched along its axis at a constant strain rate, \( \gamma \). As shown by Marble (9) and Batchelor (11), this situation leads to an exact solution of the Navier Stokes equations. With the geometry depicted in Fig. 29, the axial velocity, \( V_z \), the tangential velocity, \( V_{\theta} \), and the radial velocity, \( V_r \), can be expressed as follows

\[ V_z = \gamma z \quad (4-12a) \]

\[ V_{\theta} = \frac{\Gamma}{2\pi r} \left( 1 - e^{-\gamma r^2/4\nu} \right) \quad (4-12b) \]

\[ V_r = \frac{\gamma r}{2} \quad (4-12c) \]

where \( \gamma \) is a constant and \( \Gamma \) is the circulation. There is only an axial component of vorticity whose magnitude is

\[ \omega_z = \left( \frac{\Gamma}{2\pi} e^{-\gamma r^2/4\nu} \right) \quad (4-13) \]
Substituting Eq. (4-12a,b,c) and (4-13) into Eq. (4-10) for a steady flow results in

\[
0 = 2\pi\hat{\gamma} h\int_0^R \frac{\Gamma}{\pi} e^{-\gamma r^2/4\nu} r dr - 2\pi\hat{\gamma} h\int_0^R \frac{\Gamma}{\pi} e^{-\gamma r^2/4\nu} r dr
\]

\[(I) \quad (IIa)\]

\[
+ h\gamma R^2 \Gamma e^{-\gamma R^2/4\nu} \hat{k} - h\gamma R^2 \Gamma e^{-\gamma R^2/4\nu} \hat{k}
\]

\[(IIb) \quad (III)\]

The above equation illustrates the balance between the production of vorticity and the convection of vorticity through A, the top of the cylinder shown in Fig. 29, in terms I and IIa, and the diffusion out and convection of vorticity in through the sides of the cylinder, B, in terms IIb and III.
### SINGLE INLET RESULTS

<table>
<thead>
<tr>
<th>Velocity Profiles</th>
<th>Sense of Circulation at &quot;Far Upstream&quot; Location</th>
<th>Orientation of Inlet to the Mean Flow</th>
<th>Direction of Vortex - Viewed Looking into the Inlet from Upstream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Shear Layer (Horizontal Vortex Lines)</td>
<td>CW* (Boundary Layer)</td>
<td>0°</td>
<td>CW (stronger)</td>
</tr>
<tr>
<td></td>
<td>CCW* (Jet)</td>
<td>90°</td>
<td>CCW</td>
</tr>
<tr>
<td>Horizontal Shear Layer (Vertical Vortex Lines)</td>
<td>CCW** (Left-Right)</td>
<td>0°</td>
<td>CW</td>
</tr>
<tr>
<td></td>
<td>CW** (Right-Left)</td>
<td>90°</td>
<td>CW</td>
</tr>
<tr>
<td>Irrotational Flow</td>
<td>No Ambient Vorticity</td>
<td>0°</td>
<td>CW (small)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90°</td>
<td>CCW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>270°</td>
<td></td>
</tr>
</tbody>
</table>

* Ninety Degrees to the x-z Plane (looking along y axis from negative to positive).

** Looking Down on the Tunnel (looking along z axis from positive to negative).

*** Vertical vortex lines are bent ninety degrees to enter the lower half of the inlet. Hence, vertical vortex lines possessing CW circulation (when viewed looking down on the tunnel) will give rise to a CCW rotation vortex as seen looking into the inlet from upstream. The opposite is true for the CCW rotating vertical vortex lines.
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b) Angled Side View

Inlet

U_{\infty}

1, Separation at 12:00

2, Separation at 4:00

Separation Line

Inlet Vortex

Trailing Vortex

FIGURE 18b: Angled Side View
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(a-d)
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REFERENCES


10. Greitzer, E.M., private communication (see Appendix 4).