Counter-Current Shear Layer Vortex Generation Facility

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A counter current shear layer facility was designed and constructed using opposing converging nozzles with splitter plates. Both nozzles fed into a constant area test section. Compressed air was fed into each nozzle from a single high pressure source but into opposite sides of the splitter plates. This setup was used to create a quasi-stationary shear layer in the test section. Preliminary measurements of this flow were made using a pitot probe and laser sheet flow visualization. Pitot profiles showed that the incoming flows were equal and opposite of each other. It also showed the expansion rate at which a singular shear layer grew. Using the laser sheet visualization, the expansion rate was observed to have certain boundaries which followed a structured pattern. When the laser sheet visualization was applied to the counter flow, several interactions were noted that included, but were not limited to, vortex generation.

I. Background

Mixing layers are traditionally produced by coflowing fluid streams where two streams flow in the same direction, but differ in velocity. The shear in the mixing layer leads to the formation of vortex structures whose evolution and dynamics are responsible for the growth of the shear layer and the mixing between the two streams. Another, less common, method to produce a mixing layer is the use of countercurrent flows. In this arrangement, the flow direction opposes each other and differ in velocity.[1] The vortex size and strength is dependent upon the incoming velocity. This can be observed visually by the radius of the vortex.

Shear layers are formed by opposing viscous and pressure forces to the primary flow. Brown and Roshko (1974) detailed how the growth rate of the shear layer is tied to pairing events between large-scale turbulence structures formed in the flow, thus illustrating the important role large-scale structures play in the development of shear layers. According to Papmoschou and Roshko (1988) a fully turbulent, compressible shear layer will grow linearly. Compressible flow in this case refers to flow over Mach 0.7. These compressibility issues affect the growth rate of the shear layer when compared to incompressible flow. Higher Mach numbers correlates to a more linear expansion rate of the shear layer.[3]

Papmoschou and Roshko (1988) and Forliti, Strykowski, and Tang (2002) said little has been studied about countercurrent shear layers. Their applications are numerous with several purely scientific aspects. A countercurrent shear layer facility can be used to study the mixing of fuels in combustion engines and possibly to create higher pressure ratios in scramjets. It can also be used in active turbulent systems to increase stall angle of wings. This facility could also evaluate flows that approached Mach 1.0 so compressibility in vortices could be studied, as well as the possibility of shocklets in the flow interaction.

Our motivation for pursuing the counter-current arrangement is that our understanding of compressible

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shear layers is limited using traditional methods as the turbulent vortices produced move and evolve far too rapidly for us to study them in detail. A counter current arrangement, however, may allow us to produce these vortices in a quasi-steady position allowing for more detailed measurements

II. Facility Design and Construction

The counter current shear layer facility presented here is a prototype for a larger facility to be designed in the future. It is designed for use at lows speeds whereas the ultimate goal is a high-speed facility to investigate compressibility effects on large-scale turbulence structures. This facility was designed with simplicity of observation and construction in mind. Thus, the results presented here are preliminary by nature and primarily intended to help guide the design of a larger, high-speed facility.

The two opposing streams of the counter-current shear layers facility were established by constructing two fiberglass converging nozzles. The facility is shown below in Figure 1 and in Figure 2. The nozzles were split into two sections using a flat splitter plate that were CNC machined to the exact contour of the nozzle. Slits were cut into the sides of the nozzles to allow variable, vertical offset between the plates. The splitter plates extend into a plexiglass 2" x 2" x 4" test section. Plywood boxes were constructed on opposing sections of the nozzles (one for the top and one for the bottom). Honeycomb was placed inside the plywood boxes to create a straight and uniform flow with a minimal amount of turbulence. PVC pipe was then inserted and sealed into both of the plywood boxes and connected with a PVC tee which was connected to a regulated single source air supply. A plexiglass box was placed on one side of the PVC tee allowing for particle seeding of one of the streams to facilitate flow visualization. A butterfly valve was placed on the other side of the tee to adjust and match the inlet pressures to each of the boxes. A compressed air supply was used to drive the flow. The compressor has a maximum output of 120 pounds per square inch, which is stored in a 200 gallon tank. The supply line from the tank to the counter-current shear layer facility is approximately one hundred feet of half inch copper pipe and fifty feet of three-eighths inch rubber hose. The facility could only run for several seconds at the higher speeds (regulator set above 60 PSI) and could run for several minutes at the lower speeds (regulator set below 60 PSI). The total pressure drop between the supply line and the test section was large. A pitot-static tube and an Omega PX-653 pressure transducer with an accuracy of ±0.25% full scale and a useable pressure range of 0 to 0.5 inches of water were used. An Omega DP25-E meter was used to interpret the pressure transducer output. This was then used to measure and verify the characteristics of the opposing flows. The expected outcome of the flow interaction can be seen in Figure 4.

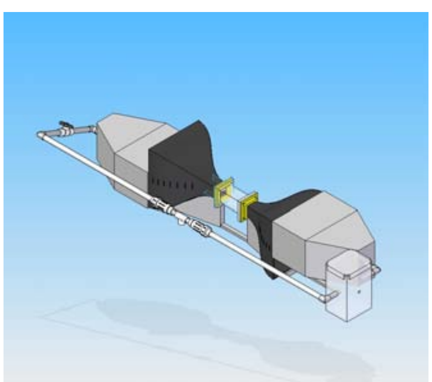

Fig. 1 Solid Edge drawing of counter-current shear layer facility.

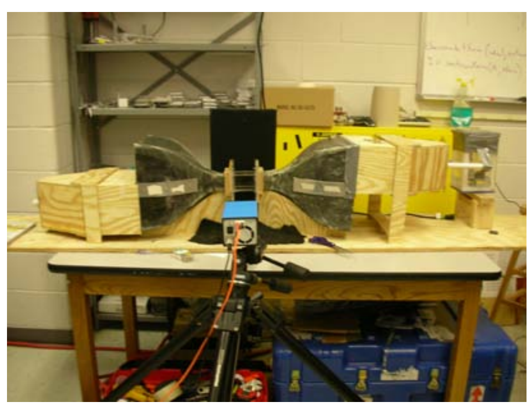

Fig. 2 A picture of the facility.

III. Benefits of a Counter Shear Facility

One way to study vortices that are formed when air is passed over a flat plate is to follow the vortex with the flow once it is created, which creates problems tracking at high and low speeds. The counter shear facility will allow a vortex to be in one central location, allowing for prolonged study, meaning there is no need to follow the vortex down stream. Another benefit for using the counter shear facility is that the stream velocity is measured with relativity to one another, meaning that for an incoming flow of mach 0.2, the relative velocity of the vortex is Mach 0.4 (Mach 0.2 incoming on both sides is added together). With this, higher velocities can be produced using lower, less costly single pressure sources. At Mach numbers greater than 0.7 the expansion layer becomes smaller. This facility would allow for the vortices that are formed at those Mach numbers to be studied with greater ease.

IV. Preliminary Tests

Tests were originally performed without a regulated air supply and without honeycomb. These tests were strictly for testing the possibility of the proposed experiment. No measurements were taken at this stage in experimentation besides pictures. An ultrasonic mister seeded the air flow with small water droplets (i.e. fog) for visualization while a 200 mW continuous wave diode laser operating at 532 nM (green) and a cylindrical lens were used to create a laser sheet to illuminate the water particles across a thin plane. At lower speeds, ten feet per second, the flow was very chaotic, but still followed the basic linear-parabolic expansion pattern in a time averaged photo. At higher speeds, seventy-five feet per second, there was insufficient water vapor for visualization using this method.

The splitter plates were adjusted in two directions, both axially and vertically with respect to the flow. This was done to assure the highest probability for favorable flow interaction. The ability to move the splitter plates allowed for the optimizations of the different flow characteristics at different speeds. The main flow characteristic that drove the preliminary design was the changing shear expansion rate at different speeds. The higher the velocity is, the more linear the shear expansion region is.[3]

The facility was then altered by the addition of honeycomb to create less chaotic flow in the nozzles, minimizing any pre-nozzle turbulent effects. An Antari Z-800II smoke generator replaced the ultrasonic mister, giving the capability of much denser flow seeding. Once these changes were made, the flow could be seen at higher speeds and was more stable at slower speeds. A differential pitot probe was used to confirm that the air speed on both sides were equal to one another. The splitter plates were then adjusted until a vortex visually appeared. The air speed was checked again at this point to reaffirm identical incoming flows. A Cooke High Speed Sensicam-QE camera was used to take one frame as well as time-averaged images of the flow. Many counter-current pictures have vortices in the middle of the test section. Most of the pictures have chaotic flow due to some pressure perturbation or acoustic disturbance that was unnoticed and undocumented. This preliminarily design would need to be reconstructed to increase insulation from the outside world as well as increase the stability of the incoming pressures, resulting in more stable vortices. Although these perturbations decreases the consistency of the formation of quasi-stable vortices, the facility provided an environment that was suited for proof of concept type experiments which mostly consisted of observation.

V. Single Shear Layer Experiments

After some preliminary experimentation with the counter current flow, one sided flow was studied to determine the shear expansion pattern. This was accomplished by shutting the valve to one of the two streams and observing the growth of a single shear layer. This helped determine the nominal growth rate of the shear layers and identify the appropriate offset to be placed between the two streams. Measurements of the splitter plates' location in combination with the pictures was used to determine where the shear layer would form. Figure 3 is a picture of one of the time-averaged, one sided experiments. Smoke (particle size order 1 microns) was used to seed the flow. To obtain a picture of the shear layer, a time average picture was taken of 64 frames with an exposure of 5 milliseconds for each frame.

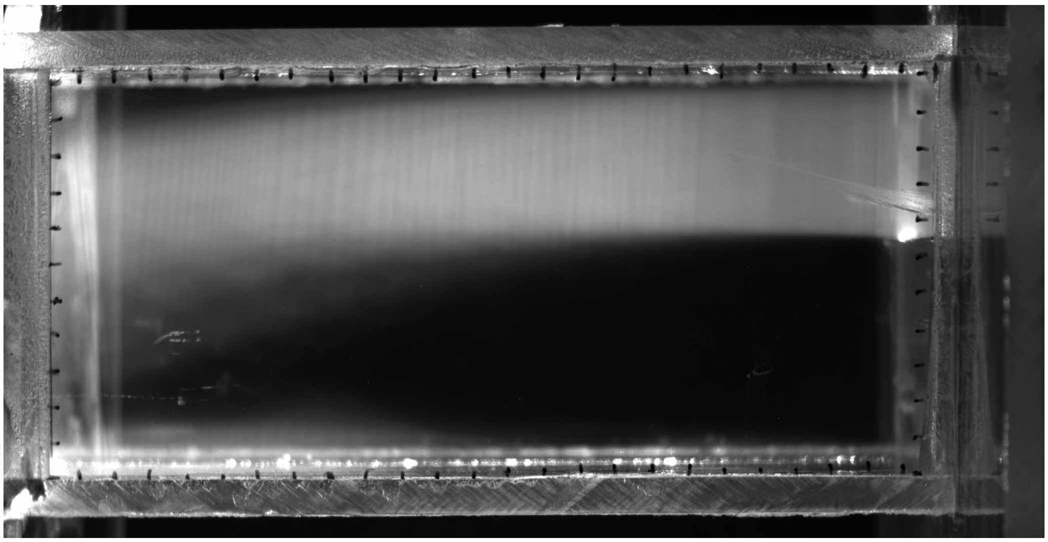

Fig. 3 One sided flow with 64 frame average used to show shear layer.

Several of these images were taken at varying air speeds and splitter plate locations. The dashes around the periphery of the test section were initially used to help plot the expansion pattern of the shear layer. Matlab was then used to draw more precise grid lines. These lines were then superimposed onto the pictures to establish predictions for the shear layer expansion boundary. The overall expansion pattern of these low velocity flows was a primary linear portion followed by a parabolic expansion region. It was observed that the growth rate of the shear layer decreased as the velocity increased. This would require the splitter plates to be adjusted closer together to produce vortices at higher speeds. Another technique of prediction that was used was that the pictures were superimposed on each other to show where each of the shear layers would be in the two sided experiments, making for a more accurate prediction of two sided flow interaction and giving a starting point for amount of separation, both axially and vertically, needed between the two splitter plates.

VI. Counter Shear Layer Experiments

Once the final setup was established, several counter shear tests were conducted in the facility. The anticipated flow is shown in the drawing in Figure 4. This figure is not to scale and shows the flows in the opposite direction of testing. Several pictures were taken as the splitter plates' geometric change in Y with respect to one another approached zero.

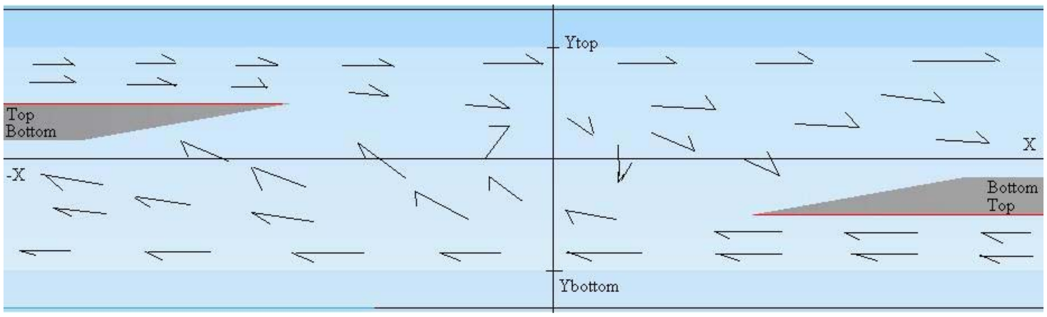

Fig. 4 Shows the anticipated flow in the test section over the two splitter plates.

The following pictures were taken with the Cooke Sensicam. Each had an exposure time of 5 milliseconds. The same 200 mW continuous wave laser operating at 532 nM and cylindrical lens that was used in the initial test was also used for these photographs. Due the length of the exposure and the velocity of the smoke particles the flow appears to be blurred. This blurred flow can be beneficial because it gives short streak lines of the smoke particles and helps depict the motion and relative velocity of the flow.

It was observed that with a large amount of separation (greater that 75% of the total Y-axis), very few large central vortices formed. Instead, the boundary of the shear layer was observed to hit the opposite splitter plate, preventing any interaction. This is shown in Figure 5 below with a 1.5 inch separation in the plates and a free stream velocity of 14.79 feet per second. A turbulent region formed in the area where interaction was limited to extremely low velocity caused by the difference in the pressure between the flows. This region appeared not to be affected by the primary flow. Instead is looked as though it was only affected by the viscous effects as well as the pressure differences between the primary flow and the chaotic region. This shows a relatively steady area in the middle in comparison to the primary flow areas. Mixing was limited to low velocity flows between the two flows, caused by an apparent pressure gradient between the center region and the primary flows.

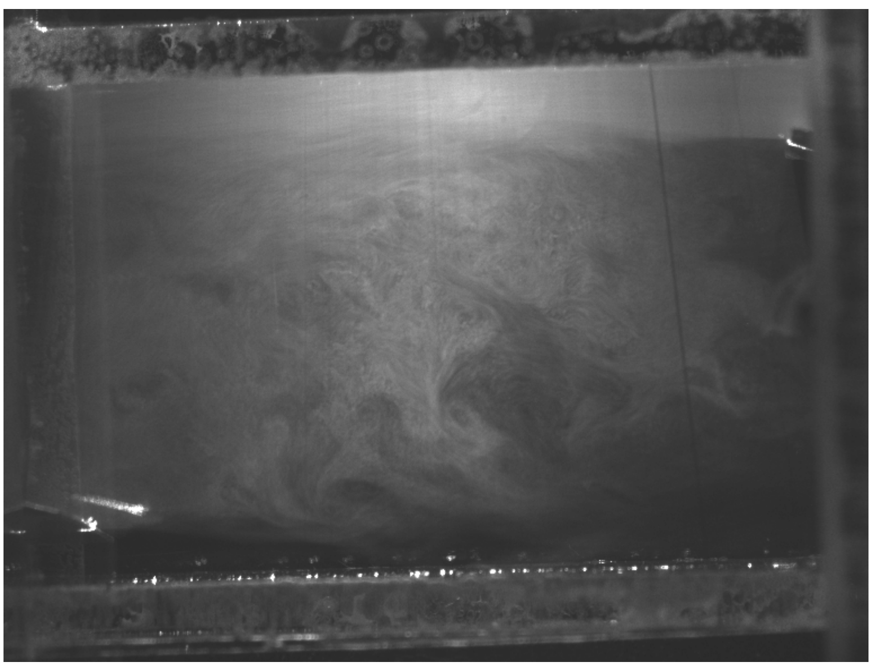

Fig. 5 Splitter plates are at a Δy that causes the shear layers to not interact yielding no central vortex to be formed.

As the plates were moved closer together, vortices would form just below each of the plates. If pushed slightly closer together, two vortices formed in the spot of interaction of the two shear layer expansion boundaries. This is shown in Figure 6 below with an 11/16" plate separation and a free stream velocity of 14.5 ft/s. This interaction shows that the vortices are dependent on where the expansive regions interact. The two vortices that formed in the area of interaction were fairly stable, meaning they would appear in approximately six out of every ten pictures taken at the particular setup. These instabilities could be attributed to pressure disturbances in the surrounding area, the low precision pressure regulator, or the leaks in the facility.

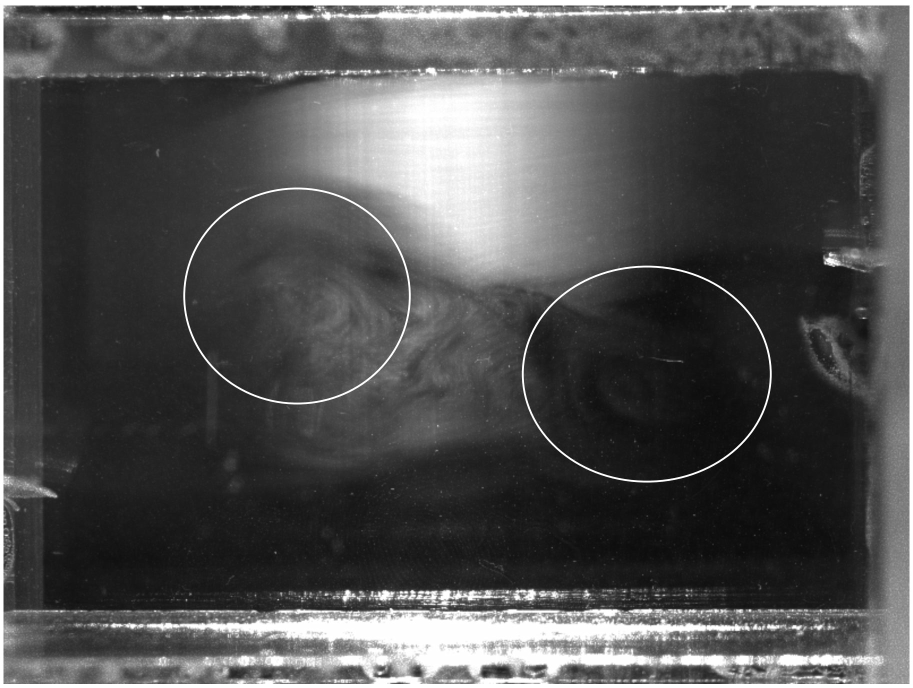

Fig. 6 Splitter plates are at a (11/16)" separated that causes the shear layers to slightly interact yielding two vortices.

If the plates were moved even closer, one vortex would form in the middle where the two shear layers intersect. This is shown below in Figure 7 where there is a 0.75 inch separation in the plates and a free stream velocity of 14.0 feet per second. As the plates would continue to get closer this vortex would move slightly up and down in the center of the test section. This bouncing of the central vortex could be caused from the shear layers starting to overlap and forcing the flows to move away from each other. This phenomenon could be attributed to the semi-steady nature of the expanding shear layers produced by a low precision pressure regulator. It may also be attributed to the acoustic disturbances in the surrounding area, or the possible leaks in the facility. All these attributes contributed a considerable amount to the steadiness that was observed in the flow.

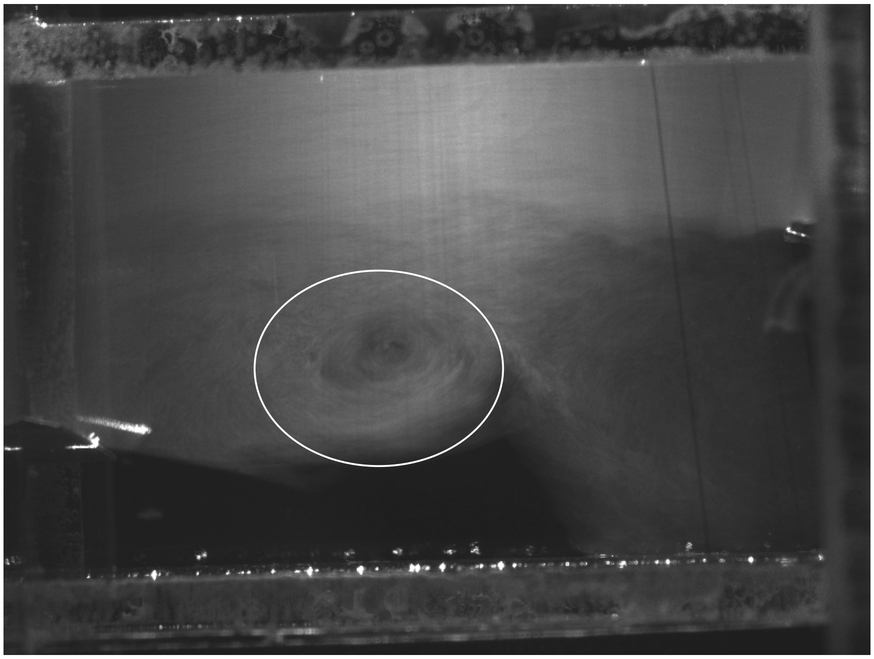

Fig. 7 Splitter plates are at a Δy that causes the shear layers to interact yielding a central vortex to be formed.

If the plates were moved closer together, the flow would become chaotic, separated flow. As shown below in Figure 8, the shear layers of the two flows are observed to overlap each other. This overlapping appears to cause a strong pressure gradient, causing the flow to wrap around the plate from which it originated as opposed to maintaining its original direction. This scenario displayed a relatively slow moving middle region caused by the equal low pressure regions formed by the high velocity flows on either side. The middle region displayed chaotic behavior whose velocity (as observed by the length of the seed streaks) seemed to depend on the equality of the pressure of the side flowing regions. The velocity in the center region, close to the primary flows, was affected by viscous effects of the flow.

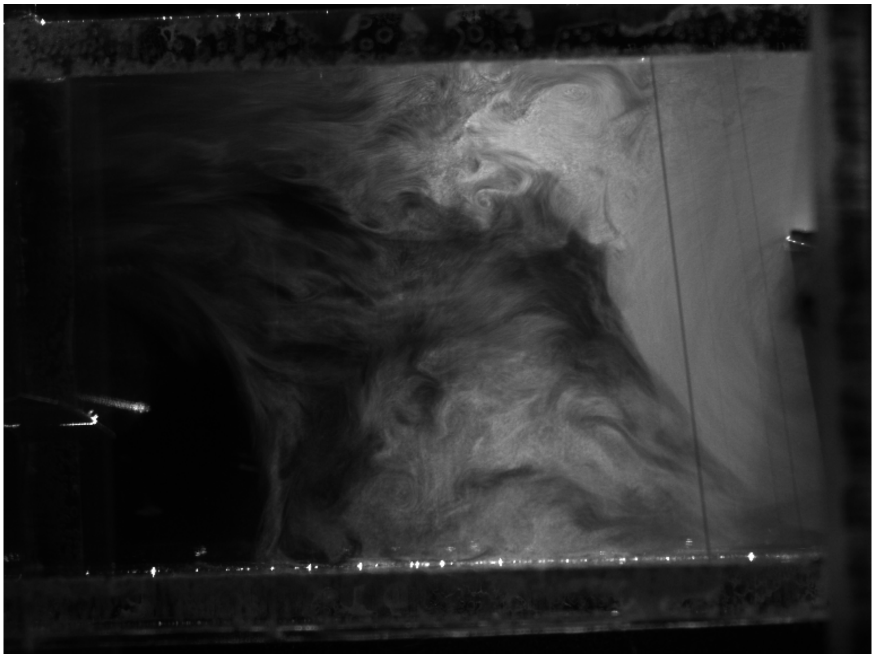

Fig. 8 Splitter plates are at a 0.625 inch separation in the plates with a free stream velocity of 11.5 feet per second

VII. Conclusions and Future Work

Counter-current formed vortices are dependent on the interaction of the shear layers formed by the incoming primary flows. The shear layers formed from these primary flows follow a distinct expansive pattern which includes a linear portion, followed by a parabolic expansion region. When correctly lined up, a central vortex is formed. This vortex, theoretically, could become stable if the incoming flows remained perfectly constant. This would produce a stable vortex, spinning at a stable speed with a stable radius. As far as the results of this experiment, the facilities and air supply were too unstable to produce long term stable vortices. Although short term stable vortices were observed and recorded, instabilities in the facility prevented the vortices from remaining stable.

Particle Image Velocimetry (PIV) would be the next step in studying with this facility. This would allow for an accurate description of the motion of the flow. Construction on a more precise facility would also be included with the PIV software. More care would be put into the construction to seal up leaks and create more laminar flow into the test section. This new facility would have more adjustments to ensure that both of the flows were identical. At the present time only two dimensional flows has been studied and this facility would allow for the analysis of three dimensional flows. This would be done with the aide of a high speed camera, a pulse burst laser system, and a galvanometric scanning mirror. Currently there is little understanding about compressibility and turbulence with the aide of this system and the new facility, turbulence and compressibility in mixing layers can be studied at Mach numbers greater than 0.5.

Placing cylinders in the flow in the span-wise direction or hemispheres on the plates could be used in the facility. With these additions the mixing layers could be tripped to form vortices where they would usually not be formed.

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VIII. References

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