1 Background and objectives.

In this experiment, we will study the flow through a Venturi section using both flow visualization and pressure measurements. A Venturi is basically a converging-diverging section (like an hourglass), typically placed between tube or duct sections with fixed cross-sectional area. We will see in class how, for example, the flow rate through a Venturi can be related to pressure measurements, using Bernoulli’s equation. Here we will explore the use of Bernoulli’s equation over a range of flow conditions, paying particular attention to the validity of the assumptions behind the derivation of Bernoulli’s equation. In particular, in deriving Bernoulli’s equation we assume that the flow in question is (I) inviscid, (II) steady, and (III) incompressible.

It turns out that conditions (II) and (III) are fairly easy to guarantee in a Venturi, but that (I) can be problematic. This is particularly true when the area ratio is large, i.e. when the narrowest part of the Venturi (variously known as the ‘throat’ or the ‘waist’) is much smaller than the widest part. The culprit is a phenomenon known as flow separation. Consider a streamline that is very close to the wall in a Venturi. An inviscid fluid will have no trouble following the contour of the wall. Provided that the area change is gradual enough and that the flow speeds are low enough, a real, viscous fluid will also easily follow the wall, and the behavior of such a real fluid can be treated as being a good approximation to the behavior of an inviscid fluid. However, as the area change becomes more abrupt and/or the flow speed increases, the situation changes; downstream of the throat, a real fluid will become unable to turn sharply enough away from the centerline to follow the wall. The term ‘flow separation’ means that the flow streamlines no longer remain ‘attached’ to the contours of the wall, as depicted in Fig. 1. Flow separation arises due to viscous effects in fluids,

![Figure 1: Flow separation from a curved wall. The flow is from left to right. The smooth streamlines that are evident on the upper part of the image clearly do not follow the sharp downward curve of the wall, i.e the streamlines separate from the wall.](image_url)

so any time flow separation is present in a flow, Bernoulli’s equation is automatically invalidated. This experiment has two parts:

- We will observe the flow pattern in a Venturi section with adjustable throat area, paying particular attention to the presence of any flow separation.

- We will measure pressures and velocities in the Venturi, and compare the results with the predictions of Bernoulli’s equation.
2 Experimental apparatus.

The experiment will use one of the wind tunnels in Krieger B-2 (the one further from the main entrance). Figure 2 shows the test section. The upper and lower walls of the Venturi are constructed of flexible metal sheet. The width of the throat can be adjusted using control wheels mounted on threaded rods.

**Pressure measurement.** Figure 2 shows the slant-tube manometer (water is the working fluid) by which we will measure pressures. Make sure you understand the principle of the manometer, which was discussed in Ch. 3 in the text (for example, which side of the manometer should be connected to higher pressures, and which to lower pressures?). The figure also shows the line of 11 pressure ports along the centerline of test section. The most upstream pressure port is located essentially in the parallel part of the tunnel (before the Venturi). This port (call it port 0) is connected to a flexible tube that can be connected directly to the manometer. The remaining 10 ports (ports 1–10) are connected to a pressure manifold that is connected to a single flexible tube; a system of valves allows the user to select the specific port to be used.

On the back side of the test section, there are 11 holes located at the same downstream positions as the pressure ports on the front side, through which a Pitot-static probe can be inserted for the measurement of dynamic pressure. Figure 3 shows the configuration of our probe; again, make sure you understand the theory of the Pitot-static probe, discussed in Ch. 6 in the text. Stagnation pressure is sensed through the hole at the tip of the probe, while static pressure is sensed through the ring of holes that lie a little bit downstream the probe tip. The same manometer used for the static pressure measurements will be used for the stagnation pressure measurement.

When using the manometer, keep these things in mind:

- Make sure to establish the reference fluid level in the manometer, i.e. the level when both sides are exposed to the same pressure. You can move the graduated scale to set the reference level somewhere convenient.

- Confirm that the manometer is level. If it isn’t, shim it up to level using the scraps of paper provided for this purpose.

- Be consistent in defining the measurement point on the meniscus. It may be easiest to assign one member of your lab group to this task for the entire experiment.
Figure 3: The Pitot-static probe used for dynamic pressure measurements. The hole at the upstream tip of the probe senses stagnation pressure, while a ring of holes just downstream of the tip sense static pressure. In this lab we will measure the dynamic pressure by reading the difference between the stagnation and static pressures directly using the slant-tube manometer.

- Let the fluid level stabilize somewhat before taking each reading, but be aware that it won’t stabilize completely; you will need to estimate the proper value through a small range of fluctuations. **Don’t take too long with each reading.** Time is tight in this lab.

**Flow visualization.** For the flow visualization, we will use the fog generation apparatus described in the separate handout. For this lab, there is one change from the handout – the apparatus has been modified to generate two fog streams instead of four.

3 **Experimental procedure.**

**Preliminaries.** (Target time: 5 minutes.) In order to perform this experiment efficiently, it is a good idea to distribute tasks among the different group members. There are four preliminary tasks to get out of the way.

1. Read the atmospheric pressure in the room, using the mercury barometer on the wall of the lab, in the corner of the room just to the right of the entrance. The TA can help you with this. Get the temperature from the thermometer located there also. You will use this information to estimate the air density.

2. Warm up the fog machine, as described in the handout.

3. Record the geometric parameters of the test section. Measure the height and width of the interior of the test section (ignore the Venturi walls for now), and measure the spacing between the pressure tap holes.

4. Adjust the Venturi walls so that the throat is 5” wide, and symmetric about the test section centerline. (There is a ruler mounted on the side wall of the tunnel to help you do this.)

**Flow visualization.** (Target time: 20 minutes.) In this part of the experiment you will use the fog apparatus to make purely qualitative observations of the flow through the Venturi. Each group member should record his/her observations individually.
1. Turn on the tunnel by flipping the switch on the control box, and set the speed to 50 on the rotary dial. (Note: if you ever need to turn the tunnel off, always return the rotary dial to zero before flipping the switch to ‘off’.)

2. With the fog machine warmed up, turn on the fog supply as described in the handout. Move the fog apparatus so the output holes on the fog plenum are almost touching the tunnel inlet screen.

3. To see the fog go through the tunnel, it is helpful to turn down the room lights and use the desk lamp to illuminate the test section. Adjust the light to minimize glare from your vantage point. You may need to stare at the test section for a short time before your eye can make out the fog, since the contrast will be low. What can you say about the streakline pattern, both upstream and downstream of the throat? A particularly good view of the streaklines can be had by having one group member shine the desk lamp on the test section, while the others look down the tunnel through the fan end.

4. Increase the tunnel speed to 70 on the dial. Repeat your observations.

5. In your recorded observations, pay particular attention to any evidence of flow separation, or streaklines that become wavy, etc.

6. If you have time, set the Venturi throat width to 2” and repeat the above.

7. Shut down the fog machine after your observations are finished.

**Pressure and velocity measurements.** (Target time: 50 minutes.) In this part of the experiment you will measure pressures and velocities in the Venturi, and you will use these results to assess quantitatively the validity of Bernoulli’s equation for this flow, along with the assumption of a one-dimensional velocity distribution.

1. Set the tunnel speed to 70, and the Venturi throat width to 5”.

2. Begin with static pressure measurements using the pressure manifold. Connect port 0 to the low-pressure side of the slant-tube manometer, and leave the high-pressure side open to the atmosphere (whose pressure you already know). Remember to ensure that the manometer is level. Record the gage pressure at port 0. Then connect the pressure manifold to the low-pressure side of the manometer, and record the gage pressure at each of the ports 1 through 8 only. Make sure the valves are fully open (the manometer level equilibrates faster that way), but note that you don’t have to gorilla-tighten them to make sure they’re closed. Not everyone needs to record all data, but everyone in the group needs access to the data for the write-up.

3. While the pressure measurements are going on, someone else can measure the Venturi width, $h_i$ (i.e. the distance between the top and bottom walls of the Venturi), corresponding to each of the pressure tap locations $i$ (this is best done on the opposite wall from the pressure manifold).

4. Having completed the static pressure measurements, connect the Pitot-static probe to the manometer (the flexible tube that is colinear with the body of the probe gives the stagnation pressure, and the perpendicular tube gives the static pressure). You can leave the manometer where it is. Take dynamic pressure measurements at ports 1–10 (not port 0). Try to keep the probe in the horizontal plane and make sure the business end faces directly upstream. You will note that at port 1, the probe can’t be pushed in flush with the side wall because the
The flange on the test section is in the way. To be consistent, for ports 2–10, only push the probe in as far as you can for port 1. There is a piece of tape on the probe that helps you do this.

5. **Important**: When the Pitot-static probe is inserted in a given port, you’ll notice that the stagnation and static pressures are actually being measured some distance upstream of that port. Assume that the dynamic pressure read on the manometer corresponds to a point halfway between the stagnation and static pressure sensing holes, and record how far upstream that point is from the port being used.

6. Reduce the tunnel speed to 50, leave the throat width at 5”, and repeat steps 2 and 4.

7. Adjust the throat to a 2” width (symmetric about the centerline), and return the tunnel speed to 70. Repeat steps 2, 3 and 4.

8. Reduce the tunnel speed to 50 and leave the throat width at 2”. Repeat steps 2 and 4.

9. When the measurements are complete, shut off the tunnel and (if Lester is serving as your TA) make sure everything else is in the condition you found it, otherwise hightail it out of there and leave janitorial tasks to the TA.

**Formal lab report.** Guidelines for the formatting and style requirements of the formal report are in a separate handout. The report should include the following observations and data analyses.

- Summarize your observations from the flow visualization portion. Say something about the possibility or observed presence of flow separation. Make sure you understand exactly what is meant by ‘flow separation’.

- Convert your dynamic pressure data to velocities. Interpolate your results (linear interpolation is fine) to get the velocity values, \( V_i \), that correspond directly to the locations of the pressure ports, \( i \). (Explain why we didn’t bother to measure static pressure at the two most downstream ports.) For each case (tunnel speed and throat width), plot the mass flow rate, calculated as \( \rho V_i A_i \), where \( A_i \) is the Venturi section area at each port location, versus \( i \). This is a check on the assumption of uniform velocities at each section (why?). Using port 0 as the reference value, calculate and plot the percent error in the mass flow rate measurements. Comment on your results.

- Use the velocities, \( V_i \), together with the *gage* static pressures, \( p_{i,g} \), to evaluate the Bernoulli constant:

\[
B_i = \frac{p_{i,g}}{\rho} + \frac{1}{2} V_i^2
\]  

at each port position where you have data available. Plot your results. Think of a *good* way to evaluate the accuracy of the assumption that \( B_i \) is a constant. Display your results and comment.

- Discuss your quantitative results in light of the possibility of flow separation.