Experiment #3: JET THRUST LABORATORY
AE 460: Aerodynamics & Propulsion Laboratory

Department of Aerospace Engineering
University of Illinois at Urbana-Champaign

This experiment is located in **Talbot 18A**.

Presentation Report Format to be given 1 week after completing the laboratory
Electronic submission of your slides is required at or before your presentation.
Bring slides on a flash drive to the presentation session if you are presenting in person.

9/20 – 9/24 Group A conducts Laboratory 3 during the first hour of the lab session
Group B conducts Laboratory 3 during the second hour of the lab session

1. SAFETY

1. Ear and eye protection should be worn at all times while the jet is being used. The jet can be noisy, and dust is easily picked up by the strong airflow, especially at high speeds.
2. Wait for the Teaching Assistant before beginning the experiment.
3. Do not lean on or touch the jet balance, load cell, or optics. The load cell is extremely delicate and can be easily damaged by excessive loads (greater than 10 pounds) or shock loading.

2. OBJECTIVES

The aims of the Jet Thrust Laboratory include:

1. Demonstration of different methods of measuring jet thrust.
2. Comparison of basic assumptions used in measuring jet thrust by different methods (e.g., uniform flow, incompressible flow, etc.).
3. Introduction of students to basic concepts and characteristics of compressible flow (e.g., isentropic flow assumption, shock waves, etc.)

3. LABORATORY EQUIPMENT

The primary pieces of equipment and instrumentation used in the jet thrust laboratory are shown in Figure 1 and listed below.

1. Particulate filter and electronic pressure regulator
2. Converging nozzle, counterbalance, and load cell
3. Stagnation pressure transducer and display
4. Schlieren system
5. National Instruments LabVIEW program

3.1. Particulate filter and electronic pressure regulator

The jet facility is controlled from shop air at approximately 90 psig which is passed through a particulate filter to remove contaminants (Figure 1). The stagnation pressure of the jet is controlled using a Watlow electronic pressure regulator, which keeps the pressure constant and will open from 0 to 100% proportional via a 0 to 10 VDC analog input. The analog input to the pressure controller is obtained from an analog output channel of the National Instruments A/D board and LabVIEW program.

3.2. Converging nozzle, counterbalance, and load cell

The subsonic and supersonic jets that will be studied in this laboratory are created utilizing the stagnation chamber and converging nozzle as shown in Figure 2. The stagnation chamber is pressurized from the previously described pressure regulator with the air supplied by the flexible hose connected to the tubing. All tubing and hose diameters were chosen so that they are large enough to avoid flow choking in them while running the jet. The stagnation chamber is large enough to slow down the flow and contains a perforated plate to reduce turbulence and swirl before the air is accelerated through the converging nozzle. Since the nozzle is converging it should be noted that the jet is under-expanded for pressures exceeding ambient at the exit. Thrust is measured directly using a Cooper 0 to 10 lb_f load cell (±0.05 % full scale). The output signal from the load cell is connected to the force display, which displays the force in units of pounds. In order to minimize the effect of the weight of the jet apparatus and hose, a counterbalance is utilized, which allows a more sensitive load cell to be used, since the jet apparatus and hose are counterbalanced by weights (Figure 1). A ball bearing is utilized at the pivot to minimize friction. Note that the hose is attached to the jet near the axis of rotation to minimize the lever arm of the resultant force, which may occur as the hose is pressurized (create stress changes in the hose jacket resulting in a negligible amount of torsion and resultant force on the balance). Please be careful not to touch the counterbalance or load cell since excessive forces or shock can damage it. Also, do not press any of the buttons on the load cell display since you may inadvertently ruin the calibration.

3.3. Stagnation pressure transducer and display

The stagnation pressure is measured with an Ashcroft 0 to 100 psi pressure transducer with an accuracy of 0.5% full scale and repeatability of 0.07%. The display and transducer have been calibrated to read out the pressure in psi absolute. Please do not press any of the buttons on the pressure transducer display since you may inadvertently ruin the calibration.

3.4. Schlieren photography system

The Schlieren photography system is shown in Figure 1 with a schematic given in Figure 3. The system consists of a point light source, which is placed at the focal point of the first concave mirror (collimating mirror). Therefore, a collimated beam is formed and directed across the jet. The second concave mirror (imaging mirror) focuses the beam down to the focal point and then into a CCD camera with a lens focused on the testing region. At the focal point of the second mirror, a knife-edge is adjusted a little less than half-way into the beam, as illustrated in Figure 4. As you may recall from physics, the index of refraction (amount of light-ray bending) changes as the density of a gas changes. Therefore, density gradients in the flow will deflect the light rays at the knife edge location more into or away from the knife-edge. The result is that the image appears brighter or darker at locations where there are density gradients in the flow field. In this way schlieren photography allows us to image density gradients caused by temperature, combustion, gas composition or, in the present laboratory experiment, from compressible flow features (such as the jet, shocks, or expansion waves). The camera digitizes the image and displays it as a streaming video image which is displayed on the computer.

3.5. National Instruments LabVIEW program

The front panel of the LabVIEW program is shown in Figure 5. This program is used to control the jet stagnation pressure and capture schlieren images from the CCD camera. The stagnation pressure of the jet is controlled by using the left mouse button and dragging the slide control at the top of the panel marked **Valve Position [% Open]**. The pressure can also be controlled by typing a number in the display above the slide control.

The two images at the bottom of the control panel show a real-time image of the schlieren photograph (left display) and the last saved schlieren image (right display). To save a new image, simply press the **[Save Image]** button. A *.bmp extension will automatically be attached to the end of the name indicating a windows bitmap file that can be opened by a variety of programs. The images are saved in the directory you specify.

Camera settings can also be adjusted using the LabVIEW program. You may need to adjust either the schlieren light source intensity (physical knob) or the camera exposure time to achieve a properly exposed image. Do not adjust any of the other camera setting parameters.

4. PROCEDURE

Please follow each of the outlined steps closely. Words denoted by square brackets (e.g., **[Start]**) indicate buttons or text boxes on the computer screen or load cell display.

4.1. Prepare the equipment

1. Before starting the laboratory, be sure that every student has ear and eye protection.

2. Log onto the computer with one of your group members' AE computer accounts.

3. Remove the protective block on the load cell.

4. Without turning on the jet, record the value displayed by the load cell (which should be zero) and the value of the stagnation pressure display (which you will use as the atmospheric pressure in your calculations).

5. Have the teaching assistant verify that the camera is plugged in and ready for communication through the LabVIEW program. Also, have the teaching assistant check that the schlieren light source is ready for operation.

6. Start the LabVIEW program by double clicking on the **[Jet Thrust Lab]** icon on the Windows desktop (or you can navigate to the Jet Thrust Lab sub-directory). When the LabVIEW program starts, navigate to a directory/folder where you will save the images on your account [username (U:) drive listed under Computer] and press the **[Current Folder]** button.

7. In the **Camera Controls** functions area, type in a name in the **[File Name]** text box to designate a base file name for the saved schlieren images. The LabVIEW code will automatically append an image number to each saved image beginning with "1".

8. Press the **[Init Camera]** radio button which reads information from the camera and sets up the USB interface to the computer.

9. Set the camera [**Exposure]** to 3.0 ms and press the **[Start Live]** button.

10. Turn the LED Driver (LEDD1B) to CW and adjust the intensity (current) potentiometer to about 25%. You should observe a gray scale image similar to Figure 5. Be sure the image is not too bright (saturated) or dark since you may lose detail in the schlieren photographs.

11. Ask the teaching assistant to help by verifying that the digital pressure regulator reads zero and turning on the ball valve to the air supply used to control the jet.

12. Press the **[Tare]** button next to the load cell display in order to zero the balance and the **[Tare Load Cell]** button in the **Jet Controls** functions area of the LabVIEW program.

4.2. Acquire Data

1. Slide the ***Valve Position [% Open]*** stagnation pressure control (or type a number in the numeric display next to it) until it reads 2.0. Note that, due to hysteresis, the valve position may give a slightly different pressure each time, so make sure the measurements are recorded during the same setting.

2. After the pressure and load cell display settles, record the stagnation chamber pressure and force from the load cell on the data sheet.

3. Click on the **[Save Image]** button to save a schlieren image to the computer. Do not be surprised if the image does not show much change at low pressures.

4. Once the file dialog window is displayed, type in a file name (note that the .bmp extension will automatically be placed at the end of the name, and you may want to create your own subdirectory) and press the **[Save Image]** button.

5. Record the file name on the data sheet provided next to the appropriate nominal pressure.

6. Repeat steps 1 thru 5 for Valve positions of:
   4.0, 6.0, 12.0, 20.0, 25.0, 35.0, and 50.0.
   Note: The air supply pressure varies day to day, so if the pressure does not increase for the highest settings, complete the highest pressure possible and make a note in your report.

7. After completing the last data point, press the **[Stop Live]** button followed by the **[Stop Program]** button on the control panel and exit out of LabVIEW. Turn the LED Driver off (rotate the potentiometer clockwise until it clicks). Verify that the schlieren light has gone out and the pressure regulator valve closed automatically. Turn off the main air supply ball valve and ask the teaching assistant to place the block on the load cell.

8. Save the schlieren images on your network drive. It is recommended that you save the images on a memory stick also before you leave the laboratory. If you save the images on a local subdirectory, be sure to transfer your images to your network drive before you leave.

5. PRESENTATION

One of the main goals of the jet thrust lab is for students to investigate different methods of analysis used to calculate jet thrust. In doing so, students will gain experience in using control volume analysis to solve fluid dynamics problems, investigate the accuracy of the different methodologies and assumptions used to measure thrust, and solidify their knowledge of the basic characteristics of supersonic flow. Here, we will give a description of how thrust will be calculated using three different analytical methodologies and a direct measurement.

Method #1. Direct thrust measurement

Shown in Figure 6 is the free body diagram that will be used to analyze the thrust from direct measurement via the load cell. The jet used in the experiment is mounted on the force balance. Since the jet is not accelerating, the principles of statics may be used. The sum of the forces in the streamwise (y) direction is given by:

$$R_{LC} + R_{bal} - W_j - Thrust = 0 \tag{1}$$

where R_{LC} is the force of the load cell, W_j is the weight of the jet apparatus, R_{bal} is the force from the counter balance, and *Thrust* is the force due to the momentum and pressure at the jet exit. Assuming that a) the ball bearing pivot friction is negligible, and b) R_{bal} is not appreciably changed due to hose pressurization, R_{bal} balances the weight of the jet apparatus. This force-balancing pair is further legitimized by taring the load cell (i.e., $R_{bal} = W_j$). Since R_{bal} is equal and opposite to W_j, we can reduce the above equation to

$$Thrust = R_{LC} \tag{2}$$

Therefore, the force recorded by the load cell is a direct measurement of the thrust.

Method #2. Thrust measurement from jet exit conditions

Consider the cylindrical control volume (CV) as defined by the control surface (CS) shown in Figure 7 where the top of the control volume is at the exit of the jet. The general y-direction momentum equation is given by

$$F_{S\,y} + F_{B\,y} = \frac{\partial}{\partial t}\int_{CV} v\,\rho\, dV + \int_{CS} v\,\rho \vec{V}\cdot d\,\vec{A} \tag{3}$$

Assuming that the flow is steady (CV properties do not change with time), and the properties at the exit of the jet (V_{exit}, p_{exit}, and ρ_{exit}) are uniform (they do not vary with r), the momentum equation can be solved for the above control volume resulting in

$$R_{LC} + R_{bal} - W_j - (P_{exit} - P_{atm})\,A_{exit} = V_{exit}^2 \rho_{exit} A_{exit} \tag{4}$$

where V_{exit} is the exit velocity, p_{exit} is the jet exit pressure, ρ_{exit} is the jet exit density, and p_{atm} is the atmospheric pressure. Now, we can assume that the body force is essentially equal to the weight of the jet apparatus (W_j) and is balanced by R_{bal} (i.e. $R_{bal} = W_j$). We also assume that the change in the reaction force of the balance (R_{bal}) due to hose pressurization and friction from the ball bearing is negligible. With this in mind, the thrust is then the force equal and opposite in direction to the reaction force from the load cell (R_{LC}). We can solve for the thrust magnitude as

$$Thrust = (P_{exit} - P_{atm})\, A_{exit} + V_{exit}^2\, \rho_{exit}\, A_{exit} \tag{5}$$

The unknowns in this equation (which need to be calculated from measurements) are the exit properties (p_{exit}, V_{exit}, ρ_{exit}). These properties can be solved by knowing the total properties (P_0 and T_0) in the stagnation chamber of the jet. The total temperature has been measured previously and is relatively constant at 295 K. The stagnation chamber pressure (P_0) will be measured at each valve position. In order to investigate the applicability of the various assumptions, three analytical methodologies will be used to calculate the jet exit properties from the total properties in the stagnation chamber: 1) the incompressible Bernoulli equation, 2) the isentropic flow assumption, 3) the isentropic/choked flow assumption.

Method #2a. Thrust measurement from jet exit conditions: Constant density and Bernoulli Equation, $P_{exit} = P_{atm}$

The Bernoulli Equation is given by

$$\frac{P_1}{\rho} + \frac{V_1^2}{2} + gz_1 = \frac{P_2}{\rho} + \frac{V_2^{\,2}}{2} + gz_2 = \text{constant} \tag{6}$$

where P is the pressure and V is the velocity and the subscripts 1 and 2 refer to two points along a streamline. Three assumptions must be applicable to use the Bernoulli equation. First, the flow must be frictionless. Secondly, the Bernoulli equation should be applied along a streamline. If we apply the equation between two points, one of them in the stagnation chamber of the jet where the velocity is approximately zero and the other point at the exit of the jet where we assume the pressure is equal to atmospheric pressure (as shown in Figure 7), we can solve for the velocity at the exit of the jet. It is given by

$$V_{exit} = \sqrt{\frac{2\,(P_{0stag} - P_{atm})}{\rho}} \tag{7}$$

where P_{0stag} is the absolute stagnation pressure and P_{atm} is the atmospheric pressure (~ 14.7 psia). It should be noted that, in order to measure a more accurate stagnation pressure, a pitot probe has been placed in the stagnation chamber of the jet facing upstream.

The third assumption in using the Bernoulli equation is that the flow must be incompressible (i.e., the density must not vary throughout the flow field). Therefore, the density at standard conditions is used in equation 7. The accuracy of this assumption (which will be investigated in this laboratory) is usually determined by the local Mach number. According to Fox and McDonald [1], if the Mach number is less than 0.3, the flow can be assumed to be incompressible. The Mach number is defined as:

$$M = \frac{V}{a} \tag{8}$$

where V is the local gas velocity and a is the local speed of sound which is given by:

$$a = \sqrt{\gamma R T} \tag{9}$$

where T is the temperature (absolute in Kelvins) of the gas, γ is the specific heat ratio (which is 1.4 for air), and R is the specific gas constant [287 J/(kg•K) for air]. If the Mach number is higher than 0.3, the effects of compressibility must be taken into consideration. Therefore, a second method which takes into consideration compressibility will be compared to the results calculated using the Bernoulli equation, demonstrating the inaccuracies at higher Mach numbers when approaching sonic velocity.

Method #2b. Thrust measurement from jet exit conditions: Isentropic Flow Assumption to determine ρ_{exit} and V_{exit} , $P_{exit} = P_{atm}$

If the converging nozzle of the jet is smooth and there are minimal losses through it, the flow can be assumed to be isentropic. Isentropic processes are those for which there are no losses (i.e., the acceleration process is reversible) and no heat transfer (i.e., the acceleration process is adiabatic). Using a one-dimensional analysis (such as a flow accelerating through a gradually converging nozzle) and assuming the process is isentropic and that the fluid behaves as an ideal gas, the velocity can be calculated relative to the stagnation conditions without the assumption of an incompressible flow. The stagnation condition is the real (or imaginary) condition that is found by isentropically decreasing the speed of the flow to zero velocity. In the present experiments, the stagnation condition can be assumed to exist in the stagnation chamber, where the velocity is approximately zero. From this one-dimensional analysis, the following equations can be derived for the temperature and pressure ratios. They are given by:

$$\frac{P_0}{P} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/(\gamma-1)} \tag{10}$$

$$\frac{T_0}{T} = 1 + \frac{\gamma - 1}{2} M^2 \tag{11}$$

where T_0 and P_0 are the absolute stagnation temperature and absolute stagnation pressure, respectively (in the stagnation chamber), M is the Mach number (which can be subsonic or supersonic), and P and T are the local absolute static pressure and temperature, respectively. It should be noted that only the pressure equation requires the reversibility assumption in the derivation. Also, the pressures and temperatures in these equations are absolute (i.e., kPa absolute for the pressure and Kelvins for the temperature), as opposed to gage pressures measured relative to atmospheric pressure. Using equations 10 and 11, with the perfect gas equation and the definition of the Mach number, we can now solve for the velocity and density at the exit of the jet. First, from equation 10 the Mach number that is achieved by expanding the flow from stagnation to ambient conditions isentropically is given by:

$$M_{exit} = \sqrt{\frac{2}{\gamma - 1}\left[\left(\frac{P_{0stag}}{P_{atm}}\right)^{(\gamma-1)/\gamma} - 1\right]} \tag{12}$$

where P_{0stag} is the absolute pressure in the stagnation chamber, and P_{atm} is the absolute pressure at the exit of the jet, which is atmospheric pressure (~ 14.7 psia) for the present case. For Mach numbers less than or equal to one (or if we assume isentropic flow throughout), the pressure at the exit is atmospheric pressure and $M_{exit} = M$ as defined in equation 12 (we will deal with the choked condition when $M > 1$ shortly). Once we know M_{exit}, (and assuming that it is less than or equal to one), we can find the static temperature at the exit of the jet T_{exit} from equation 11, which is given by:

$$T_{exit} = \frac{T_{0stag}}{1 + \frac{\gamma - 1}{2} M^2_{exit}} \tag{13}$$

where T_{0stag} is the absolute temperature (Kelvins) in the stagnation chamber, which has been measured to be constant and approximately 295 K. From the definition of the Mach number (equation 8), we can now solve for the exit velocity of the jet, which is given by:

$$V_{exit} = M_{exit} \sqrt{\gamma R T_{exit}} \tag{14}$$

We can also solve for the density at the exit (ρ_{exit}) using the perfect gas equation which is given by:

$$\rho_{exit} = \frac{P_{exit}}{R T_{exit}} \tag{15}$$

Therefore, from the stagnation pressure measurements taken in the laboratory (P_0), the velocity and density can be calculated from equations 12 - 15. The thrust can then be calculated from equation 5. One should note that in using these equations, the stagnation pressure should also be absolute pressure, and the temperature is absolute (Kelvins or Rankine depending on the units of the gas constant, R).

Method #2c. Thrust measurement from jet exit conditions: Isentropic Flow Assumption to determine ρ_{exit} and V_{exit} : Supersonic Flow (M > 1 from equation 12)

If the Mach number calculated by equation 12 is supersonic (the Mach number is greater than one) for a converging nozzle where the flow is isentropic within the nozzle, the point at which the flow is supersonic is not at the exit of the jet, but slightly further downstream (recall that a converging-diverging nozzle is required to have a supersonic flow at the jet exit which is perfectly expanded to atmospheric pressure). This is due to the fact that the jet is underexpanded and for a converging nozzle the flow is choked. Therefore, the Mach number at the exit of the jet is Mach 1 and achieves supersonic flow through a series of expansion waves approaching the isentropic value of the Mach number further downstream (this Mach number is sometimes termed the equivalent Mach number since the supersonic Mach number is achieved through expansions which occur outside of the nozzle). Returning to the control volume analysis at the exit of the jet when the Mach number calculated by equation 12 is greater than one, the following properties define the flow at the exit:

Using equation 12 if M is greater than one

$$M_{exit} = 1 \text{ (choked flow for a converging nozzle)} \tag{16}$$

Evaluating equation 13 for M_{exit} = 1 and $T_{0\ stag}$ = 295 K

$$T_{exit} = T_{0stag} / 1.20 \tag{17}$$

Evaluating equation 14 for M_{exit} = 1 and T_{exit} calculated from above

$$V_{exit} = \sqrt{\gamma R\, T_{exit}} \tag{18}$$

Since the pressure is higher than atmospheric pressure at the exit for supersonic Mach numbers, in our present case, we must evaluate P_{exit} for M_{exit} =1 and utilizing equation (10) for air we get

$$P_{exit} = P_0 / 1.893 \tag{19}$$

Again, we can solve for the density at the exit (ρ_{exit}) using the perfect gas equation, which is given by:

$$\rho_{exit} = \frac{P_{exit}}{R\, T_{exit}} \tag{20}$$

Therefore, from the stagnation pressure measurements taken in the laboratory (P_0) for the cases for which the flow is supersonic (M > 1 in equation 12), the exit velocity, pressure, and density can be calculated from equations 16 thru 20. The thrust can then be calculated from equation 5.

REFERENCES

[1] Fox, R.W., Pritchard, P.J., McDonald, A.T., *Introduction to Fluid Mechanics*, 7th Ed., John Wiley & Sons, Inc., Hoboken, NJ, 2009.

Technical Presentation Results and Discussion: Tables, Plots, Comments

For all calculations consider that the stagnation temperature (T_0) is equal to 295 K.
Jet Diameter = 0.20 inches
Convert and present all data in SI units (meters, Newtons, kg, seconds)
Include slide numbers on all slides
Table and graph notes/reminders:

a. The number of significant figures in tabulated data implies the accuracy that is presented by the data (changing units does not improve the accuracy of measurements).
b. In graphs, both axes should have legible values and titles that are not inside the graph.
c. In general, data markers are used for specific experimentally acquired data points, and values from equations should be shown simply as lines (without markers).
d. In general, graphs in presentations should not have titles and are not numbered.
e. Colors and line types on graphs should be chosen to be easily distinguished and identified in the legend.
f. The axis limits should be chosen to minimize blank space on plots in order to emphasize data.

1. Calculate and make a table of the thrust measured using the load cell (eqn. 2) for each stagnation chamber pressure. Comment on the trends and accuracy of the thrust measurement.

2. Calculate and create a graph of the isentropic (or equivalent) Mach number (eqn. 12) for each stagnation chamber pressure with the stagnation pressure on the *x*-axis and the Mach number on the *y*-axis. The equivalent Mach number is defined as the Mach number that is obtained assuming that the flow is expanded isentropically from the stagnation pressure to the atmospheric pressure. In addition to the line indicating the isentropic Mach number, plot a second line starting after the nozzle chokes indicating the actual Mach number at the exit equals one (this will be a horizontal line of $M_{exit} = 1$ since the flow is choked). Comment on the trends and implications of the Mach number on the accuracy of the Bernoulli equation. Comment on whether there is anywhere in the flow where you would expect the Mach number to approach the isentropic (equivalent) Mach number. Ensure that the lines on the graph have different styles (dotted, dashed, solid), so they can be distinguished and identified in a legend.

3. Calculate and create a graph of the exit velocity determined from the stagnation chamber pressure using three different approaches:
    1. The Bernoulli equation and constant density assumption (eqn. 7)
    2. Assuming that the flow is isentropic throughout (eqn. 14)
    3. Assuming isentropic flow for subsonic isentropic Mach numbers and choked flow for supersonic isentropic Mach numbers [eqn.14 (subsonic) or 18 (supersonic)]

   The plot should have three lines with the stagnation pressure on the *x*-axis and the velocity on the *y*-axis. Comment on the trends of each approach and where each is accurate. Ensure that the lines on the graph have different styles (dotted, dashed, solid), so they can be distinguished and identified in a legend.

4. Calculate and create a table of the thrust (eqn. 5) calculated from the stagnation chamber pressure using three methods:
   1. The Bernoulli equation and constant density assumption (eqns. 6 & 7)
   2. Assuming that the flow is isentropic throughout (eqns. 10 – 15)
   3. Assuming isentropic flow for subsonic isentropic Mach numbers and choked flow for supersonic isentropic Mach numbers (Subsonic: eqns. 10 – 15; Supersonic: eqns. 16-20)

   Comment on the trends and accuracy of the thrust measured by these methods.

5. On a single graph, plot the thrust determined from all four methods calculated above:
   1. Direct thrust measurement from the load cell
   2. The Bernoulli equation and constant density assumption
   3. Assuming that the flow is isentropic throughout
   4. Assuming isentropic flow for subsonic isentropic Mach numbers and choked flow for supersonic isentropic Mach numbers

   Put the thrust on the *y*-axis and stagnation pressure on the *x*-axis. Comment and compare the different methods used to calculate the thrust and state which is the most accurate. Ensure that the lines on the graph have different styles (dotted, dashed, solid), so they can be distinguished and identified in a legend.

6. Comment on what you observe from a sampling of the schlieren photographs and why the observed flow features occur.

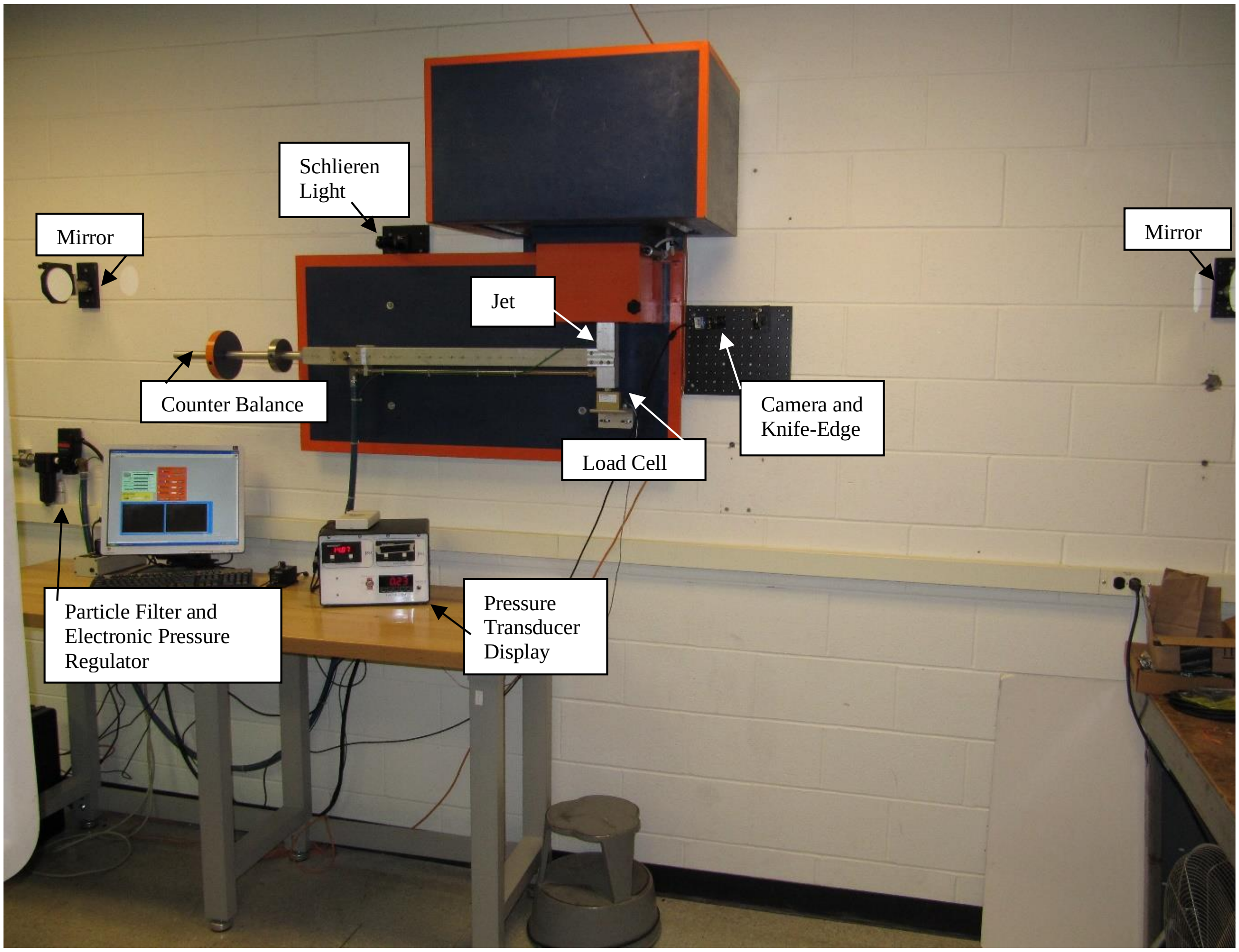
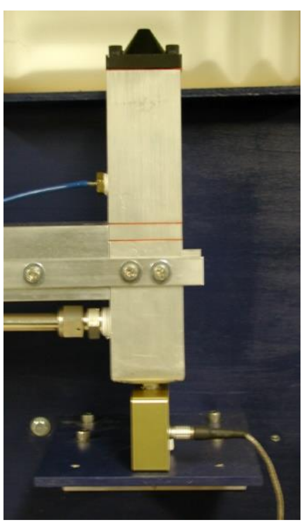


Figure 1. Set-up for jet thrust laboratory.



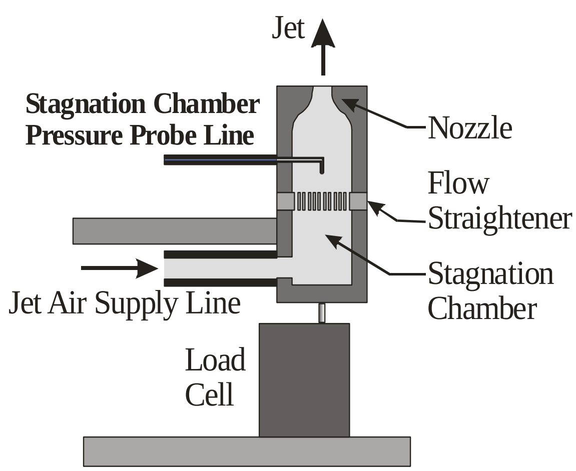


Figure 2. Converging nozzle, stagnation chamber, and load cell picture and schematic.

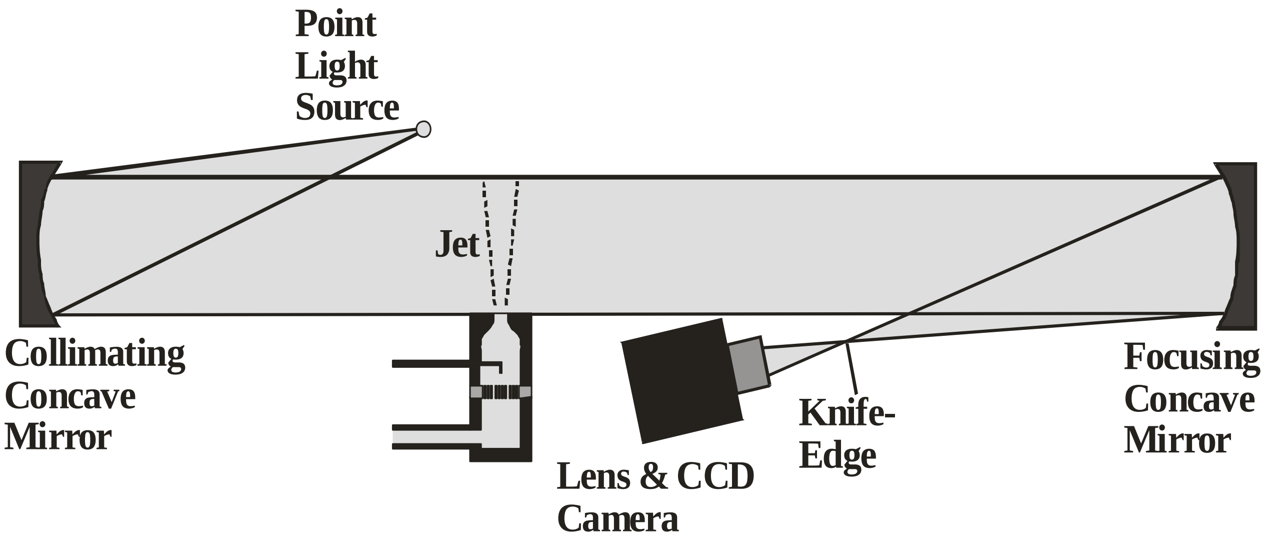


Figure 3. Schematic of schlieren system.

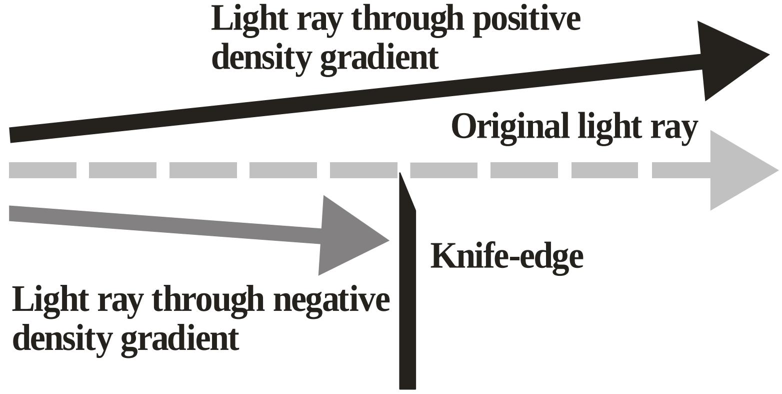


Figure 4. Schematic of light rays and knife-edge for schlieren photography.

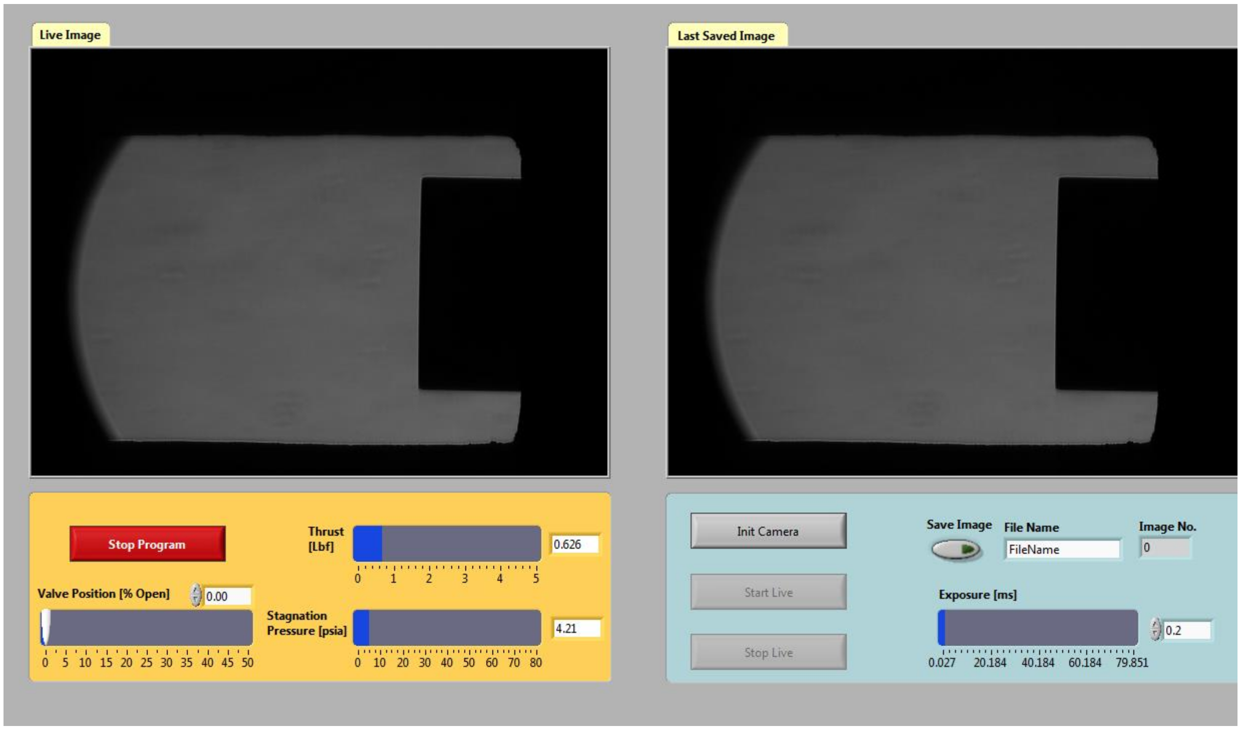


Figure 5. Front panel of LabVIEW jet thrust control program.

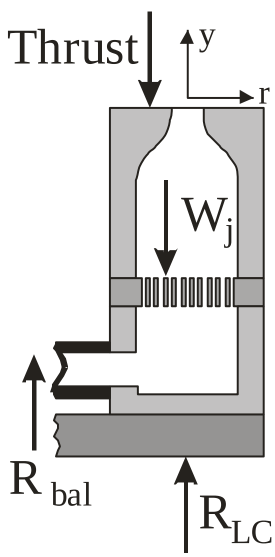


Figure 6. Free-body diagram of forces relevant to direct jet thrust measurement.

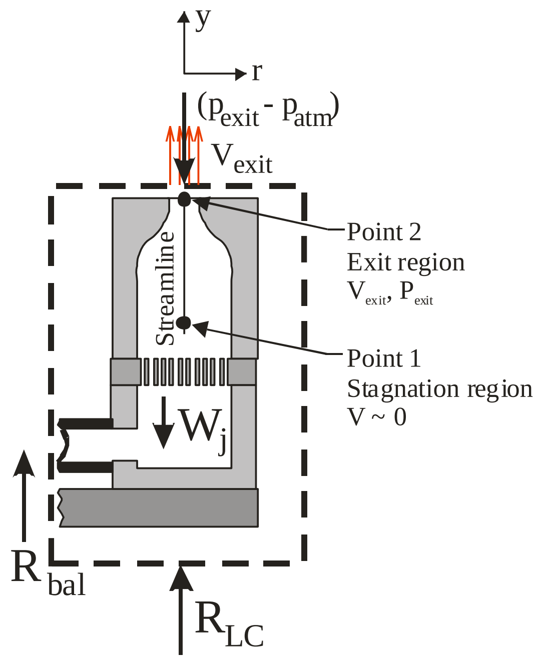


Figure 7. Control volume for calculation of jet thrust from exit conditions.

Data Table for Jet Thrust Experiment

Names: ____

Section/Group: ________________________________ Date: _______________

Conditions with jet off:

Pressure (psia): __________________

Force (Lb_f): __________________

Data Point	Valve Position %	Stagnation Pressure [psia]	Load Cell [Lb_f]	Schlieren File Name
1	2.0			
2	4.0			
3	6.0			
4	12.0			
5	20.0			
6	25.0			
7	35.0			
8	50.0			
9				
10				