

# The Engineering of Everyday Things

An Undergraduate Engineering Laboratory Curriculum  
in the Thermal and Fluid Sciences

[eet.cecs.pdx.edu](http://eet.cecs.pdx.edu)

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Gerald Recktenwald  
Mechanical & Materials Engineering  
Portland State University  
P.O. Box 751  
Portland, Oregon 97207

Bob Edwards  
Mechanical Engineering Technology  
Penn State Erie, The Behrend College  
5101 Jordan Road, REDC 242  
Erie, PA 16563-1701

## Overview

This document provides samples of the laboratory worksheets and in-class demonstrations developed for the Engineering of Everyday Things (EET) Curriculum. Additional information on the hardware, or on assessment of learning gains and student attitudes, can be obtained by contacting the authors via email, through the references listed on the following page, or via the project web site [eet.cecs.pdx.edu](http://eet.cecs.pdx.edu).

## Laboratory Exercises

Laboratory worksheets are used by students while they work in groups of four (typically) during a 1.5 to 2 hour laboratory session. The worksheets use a guided-inquiry pedagogy that attempts to engage students in measurement and reasoning typical of engineering practice. Worksheets for the following exercises are included in this booklet.

- Tank Filling
- Tank Draining
- Sudden Expansion
- Power Supply
- Blender
- Hair Dryer

At the end of the laboratory exercise, students turn in their worksheets for grading.

## In-class Demonstrations

In-class demonstrations are 15 minute exercises that can be used to motivate a classroom discussion and to provide formative assessment data. The demonstrations are small, portable experiments using everyday technology familiar to students. A notebook computer running LabVIEW, a USB-based data acquisition system, and the apparatus (with sensors) are arranged at the front of the classroom. The video signal from the notebook is connected to the projection system for the classroom so that students can see a visual display of the data as it is acquired.

In a typical demonstration, the instructor describes the apparatus and the measurements that are about to be made. A one or two-page handout with short questions is distributed to the students. The questions ask the students to predict the system behavior when the experiment is conducted. After the student responses are collected, the experiment is run and the results are discussed. In-class demonstrations for the following exercises are included in this booklet.

- Toaster
- Bicycle Pump

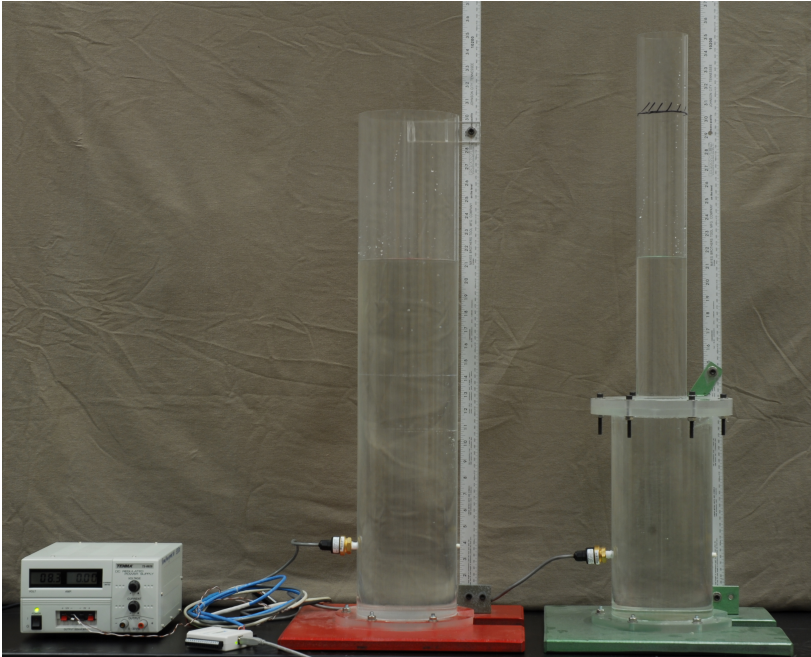
Similar demonstrations for the Blender and Hair Dryer are also available.

## References

Additional information about the exercises, including preliminary assessment results are available in the following papers and presentations. Contact the authors or visit the project web site [eet.cecs.pdx.edu](http://eet.cecs.pdx.edu) for additional information or links to electronic copies of these reports.

1. Edwards, R. and G. Recktenwald (2007), *Teaching core concepts in thermal and fluid sciences using devices familiar to students*, Engineering Teaching & Learning Practice, University of Toronto, Ontario, Canada.
2. Edwards, R. and G. Recktenwald (2008), *Guided inquiry in an engineering technology classroom*, ASEE Annual Conference and Exposition, Pittsburgh, PA, American Society for Engineering Education.
3. Edwards, R. and G. Recktenwald (2009), *Simple experiments for the thermal and fluid sciences*, ASEE Annual Conference and Exposition, Austin, TX, American Society for Engineering Education.
4. Edwards, R., G. Recktenwald, and B. Benini (2009), *A laboratory exercise to teach the hydrostatic principle as a core concept in fluid mechanics* ASEE Annual Conference and Exposition, Austin, TX, American Society for Engineering Education.
5. Hsieh, C., G. Recktenwald, and R. Edwards (2008), *Implementing Inquiry-based Experiments in a Fluid Science Laboratory Class* ASEE Annual Conference and Exposition, Pittsburgh, PA, American Society for Engineering Education.
6. Recktenwald, G. and R. Edwards (2007), *Using Simple Experiments to Teach Core Concepts in the Thermal and Fluid Sciences*, ASEE Annual Conference and Exposition, Honolulu, Hawaii, American Society for Engineering Education.
7. Recktenwald, G. and R. Edwards (2007), *The Engineering of Everyday Things*, Poster Session for the Regional ASEE Meeting, Pacific Northwest Section, Washington State University, Pullman, WA.
8. Recktenwald, G., R. Edwards, D. Howe, J. Faulkner, and C. Hsieh (2009), *The Engineering of Everyday Things: Simple experiments for the thermal and fluid sciences*, ASEE Annual Conference and Exposition, Austin, TX, American Society for Engineering Education.
9. Recktenwald, G., J. Faulkner, C. Hsieh, and R. Edwards (2008), *Using a blender to teach qualitative reasoning with the first law of thermodynamics*, AAAS – NSF CCLI Conference, Washington, DC, AAAS.

# Tank Filling Lab Exercise





# Tank Filling Lab Exercise

March 20, 2009

Participant Code: \_\_\_\_\_

## 1 Apparatus

Figure 1 shows the equipment for this laboratory exercise. The key components are:

1. Two cylindrical tanks, one with straight walls (single diameter) and another with a step-shaped wall (two diameters);
2. A pressure transducer mounted on the side of each tank;
3. A power supply to provide electrical energy to the transducer;
4. A data acquisition device (DAQ) for digitizing the transducer output;
5. A computer to record and display the digitized output of the transducer.

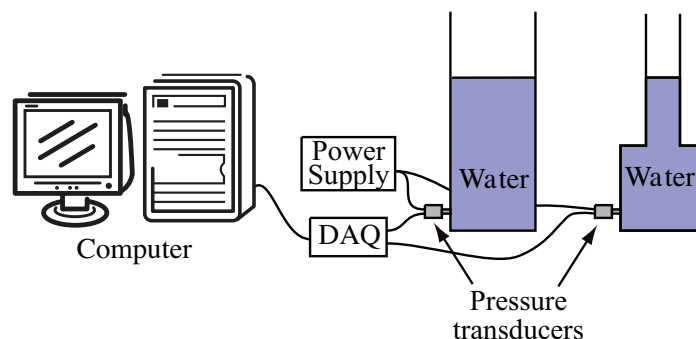


Figure 1: Apparatus for the tank-filling experiment.

## 2 Lab Preparation

This experiment is likely to take about 1.5 hours to complete. If you are participating in the study and have forgotten your code number the instructor can look it up for you. If you are not participating in the study write “not in study” in the space for *Participant Code* at the top of the page.

You will be asked to take a brief quiz before you start the lab exercise, and another brief quiz at the end of the exercise. These quizzes will not affect your grade, but you will earn participation points for making an honest effort to answer the questions on the quizzes. The answers on the quiz are a way to measure how well the lab exercises helps you to learn the material.

As part of the lab exercise you will be asked to make simple plots of measured data. You can use Excel or MATLAB if you wish, but you must attach hard copies of your plots to these worksheets. If you are working in a group make sure each member of the group has a hard copy of each plot attached to their worksheets. Make sure the plots are labelled so that the instructor can correctly grade the plots as part of the worksheet.

## Learning Objectives

The laboratory exercise involves measurements and analysis related to the variation of pressure with the amount of water in a tank.

After successfully completing this exercise students will be able to

- Identify a pressure transducer and explain its role in measuring/transmitting pressure values to a data collection system;
- Identify the fluid properties and other physical variables that determine the pressure at some depth in a tank partially filled with water and open to air;
- Predict the trend in pressure with tank depth;
- Compute the pressure at any depth below the free surface of a tank partially filled with liquid;
- Predict how the relationship between pressure and depth changes with the shape of the tank.



Before continuing, please complete  
the pre-lab quiz.

INSTRUCTOR APPROVAL

### 3 Tank with Uniform Diameter

This exercise involves recording the pressure transducer output with different amounts of water in the straight-walled tank. The pressure is measured with a pressure transducer connected to the data acquisition system and the personal computer.

#### 3.1 Pressure Transducer Measurements

1. Start the *Virtual Instrument (VI)*. The Lab Assistant should have LabVIEW running on the computer running and the VI loaded.
  - a. Click on the “Run” arrow
  - b. The display of the transducer voltage should change in the least significant digits.
2. Data collection.
  - a. Add some water to the tank.
  - b. In Table 1, record the depth of water in the tank and the voltage output from the transducer. For now, ignore the last three columns (“Pressure”, “Independent variable ( $x$ )” and “Dependent variable ( $y$ )”).
  - c. Repeat steps (1) and (2) enough times to establish a clear trend in the data. At least four readings are necessary. Make sure your readings are spread over the entire range of the possible fluid depths for the tank.
  - d. Inspect the raw data you have recorded
    - Be sure to label the data with appropriate units. Be sure your units are consistent.
    - What is the appropriate reference point for the depth of water measurement? In other words, where is the physical location of the “zero depth” point in the tank?

Table 1: Data for the straight-walled tank experiment.

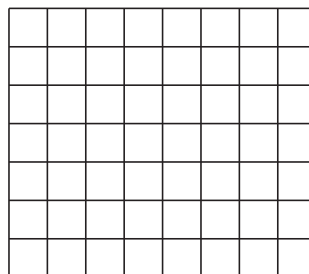
Measured		Calculated		
Water Depth	Transducer Output	Pressure	Independent variable ( $x$ )	Dependent variable ( $y$ )

### 3.2 Calibration and Data Conversion

To relate the preceding measurements to the standard model of fluid behavior, the voltage output of the pressure transducer must be converted to pressure.

Calibration data from the manufacturer: At  $p = 0$  the transducer output is 1 V. At  $p = 1$  psig, the transducer output is 5 V.

1. Use the grid to the right to create a plot of pressure versus voltage for the transducer. Be sure to label the axes. Assume that the transducer output is linear with pressure.



2. Using the plot you just created as a guide, what is the calibration formula for the pressure transducer? In other words, if  $p = f(v)$  what is  $f(v)$ ?
3. Apply your calibration formula to the transducer output data from table 1 and fill in the *Pressure* column in the Table 1.

### 3.3 Analysis of Pressure Data

1. What is (are) the independent variable(s) for the measured and converted data in Table 1? What is (are) the dependent variables?

Dependent Variable(s):

Independent Variable(s):

Choose one pair of definitions for the dependent and independent variables to complete the last two columns of Table 1. It may be helpful to read the next step (on the next page) before you complete Table 1.

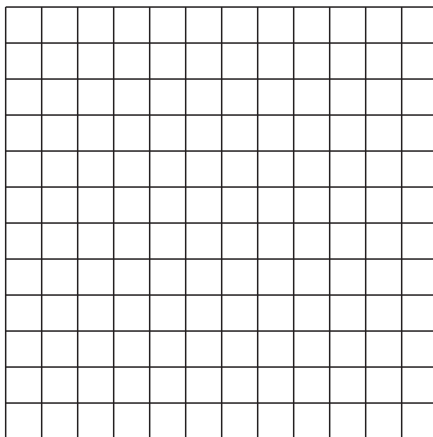
**Definitions:**

An *independent variable* is an input or parameter that is directly controllable by the person performing the experiment. An independent variable is often, though not always, the quantity on the  $x$  axis of a plot.

A *dependent variable* is the output or result of changing a system. A dependent variable is often, though not always, the quantity on the  $y$  axis of a plot.

In an experiment, both independent and dependent variables are measured.

2. Use following the grid to make a plot of the data in the last two columns of Table 1. Plot your choice of the independent variable on the horizontal axis and the dependent variable on the vertical axis. Be sure to label your axes.



3. What, if any, observations can you make from the plot you just created?
4. Is the pressure related to the water depth, water volume, or some other parameter? How does the data support your answer?
5. List at least two possible parameters that may effect the pressure. (*Hint*: One of the parameters is a property of the fluid.)



Before continuing, show your lab manual to the instructor. It's important at this point to make sure you are on the right track.

INSTRUCTOR APPROVAL

## 4 The Step-Walled Tank

Repeat Experiment from Section 3.1, but use the step-walled tank instead of the straight-walled tank. Record your data in the Table 2 below.

- Since the tank diameter varies with depth, record the tank diameter at the free surface along with the depth measurement. The values in first column will be either 7.62 cm (3 inch) or 15.2 cm (6 inch).
- Make at least two measurements from water levels in the larger diameter tube and two measurements from water levels in the smaller diameter tube.
- Be sure to add units to the table.
- Use the calibration developed in Section 3.2 to convert the pressure transducer output to pressure.

What your independent and dependent variables for this experiment?

Dependent Variable(s):

Independent Variable(s):

Table 2: Data for the step-walled tank experiment.

Diameter	Measured		Calculated	
	Water Depth	Transducer Output	Independent variable ( $x$ )	Dependent variable ( $y$ )

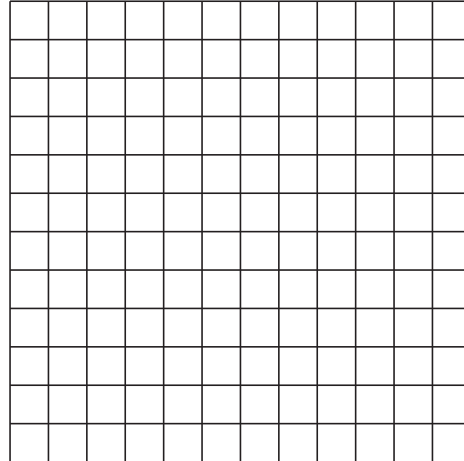


Before continuing, show your lab manual to the instructor. It's important at this point to make sure you are on the right track.

INSTRUCTOR APPROVAL

## 5 Comparing Measurements from the Two Tanks

Plot the data measured in Section 3.1 and Section 4 on the same axes. Label the axes appropriately.



1. Does the change in diameter at the free surface affect the pressure? Does this make sense based on your personal experience or intuition?
2. Draw a line on the graph that follows the data as closely as possible. What the numerical value of the slope? What are the units of the slope? For example, if you plotted pressure as a function of depth, what is the nominal value of the slope in units of  $\text{N/m}^3$  or  $\text{lb}_f/\text{ft}^3$ ?
3. What theory can be used to explain the data? In other words, if you were to add a third set of data, and that data was created by a formula instead of measurements, what formula would you use?
4. In order to use the theoretical equation identified in your answer to the previous question, what other information is needed in order to compute numerical values before adding data to the plot? Could the missing values (data) in the formula be obtained from the measured data? How?



Before continuing, show your lab manual to the instructor. It's important at this point to make sure you are on the right track.

INSTRUCTOR APPROVAL

## 6 Reflection, Discussion and Extension

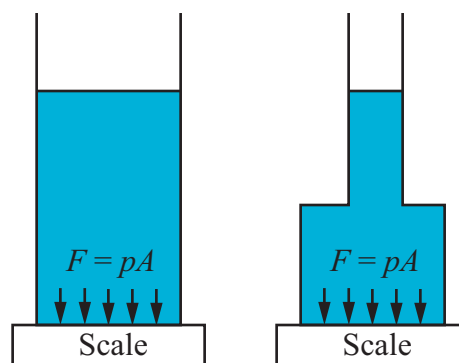
1. List the key similarities and differences for the two tanks.

Similarities:

Differences:

2. How do the differences in the shape of the tanks affect the variation of pressure with depth?
3. Does the theory “explain” the data? In other words, given the agreement (or disagreement) between the theory and measurements, how well will theory predict the pressure versus depth relationship for any shape of tank?
4. If a heavy object such as a rock was placed into either of the tanks before the water was added, what effect would it have on the pressure indicated by the transducer? Why? If the rock was added after the water was filled to a given depth, would the result be different? Why?

5. Suppose the two tanks are placed on scales as depicted in the sketch to the right. For a given depth of water, the straight-walled tank will weigh more than the step-walled tank. Considering the static equilibrium at the interface between the bottom of the tank and the top of scales, it would appear that the pressure in the bottom of the step-walled tank needs to be less than the pressure at the bottom of the straight-walled tank. How do resolve the paradox?

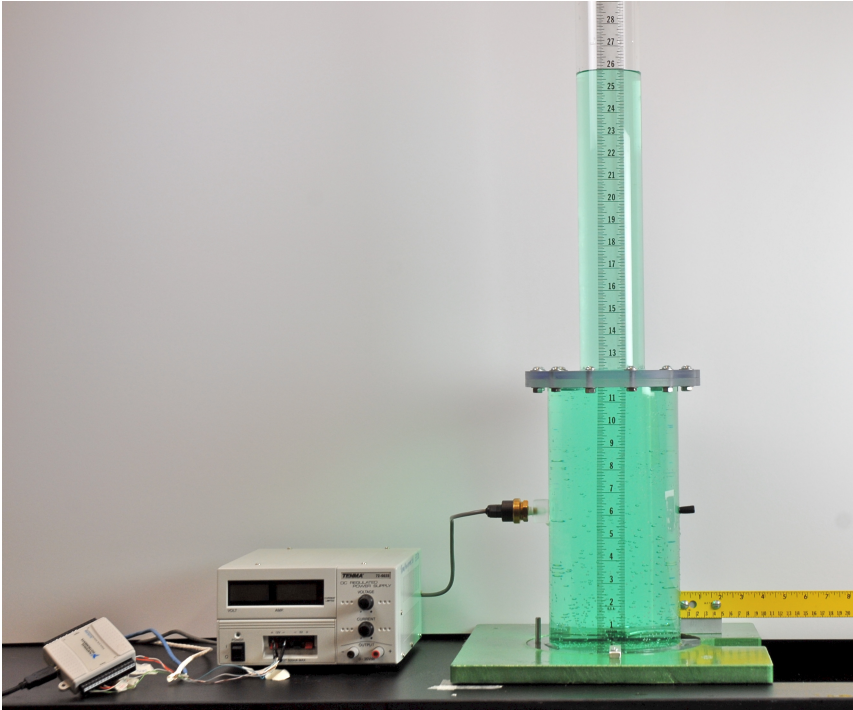


Give your completed worksheet to the instructor and take the post-lab quiz before leaving.

INSTRUCTOR APPROVAL



# Tank Draining Lab Exercise



## 1 Apparatus

Figure 1 shows the equipment for this laboratory exercise. The key components are

1. Two cylindrical tanks, one with straight walls (single diameter) and another with a step-shaped wall (two diameters).
2. A pressure transducer mounted on the side of each tank, and at a distance  $H$  from the base.

Not shown in the sketches are

3. A digital camera and tripod used to capture images of the free jet of water.
4. A power supply to provide electrical energy to the transducer.
5. A data acquisition device (DAQ) for digitizing the transducer output.
6. A computer to record and display the digitized output of the transducer

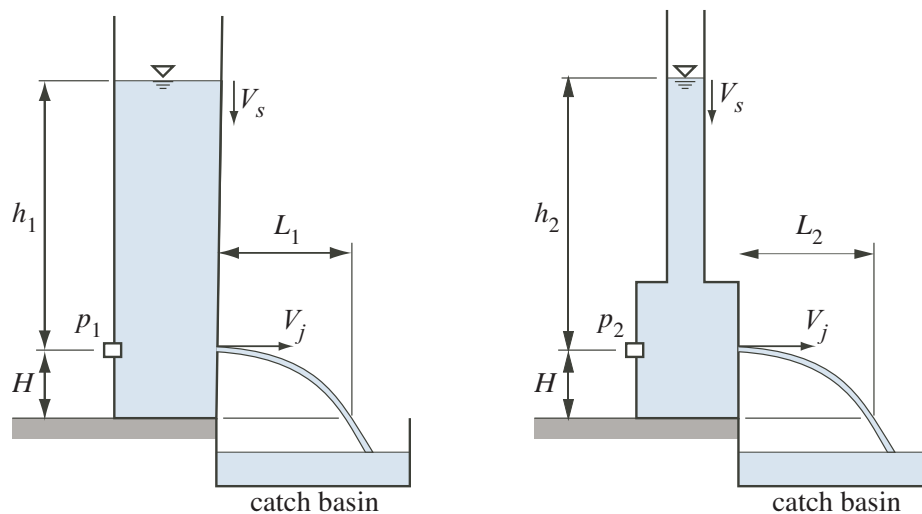


Figure 1: Apparatus for the tank-draining experiment.

## 2 Learning Objectives

After completing this lab exercise students will be able to

1. Apply mass conservation to a control volume with a time-varying mass.
2. Apply the Bernoulli and Energy Equations to compute the velocity of a free jet emerging from a hole in a tank;
3. Determine the pressure at depth in a tank with a small hole in its side;
4. Use digital photographs to measure geometric features, specifically the trajectory of the jet.

### 3 Background and Review

Read this section before coming to the laboratory.

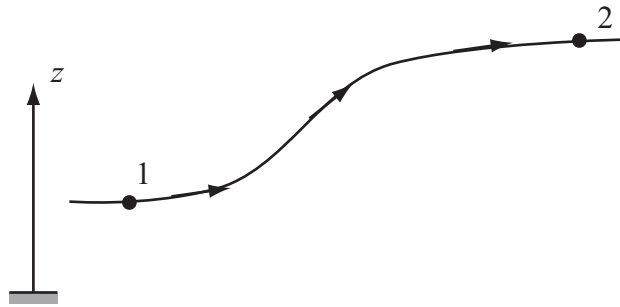
#### 3.1 Bernoulli and Energy Equations

The Bernoulli equation is

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 \quad (1)$$

where  $p$  is the static pressure,  $\gamma$  is the specific weight of the flowing fluid,  $V$  is the velocity magnitude, and  $z$  is the elevation above a fixed datum. The Bernoulli equation only applies along a streamline *if*

1. The flow is steady.
2. The flow is incompressible.
3. There is no heat or work interactions between stations 1 and 2.



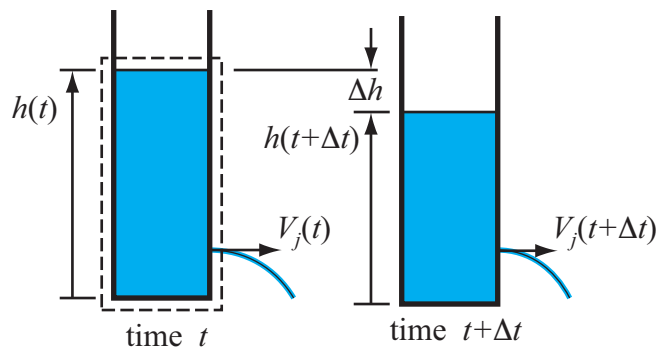
The steady flow energy equation is

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 - h_p + h_f \quad (2)$$

where  $h_p$  is the head increase due to shaft work by a pump and  $h_f$  is the head loss.

#### 3.2 Mass Conservation

The following diagram represents a cylindrical tank with a hole in its side. A jet of water with velocity  $V_j$  issues from the hole. The left diagram shows the tank at time  $(t)$ . The right diagram shows the tank at a later time  $t + \Delta t$ . The depth of the water is  $h(t)$ . The cross-sectional area of the tank is  $A_t$ . The cross-sectional area of the jet is  $A_j$ .



### Reynold Transport Theorem

Apply the Reynolds Transport Theorem to mass conservation for the dashed control volume.

$$\frac{\partial}{\partial t} \int_{CV} \rho dV + \int_{CS} \rho(\mathbf{V} \cdot \hat{\mathbf{n}}) dA = 0 \quad (3)$$

For the tank, the differential element of volume is  $dV = A_t dh$ . The first term simplifies to

$$\frac{\partial}{\partial t} \int_{CV} \rho dV = \frac{\partial}{\partial t} \int_0^h \rho A_t dh = \rho A_t \frac{dh}{dt}.$$

The integral over the control surface can be simplified by assuming that the water velocity is uniform over the control surface

$$\int_{CS} \rho(\mathbf{V} \cdot \hat{\mathbf{n}}) dA = \rho V_j A_j.$$

Substituting the pieces back into the Reynolds Transport Theorem yields

$$\rho A_t \frac{dh}{dt} + \rho V_j A_j = 0$$

Canceling the  $\rho$  and rearranging this equation gives

$$\frac{dh}{dt} = -\frac{A_j}{A_t} V_j. \quad (4)$$

### System Balance Formulation

Compare the fluid volume at two different times:  $t$  and  $t + \Delta t$ :

$A_t \Delta h$  = change in fluid volume during  $\Delta t$   
 $V_j A_j \Delta t$  = volume of fluid leaving via the jet

Equating those volumes and rearranging slightly gives

$$A_t \frac{\Delta h}{\Delta t} = V_j A_j$$

In the limit as  $\Delta t \rightarrow \infty$ , the ratio  $\Delta h/\Delta t$  becomes  $dh/dt$ . Since the depth of the water is decreasing the derivative is negative. Therefore the preceding equation becomes

$$\frac{dh}{dt} = -\frac{A_j}{A_t} V_j. \quad (5)$$

which is identical to Equation (4).

### 3.3 Study Questions

1. Although the fluid in the tank is moving, can the hydrostatic equation be used to related the pressure measured by the transducer to the depth of the water in either tank?
2. If the tank drains slowly, then the upper surface of the tank can be assumed to have zero velocity. Under this circumstance, the flow would be considered to be quasi-steady. In order for the tank flow to be considered quasi-steady, what must be the size relationship between the area of the tank and the area of the jet?
3. Regardless of whether the velocity at the upper free surface is negligible, can the steady form of the mass conservation equation be used to determine the relationship between  $V_0$ , the velocity at the upper free surface, and  $V_j$ , the velocity of the jet?

### 3.4 Pressure versus Depth

In a stationary liquid, the pressure at depth  $h$  is  $p = \gamma h$ , where  $\gamma$  is the specific weight of the liquid. Can that formula be applied when water is flowing out through the hole in the side of the tank?

Figure 2 depicts two streamlines that converge at the hole at Station 3 in the side of the tank. Station 1 is at the free surface. Station 2 is adjacent to the pressure transducer attached to the tank wall. Station 4 is on the streamline immediately outside of the tank. The following analysis shows that under some very reasonable assumptions, the pressure at Station 2 is determined only by the depth of water in the tank.

Write the Bernoulli Equation for the streamline from Station 1 to Station 3.

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_3}{\gamma} + \frac{V_3^2}{2g} + z_3 \quad (6)$$

Since Station 1 is a free surface:  $p_1 = 0$ ,  $V_1 = 0$ . Choose  $z_3 = 0$ .

$$\implies p_3 = \gamma z_1 - \frac{1}{2}\rho V_3^2 \quad (7)$$

Write the Bernoulli Equation for the streamline from Station 2 to Station 3.

$$\frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 = \frac{p_3}{\gamma} + \frac{V_3^2}{2g} + z_3 \quad (8)$$

Since Station 2 is adjacent to the wall,  $V_2 = 0$ . Also  $z_1 = z_3 = 0$ .

$$\implies p_2 = p_3 + \frac{1}{2}\rho V_3^2 \quad (9)$$

Combine Equation (7) and Equation (9) to obtain a formula for  $p_2$  as a function of  $z_1$ .

$$p_2 = \left( \gamma z_1 - \frac{1}{2}\rho V_3^2 \right) + \frac{1}{2}\rho V_3^2$$

Therefore,

$$\boxed{p_2 = \gamma z_1} \quad (10)$$

#### Your Summary:

Based on the preceding analysis, list two conditions under which  $p = \gamma h$  can be used to measure the instantaneous tank depth with the pressure transducer attached to the side wall of the tank.

- 1.
- 2.



Before continuing, show your lab manual to the instructor. It's important at this point to make sure you are on the right track.

INSTRUCTOR APPROVAL

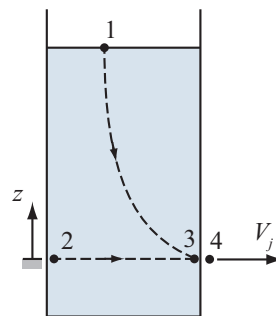


Figure 2: Streamlines used to determine pressure at tank side wall during tank draining.

### 3.5 Trajectory of a Free Jet

Figure 3 depicts the trajectory of the jet of water emanating from the hole in the side of the tank. The goal of the following exercise is to obtain a formula for  $L_{\text{jet}}$  as a function of the velocity  $V_j$  of the fluid as it leaves the hole. The water jet is assumed to retain the same diameter as it flows. The water is assumed to have a purely horizontal velocity component  $V_j$  when it leaves the hole at  $x_p = 0$ ,  $y_p = H$ .

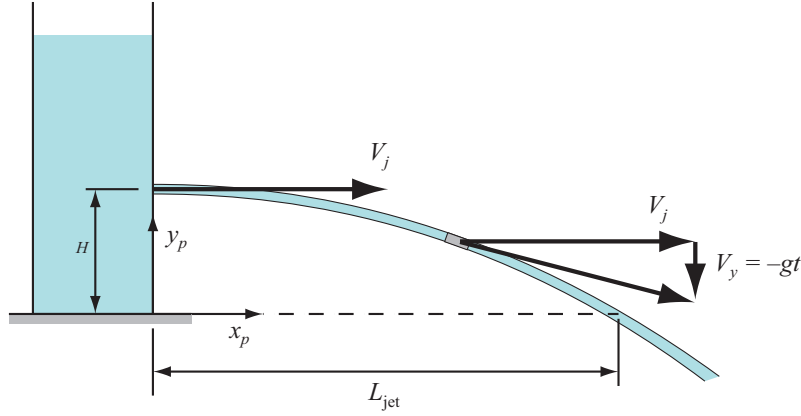


Figure 3: Arc of the water jet. The path of the fluid is assumed to be the same as that of a rigid particle falling under the influence of only gravity, and having an initial horizontal velocity  $V_j$ .

#### 3.5.1 Jet Shape Determined by Equations for Particle Motion

Consider the trajectory of a particle of water emerging from the hole in the side of the tank. Rearranging Newton's law of motion  $F = ma$  as  $a = F/m$ , and writing the differential form of the acceleration in the  $x$  and  $y$  direction gives.

$$\frac{d^2x_p}{dt^2} = 0 \quad \frac{d^2y_p}{dt^2} = -g$$

Integrate the equations of motion with the initial conditions ( $t = 0$ )

$$\frac{dx_p}{dt} = V_j, \quad x_p = 0, \quad \frac{dy_p}{dt} = 0, \quad y_p = 0.$$

The particle crosses the  $y_p = 0$  plane when  $\frac{1}{2}gt_0^2 = H$  or at time  $t_0 = \sqrt{2H/g}$ . At time  $t_0$  the particle has travelled a horizontal distance  $L_{\text{jet}} = V_j t_0$ . Therefore,

$$L_{\text{jet}} = V_j \sqrt{\frac{2H}{g}} \quad (11)$$

#### 3.5.2 Analytical Model of Jet Velocity

Apply the Bernoulli Equation between Station 1 and Station 4 in Figure (2) on page 5.

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_4}{\gamma} + \frac{V_4^2}{2g} + z_4$$

At the free surface,  $p_1 = 0$ , and  $V_1 = 0$ . At the jet exit,  $p_2 = 0$ . Making these assumptions the equation becomes

$$z_1 = \frac{V_4^2}{2g} + z_4$$

or

$$\frac{V_4^2}{2g} = z_1 - z_4. \quad (12)$$

Since  $V_j$  is the same as  $V_4$ , we finally get

$$V_j = V_4 = \sqrt{2gh}. \quad (13)$$

Substituting Equation (13) into Equation (11) gives

$$\boxed{L_{\text{jet}} = 2\sqrt{Hh}} \quad (14)$$

### 3.6 Study Questions

1. What physical effect(s) could cause the jet to not follow the trajectory of a rigid particle?
2. Suppose you had a series of measurements of  $L_{\text{jet}}$  and  $h$  at different times. After making a plot of  $L_{\text{jet}}$  versus  $h$ , how would you make a *quantitative* (i.e., numerical) comparison between the data in the plot and Equation (14)?



Before continuing, show your lab manual to the instructor. It's important at this point to make sure you are on the right track.

INSTRUCTOR APPROVAL

## 4 Tank Draining Transient

In this exercise, you will use LabVIEW software to simultaneously capture images of the trajectory of the water jet, and the pressure versus depth of the water in the tank as it drains.

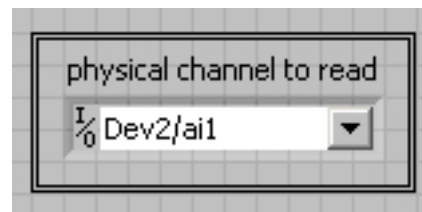
Estimate how long it will take the uniform tank to drain through the hole in the side of the tank. Will it take 3 seconds, 30 seconds, 3 minutes, or 30 minutes?

### 4.1 Uniform Tank Draining

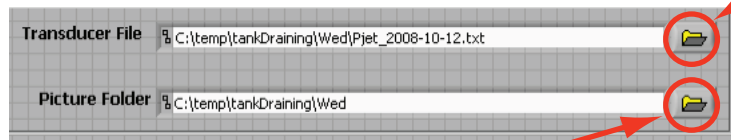
1. Make sure that the plug is securely in the hole on the side of the tank. Do not use excessive force with the plug. You want to be able to remove the plug with your fingers.
2. Fill the tank with water up to the black line near the top.
3. Set up the camera so that the view finder is centered on the ruler, the plugged hole is visible on the left edge, and the far end of the ruler is visible on the right edge.

4. Prepare the VI.

The data acquisition (DAQ) device and channel are specified with a string like DevN/ai1 for the straight tank and DevN/ai0 for the stepped tank. N is the device number, which depends on the workstation used for the experiment. Consult the TA or documentation attached to the experimental apparatus.



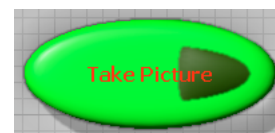
5. Choose a name for your pressure data file.



Click here  
to set folder for image data

Click here to  
set file name  
for pressure data

6. Start the VI, pull the plug, and while the tank is draining, press the "Take Picture" button. Wait until the picture button turns green again before attempting to take another picture.



7. To stop the experiment, press the large "Stop Measurements" button. Do not press the stop button on the LabVIEW menu bar.







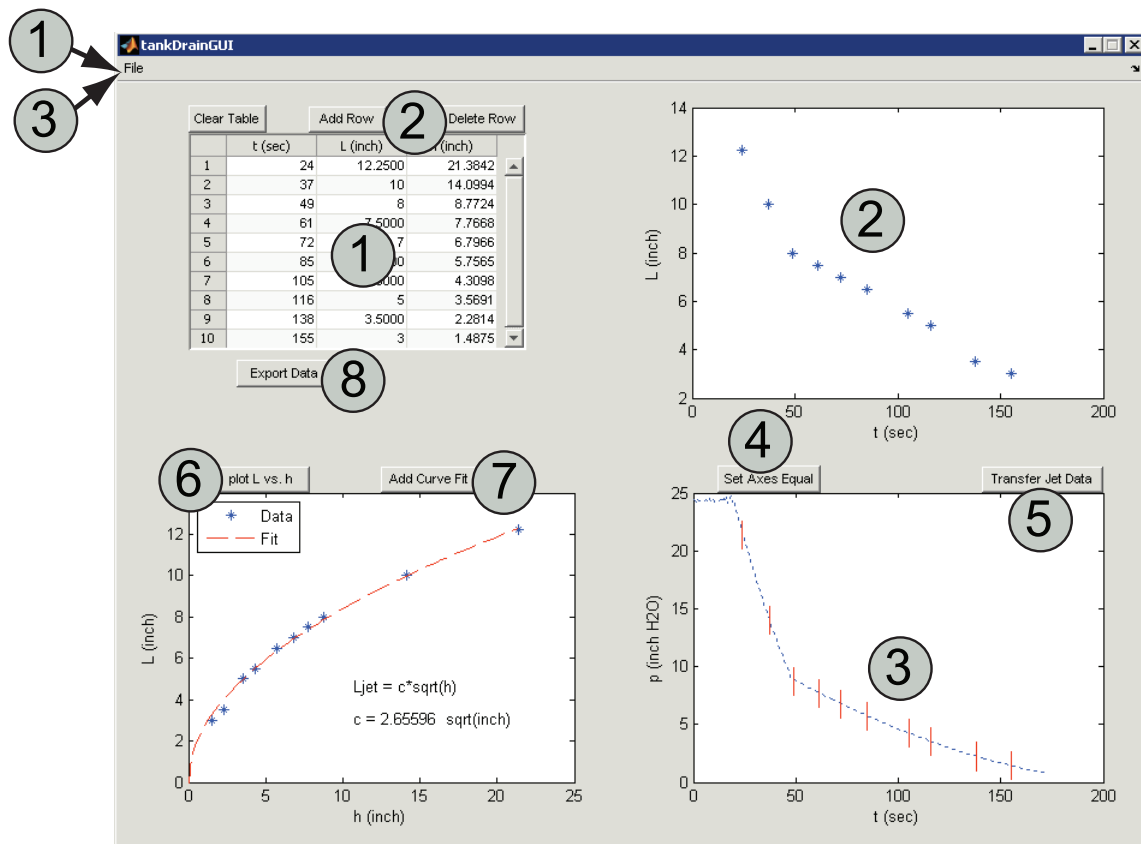


Figure 5: Annotated screen shot of the tankDrainGUI program.

### 4.3 Automated Analysis of Jet and Transducer Data

Start MATLAB and run the `tankDrainGUI` program by typing

```
>> tankDrainGUI
```

at the command prompt. Use the following steps to analyze the data. The numbers of the items in the list correspond to the large numbers in circles in Figure 5.

1. Enter  $(t, L_{\text{jet}})$  data in the table in the upper left quadrant of the GUI. Alternatively, if you have already saved some  $(t, L_{\text{jet}})$  data from previous work with `tankDrainGUI`, then load it by selecting **File**→**Open Jet Data** from menu at the top of the GUI window.
2. Data entered in the table is automatically plotted in the figure pane in the upper right quadrant of the GUI. You can directly edit data in the first two columns of the table. Row and table-level actions are achieved with the three buttons at the top of the table.

Clear Table replaces all values in the table with zeros.

Add Row inserts a new row at the bottom of the table.

Delete Row removes the row that is currently selected. A row is selected by clicking on a cell in the  $t$  or  $L$  columns.

Note that data in the  $h$  column is calculated by the program and cannot be edited manually.

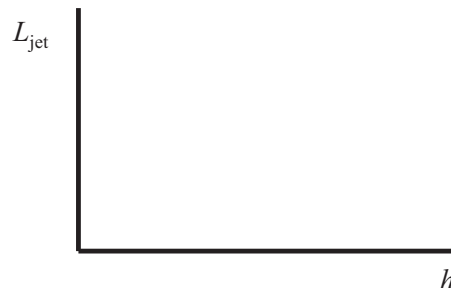
3. Load pressure versus time data by selecting **File**→**Open Pressure Data** from the menu at the top of the GUI window. Locate the file that was saved by the LABVIEW VI. After it is loaded, the  $(t, p)$  data is displayed in the figure pane in the lower right quadrant of the GUI.
4. The  $t$  axis scaling for the  $L_{\text{jet}}(t)$  and  $p(t)$  plots are unlikely to be the same. Click the **Set Axes Equal** button to use the same scale for  $t$  in both plots.
5. After  $L_{\text{jet}}(t)$  and  $p(t)$  have been loaded, click the **Transfer Jet Data** button. This causes the  $t$  values from the  $L_{\text{jet}}(t)$  data set to be transferred to the  $p(t)$  plot. Those  $t$  values are represented by short vertical lines that cross the  $p(t)$  data.

For each of the  $t$  values in the  $L_{\text{jet}}(t)$  data set, a new pressure value, call it  $\hat{p}$ , is obtained by interpolating in the measured pressure data set. The interpolated  $\hat{p}$  values are taken as the pressure (and hence tank depth) for each of the  $L_{\text{jet}}(t)$  values. Note that when the pressure is given in units of head, the pressure value is  $h$ , the depth of water measured from the location of the pressure transducer.

6. Click the **plot L vs. h** button to combine the jet length and pressure measurements in a single plot in the lower left quadrant of the GUI.
7. Click the **Add Curve fit** button to compute and plot a curve fit of the form  $L_{\text{jet}} = c\sqrt{h}$ . The curve fit to the data appears as a dashed red line. The curve fit coefficient  $c$  is displayed on the plot.
8. Click the **Export Data** button at the bottom of the data table in the upper left quadrant of the GUI. This opens a dialog box for specifying the file name and location of the data file. The file consists of the three columns of data shown in the upper left quadrant of the GUI.

#### 4.4 Qualitative Analysis of Tank Draining Data

On the axes to the right, sketch the relationship of  $L_{\text{jet}}$  versus  $h$ . Use an arrow to indicate the direction that the data on the curve follows as time increases during the tank draining experiment.



#### 4.5 Anticipation of Results for the Step-shaped Tank

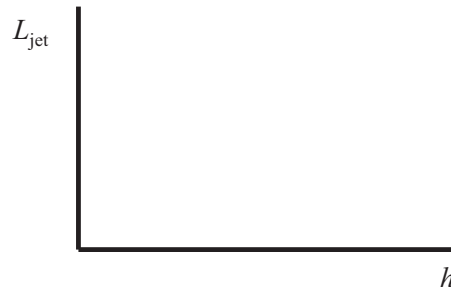
On the axes to the right, sketch the relationship of  $L_{\text{jet}}$  versus  $t$  for the step-shaped tank. Put a circle on the curve to identify the time where the free surface passes the change in area of the tank.



On the axes to the right, sketch the relationship of pressure transducer output versus  $t$  for the step-shaped tank. The pressure recorded by the transducer is proportional to the depth of water in the tank so the vertical axis is labeled  $h$ . Put a circle on the curve to identify the time where the free surface passes the change in area of the tank.



On the axes to the right, sketch the relationship of  $L_{\text{jet}}$  versus  $h$  for the step-shaped tank. Use an arrow to indicate the direction that the data on the curve follows as time increases during the tank draining experiment. Add a dashed curve to indicate the  $L_{\text{jet}}(h)$  relationship for the *straight* tank.



Before continuing, show your lab manual to the instructor. It's important at this point to make sure you are on the right track.

INSTRUCTOR APPROVAL



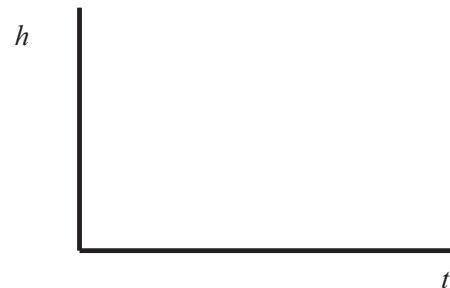
## 5 Comparison of the Two Tanks

### 5.1 Qualitative Results

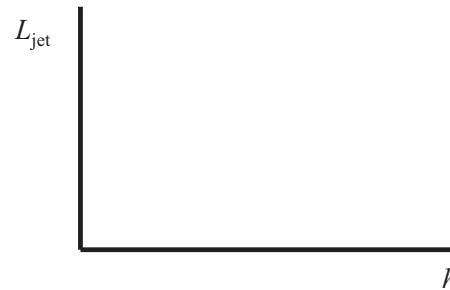
On the axes to the right, sketch the  $L_{\text{jet}}$  versus  $t$  curves for the two tanks.



On the axes to the right, sketch the water depth (pressure) versus  $t$  curves for the two tanks.



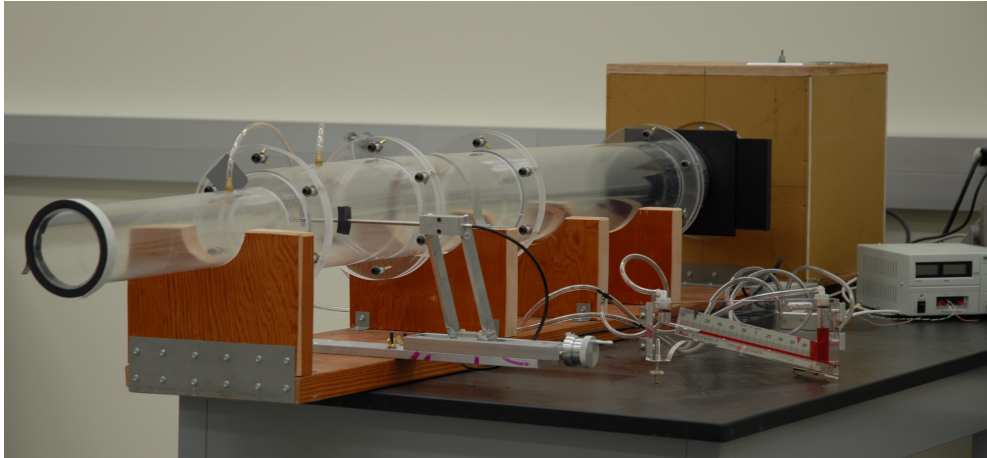
On the axes to the right, sketch the relationship of  $L_{\text{jet}}$  versus  $h$  relationship for both tank.



### 5.2 Conceptual Analysis and Conclusions

1. When the distance,  $h$ , between the free surface and the hole in the side of the tank is the same for the straight and the step-shaped tanks, which tank has the higher  $V_j$ ?
2. For the same  $h$ , which tank has the larger  $L_{\text{jet}}$ ?
3. At the start of the experiment the depth of the step-shaped tank decreases more rapidly than the straight-walled tank. Mass conservation would seem to imply that a higher rate of decrease in  $h$  would correspond to a greater exit velocity  $V_j$ . What is the error in that reasoning? Equation (4) and Equation (5) on page 4 may be useful.
4. Consider two straight-walled tanks that have holes with different diameters, say  $d_1$  and  $d_2$ , with  $d_1 > d_2$ . At the same  $h$ , which tank would have the larger  $L_{\text{jet}}$ ? At the same  $h$ , which tank would have the larger  $V_j$ ?

## Sudden Expansion Lab Exercise



# 1 Introduction

The objective of this experiment is to investigate the relationship between pressure drop, velocity profile, and area change for a sudden expansion in a duct. The experiments are designed to answer the following questions:

- What is the velocity profile downstream of the sudden expansion?
- What is the relationship between the velocity profile and the flow rate?
- What are the qualitative and quantitative relationships between the velocity and pressure as the air crosses the expansion?

## 1.1 Learning Objectives

After completing this lab exercise students will be able to

1. Sketch the velocity profile downstream of a sudden expansion.
2. Sketch the velocity profile at two flow rates.
3. Use the conservation of mass to calculate the inlet velocity from the measured velocity downstream of the sudden expansion.
4. Explain why or why not the Bernoulli equation can be used to compute to the pressure change across the sudden expansion.
5. Apply mass conservation to a measurement of velocity profile in a duct.
6. Apply the Bernoulli and Energy Equations to calculation of the pressure change across a sudden expansion;

## 1.2 Sudden Expansion Device

Air and water transport systems consist of long straight sections of duct, as well as elbows, tees, valves and area changes. A sudden expansion occurs whenever a smaller duct is joined to a larger duct. In this lab, you will study the behavior of air flowing through a sudden expansion.

Figure 1 depicts the main components of the laboratory apparatus. A blower draws air through a duct constructed from acrylic tubing of two diameters. The inlet end of the duct has diameter  $d_1$  and length  $L_1$ . A longer section of tubing with diameter  $d_2 > d_1$  connects the inlet section to the blower. The transition from  $d_1$  to  $d_2$  is abrupt.

The flow rate through the duct is controlled by adjusting the blower speed switch (either high or low) and a sliding damper, also called a *blast gate*. Velocity downstream of the sudden expansion is measured by a velocity sensor. The pressure change across the sudden expansion is measured with an inclined manometer and a differential pressure transducer.



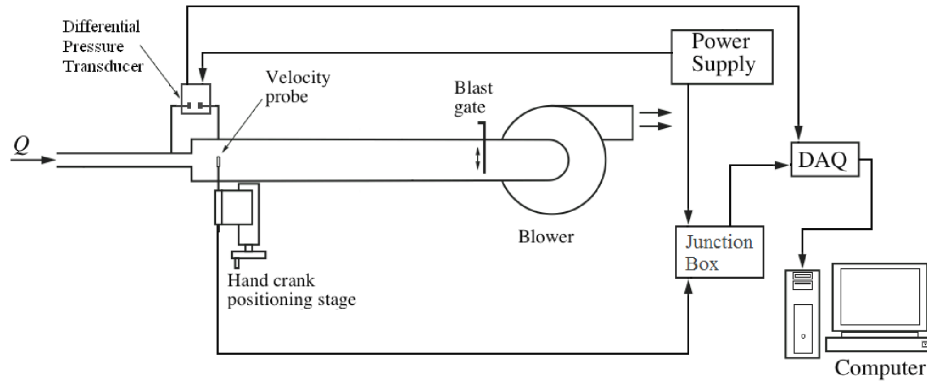


Figure 1: Apparatus for measuring flow downstream of a sudden expansion.

## 2 Background and Review

Read this section before coming to the laboratory.

### 2.1 Bernoulli and Energy Equations

The Bernoulli equation is applied between stations 1 and 2 along a streamline

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 \quad (1)$$

where  $p$  is the static pressure,  $\gamma$  is the specific weight of the flowing fluid,  $V$  is the velocity magnitude, and  $z$  is the elevation above a fixed datum. The Bernoulli equation only applies along a streamline *if* (1) the flow is steady, (2) the flow is incompressible, and (3) there is no heat or work interactions (including flow losses) between stations 1 and 2. The steady flow energy equation is

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 - h_p + h_f \quad (2)$$

where  $h_p$  is the head increase due to shaft work by a pump and  $h_f$  is the head loss.

### 2.2 Mass Conservation: Numerical Integration of the Velocity Profile

The average velocity at any axial location in the duct is

$$V = \frac{1}{A} \int_A u dA \quad (3)$$

where  $u$  is the velocity component along the duct axis, and  $A$  is the cross-sectional area of the duct. Values of  $u$  at different radial locations are obtained when the velocity transducer is traversed across the duct. Because the  $u(r)$  data consists of discrete measurements, Equation (3) must be evaluated numerically.

Approximate the velocity profile as a series of straight lines. The integral in Equation (3) is then a sum of trapezoidal areas as shown in the sketch to the right.

$$\int_{r_a}^{r_b} f(r) dr \approx \sum a_i$$

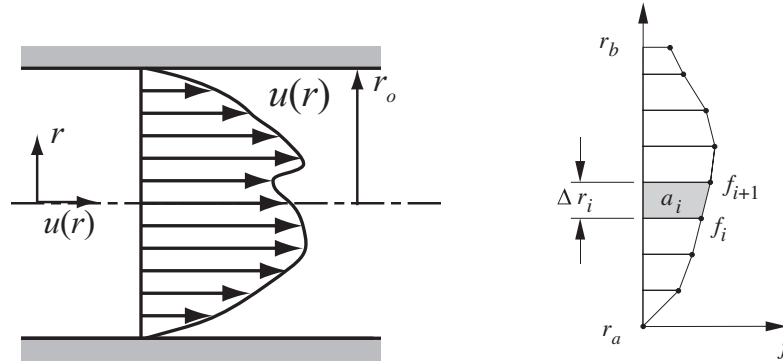


Figure 2: Left: non-uniform velocity profile in a duct. Right: Trapezoid rule for numerical integration of the velocity profile.

The area of a typical trapezoid is

$$\begin{aligned}
 a_i &= (r_{i+1} - r_i)f_i + \frac{1}{2}(r_{i+1} - r_i)(f_{i+1} - f_i) \\
 &= \frac{1}{2}(f_{i+1} + f_i)(r_{i+1} - r_i) \\
 &= \frac{1}{2}(f_{i+1} + f_i)\Delta r_i
 \end{aligned}$$

where  $\Delta r_i = r_{i+1} - r_i$ . The numerical approximation to the integral is known as the trapezoid rule

$$\int_{r_a}^{r_b} f(r) dr \approx \sum \frac{1}{2}(f_{i+1} + f_i)\Delta r_i \quad (4)$$

Note that the  $a_i$  in the trapezoid rule is the area of a trapezoid, *not* an element of duct area in Equation (3). For the numerical integration of Equation (3),

$$f_i = 2\pi r_i u_i.$$

## Apparatus

### Duct Geometry

The purpose of this section is to become familiar with the apparatus. Your first task is to measure the dimensions of the duct and record the values in Table 1.

### Velocity Sensor

Air velocity is measured with a TSI Model 8455 Air Velocity Transducer<sup>1</sup>. The velocity transducer is a thermal anemometer. A small electrical current is passed through the probe tip and the rate of cooling is calibrated to the oncoming velocity. A velocity sensor is mounted on a manual positioning stage that allows the sensor to be moved radially across the larger duct. As shown in the schematic in Figure 3, the velocity sensor is connected to a signal conditioner, a power supply, and a data acquisition DAQ unit. The DAQ is connected to a computer via a USB cable.

<sup>1</sup>TSI Incorporated, Environmental Measurements and Controls Division, 500 Cardigan Road, Shoreview, Minnesota, [www.tsi.com](http://www.tsi.com).

Table 1: Geometric data for sudden expansion apparatus.

Feature	Dimension (cm)
Small Duct ID	
Wall Thickness	
Large Duct OD	
Large Duct ID	
<b>Probe tip offset:</b> Distance from tip of the anemometer to the virtual measurement point.	
<b>Traverse offset:</b> Indicator value when probe tip touches the far wall of the duct, $s_o$ .	

Figure 4 shows the location of the sensing element in the probe tip. The sensing element looks like a small cylinder suspended in the center of an opening in the otherwise solid probe assembly. For the purpose of this laboratory exercise the velocity is assumed to be measured at a *virtual sensor* location at the center of the opening in the probe tip. In other words the velocity measurement is assumed to occur at a distance  $w_t/2$  from the physical end of the probe.

The signal conditioning unit controls the power to the sensing tip and provides an output voltage. The signal conditioner linearizes the signal so that the output voltage is linearly related to the air velocity past the sensor. The DAQ converts the analog voltage to digital values that are transmitted to and stored on the computer.

The location of the velocity sensor in the duct is controlled by a manual positioning stage. The user cranks the stage to move the probe. The position is indicated by a linear scale on the side of the positioning stage. Figure 4 shows the schematic relationship between the probe position in the duct and the position indicated on the positioning stage. The indicator on the positioning stage defines the value of  $s$ . When the probe tip is touching the inner surface of the duct wall the indicator on the positioning stage has a value of  $s$  called  $s_0$ .

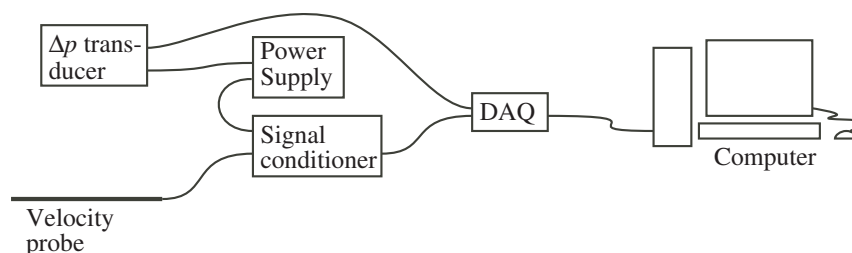


Figure 3: Connection of the sensors to the acquisition system.

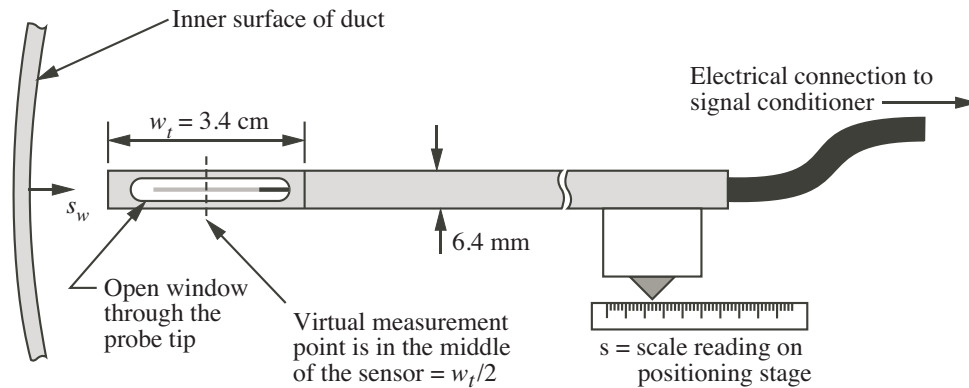


Figure 4: Detail of the velocity probe tip.

## Pressure Measurement

The pressure change across the sudden expansion is measured manually and with electronic instruments. The manual readings are taken with a Dwyer Model 102.5 Durablock portable inclined manometer<sup>2</sup>. The electronic system consists of an Omega PX653-0.5D5V differential pressure transducer and a data acquisition system described in the next section. The two pressure taps on the duct wall are located 3 inches upstream and 6 inches downstream of the sudden expansion, respectively.

## Data Acquisition

Output of the velocity and pressure sensors is digitized with a USB-6008 data acquisition device from National Instruments<sup>3</sup>. The LabVIEW software system (also from National Instruments) is used to control and obtain readings from the DAQ device. A LabVIEW *virtual instrument* (VI) provides a user interface for the data collection.

<sup>2</sup>Dwyer Instruments Inc., Michigan City, Indiana, [www.dwyer-inst.com](http://www.dwyer-inst.com).

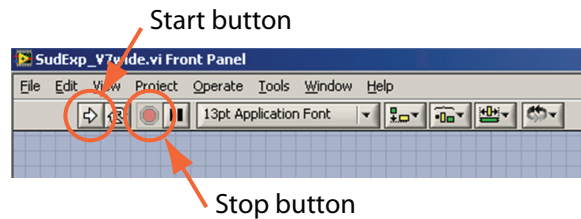
<sup>3</sup>National Instruments, Austin, Texas, [www.ni.com](http://www.ni.com).

### 3 Measurement of the Velocity Profile

The purpose of this section is to obtain data for the axial velocity as a function of position across the duct.

#### 3.1 Device Dimensions

1. Turn the blower on and set the air speed by adjusting motor speed (high/low) and the blast gate. **Keep the blower speed and damper position fixed for the remainder of the velocity profile measurements.**
2. Start the LabVIEW VI by clicking the start button



3. Turn the crank on the linear stage until the probe is near the centerline. Inspect the probe tip by looking axially along the duct from the open end. Refer to Figure 4. In the box marked *Probe tip offset* record the distance from the free end of the probe to the center of the sensor.

**Probe tip offset:** \_\_\_\_\_ cm

4. Move the probe tip fully into the duct so that it gently touches the far wall. Enter the value indicated on the (physical) scale in the *Traverse offset* box on the left side of the LabVIEW screen. Record the value of **Traverse offset** in the space below.

**Traverse offset:** \_\_\_\_\_ cm

The *Probe tip offset* and the *Traverse offset* will not need to be entered again for the remainder of the lab exercise.

#### 3.2 Velocity Profile

1. Scroll the LabVIEW VI slightly to the right so that the four plots labeled “Transient Data from Senors” are visible in the middle of the screen.
2. Repeat the following steps at least 10 times. Take data at radial increments of 1 cm or less, with closer spacing near the walls.
  - a. Rotate the handle on the positioning stage to move the probe to a new radial location.
  - b. Watch the plots of instantaneous velocity and pressure signals. After two or three bursts of data acquisition, when the histograms of the velocity and pressure signals have settled down, press the green *Push to Collect Data* button. Watch the screen, it quickly flashes and goes back to near normal operation. When the *busy* light has turned from red to green, it is OK to return to step 2a take measurements.

- c. After recording several velocity values across the duct, press the *Stop Experiment...* button.

**Be patient:** The computer may pause a few seconds while the last burst of measurements are retrieved and the summary calculations are performed. *Do not* click the *Stop Experiment...* button more than once.

Step 3:  
Compute Flow Rate

STOP EXPERIMENT  
and Compute Flow  
Rate & Ave. Delta P

- d. Record the summary data

Diameter ratio,  $d_2/d_1$  \_\_\_\_\_  
 $Q_{\text{total}}$  \_\_\_\_\_  $\text{m}^3/\text{s}$   
 Average velocity \_\_\_\_\_  $\text{m}/\text{s}$   
 Average  $\Delta p$  \_\_\_\_\_  $\text{cm H}_2\text{O}$

3. On the following mesh, sketch the velocity profile by transferring the data from the screen of the the LabVIEW VI.



- a. Which variable should be aligned along the  $x$  axis?
- b. Identify the location of the duct walls in your experiment.



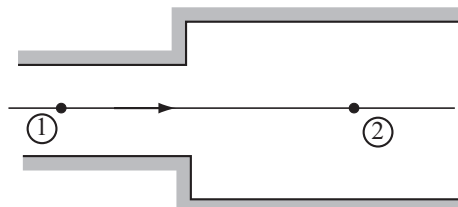
Before continuing, show your lab manual to the instructor. It's important at this point to make sure you are on the right track.

INSTRUCTOR APPROVAL

## 4 Prediction and Measurement of Pressure Change

The purpose of this set of measurements is to determine how the pressure change across the sudden expansion varies with flow rate through the system.

### 4.1 Predict the Sign of the Pressure Change



1. Turn off the blower.
2. Consider the streamline along the centerline of the duct as represented in the preceding sketch. The pressure difference from station 1 to station 2 is (circle one)
  - a.  $p_1 - p_2 > 0$
  - b.  $p_1 - p_2 < 0$
  - c.  $p_1 - p_2 = 0$  (exactly)
  - d.  $p_1 - p_2 < 0$  or  $p_1 - p_2 > 0$  depending on the flow rate and  $d_2/d_1$  ratio.
3. What theoretical model or equation can you use to predict the answer to the previous question?
4. What evidence from the experiment can you use to determine which answer to the previous question is correct?
5. Turn on the blower and perform a simple experiment to determine the sign of  $p_1 - p_2$ .
  - a. Describe your experiment in one or two sentences.
  
  - b. What is the result of your experiment? (One or two sentences.)



Before continuing, show your lab manual to the instructor. It's important at this point to make sure you are on the right track.

INSTRUCTOR APPROVAL





### 4.3 Theoretical Model of the Pressure Change versus Flow Rate

1. Write a theoretical model (a basic formula) that can be used to predict the pressure change  $p_2 - p_1$ .
2. Rearrange the formula from the preceding step to the form  $p_2 - p_1 = \dots$
3. Use the formula from the preceding step to complete the last column of Table 2. Show your calculations for at least one row of the table in the space below.

### 4.4 Comparison of Measured and Computed Pressure Change

1. How well do the measured and theoretical values of pressure difference compare?
2. Name at least two reasons for the discrepancy between the measured and computed values of  $\Delta p$ ?
3. Can you suggest a better theoretical model (a better formula)? What is it? How might that formula account for the true physics in the experiment?



Before continuing, show your lab manual to the instructor. It's important at this point to make sure you are on the right track.

INSTRUCTOR APPROVAL

# Power Supply Lab Exercise



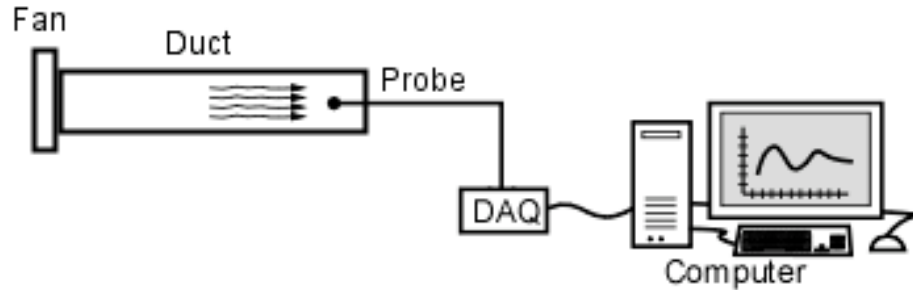


Figure 1: Apparatus for the power supply experiment.

## 1 Apparatus

Figure 1 shows the equipment for this laboratory exercise. The key components are:

1. A fan mounted on a round duct.
2. A pitot tube and differential pressure transducer to measure velocity.
3. A data acquisition device (DAQ) for gathering data from the transducer.
4. A computer to record the output of the transducer and to calculate the volumetric flow rate.

## 2 Learning Objectives

As a result of completing this laboratory exercise you will be able to

1. Recognize that the flow rate of fans depends on the flow resistance that the fan must work against.
2. Recognize that the flow rate vs. flow resistance relationship for a fan is a well-defined and intrinsic characteristic of the fan, and can be shown graphically as a “fan curve”.
3. Plot the “fan curve” for a fan using an air flow bench.
4. Recognize that the flow rate vs. flow resistance relationship for a system is a well-defined and intrinsic characteristic of the system, and can be shown graphically as a flow impedance curve.
5. Plot the flow impedance curve for a system using an air flow bench.
6. Recognize that it is impractical to measure the flow impedance curve for a large system, Calculations or simulations must be used to determine these curves.
7. Determine the actual operating point of a fan by superimposing the fan curve on the system impedance curve.
8. Recognize the relationships for flow rate and pressure for fans in parallel and fans in series.

### 3 Lab Preview

#### 3.1 Fan Operating Point

Fan catalogs often rate fans by their maximum flow rate and/or maximum pressure output. These ratings can be very deceiving. The fan will never produce the maximum flow or the maximum pressure output, and will certainly never produce both at the same time. The flow rate produced by a fan varies depending on how much back pressure there is in the system it is attached to. This relationship is shown on what is called a characteristic curve for the fan, or a fan curve.

The back pressure in the system varies by the amount of air flowing through it. This can also be plotted as a system characteristic curve known as a flow impedance curve. Superimposing the two curves will indicate the actual operating point for the fan (Figure 2). This operating point will be at the intersection of the two curves which is the only point at which the component characteristics match.

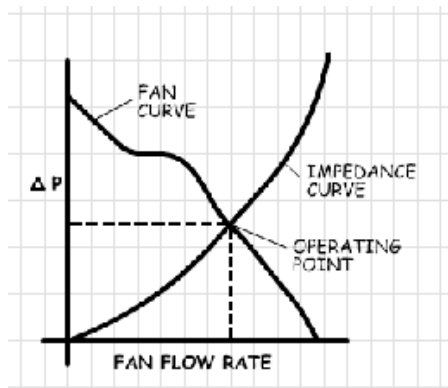


Figure 2: Operating point for a fan

Notice that the operating point is significantly lower than the maximum rated flow rate. Also note that the back pressure is significantly lower than the maximum rated pressure for the fan. This is very important information to have for any system to assure that the system specifications are met.

During this lab exercise you will take all of the measurements needed to predict the actual amount of air that will flow through a typical computer power supply. You will then measure the actual operating point for the same supply.

### 3.2 Parallel and Series Fans

The theoretical fan curves for fans in parallel and fans in series can be created by knowing the fan curve for an individual fan.

The pressure drop across fans in series is the sum of the pressure drop across each of the individual fans. The flow rate remains the same as for an individual fan (Figure 3). For parallel fans the pressure drop remains the same as for an individual fan, but the flow rate is multiplied by the number of fans in the parallel configuration (Figure 4).

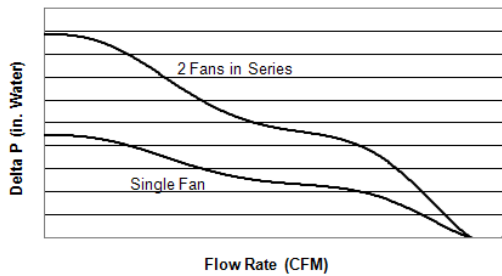


Figure 3: Fans in series

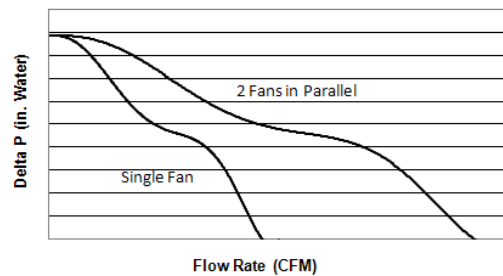


Figure 4: Fans in parallel

In actual operation the series configuration will never reach the theoretical maximum pressure and the parallel configuration will never reach the theoretical maximum flow rate. This is due in large part to flow interference that is set up when the fans are placed too close together, which is common in a real application.

During this lab exercise you will measure and plot the results for actual series and parallel fan configurations.

#### 4 Flow rate through a computer power supply – Fan operating point

- Using the air flow bench gather data to plot a fan curve for the fan used in the computer power supply. Place these values on the table below. Include units.

$\Delta P$ fan	$\Delta P$ nozzle	Flow rate

- Use the MATLAB program “nozzle” to calculate the flow rates based on the pressure drop across the nozzle. Place these values on the table above.
- Use Excel to plot the fan curve.
- Using the air flow bench gather data to plot a flow impedance curve for the power supply housing. Place these values on the table below. Include units.

$\Delta P$ housing	$\Delta P$ nozzle	Flow rate

- Use the MATLAB program “nozzle” to calculate the flow rates based on the pressure drop across the nozzle. Place these values on the table above.

- Use Excel to plot the flow impedance curve on the same graph as the fan curve. Make a hand sketch of the Excel graph in the space below.

- Determine the flow rate at the intersection of the two curves. Insert the value in the box below. Be sure to include units.

- Re-install the fan inside the power supply housing. Mount the device on the air flow bench. Turn on the flow bench and adjust the blast gate until the pressure drop across the power supply is zero. Measure the pressure drop across the nozzle. The flow rate determined by this pressure drop is the operating point for the device.

- Use the MATLAB program “nozzle” to calculate the flow rate for the actual operating point based on the pressure drop across the nozzle. Insert the value in the box below. Be sure to include units.

- Compare the operating point flow rate determined by the intersection of the curves with the operating point determined by direct measurement. Use the measured flow rate as the basis for calculating a percent difference:

$$\text{Percent difference} = \frac{|\text{Measured value} - \text{Predicted value}|}{\text{Measured value}} \times 100$$

**5 Fans in series**

- Using the air flow bench gather data to plot a fan curve for the individual fan used in the series configuration. Place these values on the table below. Include units.

$\Delta P$ fan	$\Delta P$ nozzle	Flow rate

- Use the MATLAB program “nozzle” to calculate the flow rates based on the pressure drop across the nozzle. Place these values on the table above.
- Using the air flow bench gather data to plot a fan curve for the series fan configuration. Place these values on the table below. Include units.

$\Delta P$ fan	$\Delta P$ nozzle	Flow rate

- Use the MATLAB program “nozzle” to calculate the flow rates based on the pressure drop across the fans in series. Place these values on the table above.



- Compare the data for the maximum flow rate and the maximum differential pressure from the tables above.

	Single Fan	Series Fans
Maximum Flow		
Maximum $\Delta P$		

- Based on the results for the individual fan, what should the maximum flow be for the series configuration?
- Based on the results for the individual fan, what should the maximum  $\Delta P$  be for the series configuration?
- Does the data shown in the table above make sense based on your knowledge of actual fan systems? Explain.

## 6 Fans in parallel

- Using the air flow bench gather data to plot a fan curve for the parallel fan configuration. Place these values on the table below. Include units.

$\Delta P$ fan	$\Delta P$ nozzle	Flow rate

- Use the MATLAB program “nozzle” to calculate the flow rates based on the pressure drop across the fans in series. Place these values on the table above.
- Compare the data for the maximum flow rate and the maximum differential pressure from the tables above.

	Single Fan	Parallel Fans
Maximum Flow		
Maximum $\Delta P$		

- Based on the results for the individual fan, what should the maximum flow be for the parallel configuration?
- Based on the results for the individual fan, what should the maximum  $\Delta P$  be for the parallel configuration?
- Do the differences shown in the table above make sense based on your knowledge of actual fan systems? Explain.

# Blender Lab Exercise



April 15, 2009

## 1 Apparatus

Figure 1 shows the equipment for this laboratory exercise. The key components are

1. A food blender, partially filled with water.
2. Thermocouples (temperature sensors) suspended in the water.
3. A data acquisition device (DAQ) for digitizing the thermocouple output.
4. A computer to record the output of the thermocouples

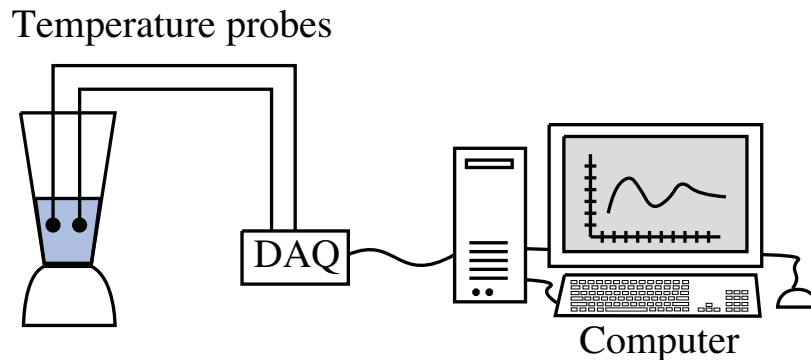


Figure 1: Apparatus for the blender experiment.

## 2 Learning Objectives

As a result of completing this laboratory exercise you will be able to

1. Recognize and describe the roles of heat, work, and energy storage in the operation of a food blender.
2. Identify and qualitatively describe the relationship between terms in the first law of thermodynamics and the physical parameters affecting the performance of a blender.
3. Use qualitative reasoning to predict and verify the changes in measurable system parameters (temperature, power input) that result from changing blender speed, quantity of liquid in the blender, and initial temperature of the liquid in the blender.

### 3 Preliminary Analysis

It is helpful to use a common language when describing the behavior of the blender. Work through the questions in this section to prepare for the measurement exercises. Return to the concepts developed here as you work in the lab.

Try your best to answer the questions in this section, and only then ask the teaching assistant for help. Make sure you are comfortable with your answers before moving on to section 4.

#### 3.1 First Law of Thermodynamics

The First Law of Thermodynamics can be written in two forms

$$\Delta U = Q + W \quad (1)$$

$$\frac{dU}{dt} = \dot{Q} + \dot{W}. \quad (2)$$

To prepare for the lab exercise, answer the following questions

1. What is the primary difference between these two equations?
2. Can both versions of the First Law be true for a given situation?
3. Which of these equations do you think will be most useful in analyzing the behavior of the blender?

Why?

#### 3.2 Lab Preview

For a system consisting of a fixed mass and fixed volume we can write Equation (2) as

$$mc_v \frac{dT}{dt} = \dot{Q} + \dot{W}. \quad (3)$$

where  $m$  is the mass of the system, and  $c_v$  is the specific heat at constant volume. In the lab exercise, each term in Equation (3) will be studied.

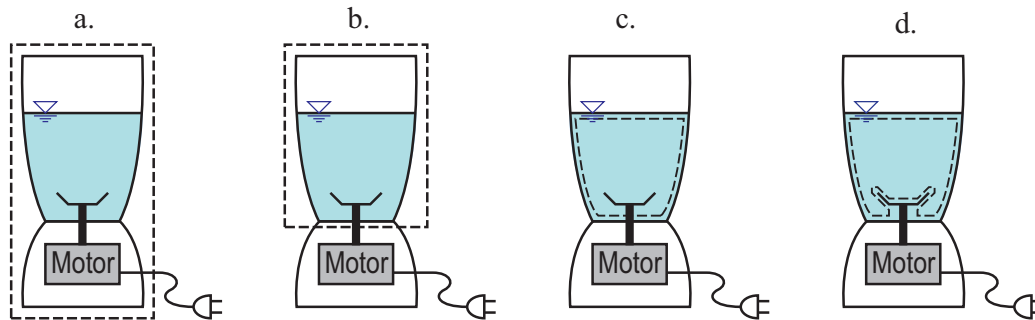
$mc_v \frac{dT}{dt}$  Energy storage: energy content of the energy content, and hence system energy increases when  $dT/dt > 0$ .

$\dot{Q}$  Heat transfer *to* the system from the surroundings.

$\dot{W}$  Work done on the fluid by the surroundings.

### 3.3 Define the System

The following diagrams show four ways of defining the system boundary for the blender. The First Law of Thermodynamics can be applied to each of the four systems, but some system definitions are easier to work with than others. The table below the diagram describes the advantages and disadvantages of each system definition. Use the diagram and the table to assist with your answers to the questions on the next page.



	Work input	Heat Input	Energy Storage
a.	Electrical work enters the control volume through the wires.	Small heat loss from outside surface of pitcher because the air is calm and the thick walls of the pitcher heat up slowly.	Energy storage occurs in the motor, blades, pitcher, and water, but only water temperature is measured.
b.	Work enters through the rotating shaft.	Small heat loss from outside surface of pitcher because the air is calm and the thick walls of the pitcher heat up slowly.	Energy storage occurs in the blades, pitcher, and water, but only water temperature is measured.
c.	Work enters through the rotating shaft.	When pitcher is cooler or warmer than the water, significant heat transfer is caused by the vigorously mixed water.	Energy storage occurs in the water, and is indicated directly by water temperature.
d.	Work applied to system surface by shear stress between blades and water.	When pitcher is cooler or warmer than the water, significant heat transfer is caused by the vigorously mixed water.	Energy storage occurs in the water, and is indicated directly by water temperature.

### 3.3.1 Work Alone

Answer the following questions by yourself:

1. Which control volume(s) provides the easiest way to measure  $\dot{W}$ ?
2. When a wattmeter is used to measure the electrical power input,  $\dot{W}_{e,\text{in}}$ , and the motor efficiency is  $\eta$ , how much power is delivered to the water in the pitcher?
3. Which control volume(s) provides the easiest definition for measuring the increase in energy storage, which is indicated by  $dT/dt$ .
4. Are any of the control volumes more likely to show heat transfer effects?

### 3.3.2 Share and Compare

Discuss your answers with the other members in your group. Keep your answers on the worksheet, and write the group's consensus next to your answer, and label the groups' consensus with a mark like "G" or "Group".

### 3.3.3 Reconsider

As you work through the lab exercise, your opinion, and that of the group may change. Record your final opinion on the answer sheet and label it with a mark like "F" or "Final".

## 4 Energy Storage Experiments

The first set of experiments are focused on the energy storage term in the First Law. The learning objectives are

- Be able to identify the independent and dependent variables in the energy storage term.
- Be able to quantitatively predict the effect of changing the amount of water in the blender.
- Be able to verify the effect of changing the amount of water in the blender.

### 4.1 Preliminary Analysis


1. The energy storage term is

$$\frac{dU}{dt} = mc_v \frac{dT}{dt}$$

where  $m$  is the mass of the system,  $c_v$  is the specific heat at constant volume,  $T$  is temperature, and  $t$  is time. The following table lists the separate terms that make up  $dU/dt$ . Which of the terms that make up  $dU/dt$  can be readily controlled by adjusting the blender settings given the materials in the laboratory? Which of the terms can only be measured?

Term	Controllable, or only measurable?	How to control, or how to measure?
$\frac{dT}{dt}$		
$m$		
$c_v$		

2. For each of the parameters that can be adjusted to change  $dU/dt$ , predict whether the change will increase or decrease the magnitude of  $dU/dt$  when all other system settings, e.g., blender speed, are kept constant.



Before continuing, show your lab manual to the instructor. It's important at this point to make sure you are on the right track.

INSTRUCTOR APPROVAL



## 4.2 Measurement

The experimental results are improved by using water that is at room temperature. If the Teaching Assistant has not provided a pitcher of room temperature water, adjust the tap water temperature so that you put room temperature water in the blender.

### Preliminary Set-up

1. Add water so that the blender is about half full. Record the amount of water in the blender pitcher.
2. Start the data acquisition program.
  - (a) The teaching assistant should have the LabVIEW program running. If not, launch the LabVIEW Virtual Instrument by double-clicking on it.
  - (b) Define a file name for storing the results of this exercise.
  - (c) Click on the *run* arrow to start the VI.
3. Use the “pulse” feature of the blender to turn on the motor for two or three short bursts (approximately one second each). Pulsing the motor will mix the water so that the temperature is uniform at the start of the experiment.
4. Wait for the temperature readings of the thermocouples to stabilize.

While you are waiting for the thermocouples to stabilize, decide what blender speed to use for the energy storage experiment. Should the speed matter?

### First Reading

1. When the temperature of the thermocouples has stabilized, and with the data acquisition program running, Turn on the blender at a chosen speed.
2. Record the blender speed, the wattmeter reading, and the amount of water in Table 1 at the bottom of the page.
3. Let the blender run for approximately one or two minutes. Stop the experiment when you can see a clear trend in the temperature versus time data.
4. Do not stop the data acquisition program.
5. Turn off the blender

### Second Reading

1. Add water to the blender pitcher until the pitcher is approximately three quarters full.
2. With the data acquisition program running, turn on the blender to the same speed as in the preceding experiment.

Table 1: Data for the energy storage experiment. The  $dT/dt$  value is extracted from the data stored by the LabVIEW program.

Run	Blender speed	Water volume	Electrical Power (W)	$\frac{dT}{dt}$
1				
2				

3. Record the blender speed, the wattmeter reading, and the amount of water in Table 1.
4. Let the blender run for one or two minutes.
5. Turn off the blender
6. Stop the data acquisition program.

**Extracting the Slope of Temperature versus Time**

1. Load the data into the MATLAB slope extractor tool.
2. Using the MATLAB program, extract the slope of temperature versus time for the First and Second Readings, and record the data in Table 1.

### 4.3 Analysis

The experiment is performed with two different amounts of water in the blender. We start by setting up a formula by taking the ratio of the First Law for two different experiments. You are then asked to complete the derivation and apply the formula to your data..

#### 4.3.1 Scaffolding: Form a Ratio of Terms

If we write the First Law for each experiment we get

$$m_1 c_1 \left( \frac{dT}{dt} \right)_1 = \dot{Q}_1 - \dot{W}_1 \quad m_2 c_2 \left( \frac{dT}{dt} \right)_2 = \dot{Q}_2 - \dot{W}_2$$

Taking the ratio those two instances of the energy equation gives

$$\frac{m_2 c_2 \left( \frac{dT}{dt} \right)_2}{m_1 c_1 \left( \frac{dT}{dt} \right)_1} = \frac{\dot{Q}_2 - \dot{W}_2}{\dot{Q}_1 - \dot{W}_1} \quad (4)$$

Equation (4) can be usefully simplified by assuming that  $\dot{Q}_2 - \dot{W}_2 \approx \dot{Q}_1 - \dot{W}_1$ , which is reasonable since the speed does not change and  $\dot{Q}$  is small.

#### 4.3.2 Complete the Analysis

Using the following steps, transform Equation (4) into a formula for analyzing your measurements.

1. Write a simplified form of Equation (4) obtained by assuming that  $\dot{Q}_1 \ll \dot{W}_1$  and  $\dot{Q}_2 \ll \dot{W}_2$ .
2. Further simplify the equation obtained in the preceding step by assuming that  $\dot{W}_2 \approx \dot{W}_1$ . Rearrange the equation as a ratio of time derivatives of temperature.
3. Use the formula you just derived to check the data in Table 1. Is the data in Table 1 consistent with the Equation obtained in Step 2? If not, suggest at least one reason for the disagreement.

### 4.3.3 Study Questions

Reconsider the control volumes shown on page 4.

1. For the control volumes that include both the glass pitcher and the water, what is the meaning of (or value of) the product  $mc$  for the energy storage term in the First Law?
2. What happens to the energy storage in the water when heat is transferred from the water to the glass?
3. Use qualitative reasoning to compare the relative sizes (i.e., estimate which is bigger) of the rate of heat transfer from the water to the glass versus the rate of heat transfer from the glass to the air.
4. Are  $m_1$  and  $m_2$  just the masses of water?



Before continuing, show your lab manual to the instructor. It's important at this point to make sure you are on the right track.

INSTRUCTOR APPROVAL



## 5 Work Input Experiments

The next set of experiments are focused on the work term in the First Law.

### 5.1 Preliminary Analysis

Review your answers to the exercises in Section 3.3 regarding the definition of the system for the First Law analysis.

1. List the measurable variables that can be used to quantify the work term in the first law of thermodynamics.
2. Which of these terms can be readily adjusted by changes to the system configuration given the materials in the laboratory? In other words, what can you change to cause a measurable change in the rate of work on the system?
3. For each of the changes listed in item 2, predict whether the change will increase or decrease the magnitude of the work term.

### 5.2 Measurement

For these measurements the amount of water in the blender is held constant. Changing the speed of the blender motor changes the rate at which work is done on the water.

#### Preliminary Set-up

1. Add water so that the blender is about half full. Record the amount of water in the blender pitcher.
2. Start the data acquisition program.
3. Use the “pulse” feature of the blender to turn on the motor for two or three short bursts (approximately one second each).
4. Wait for the temperature readings of the thermocouples to stabilize.

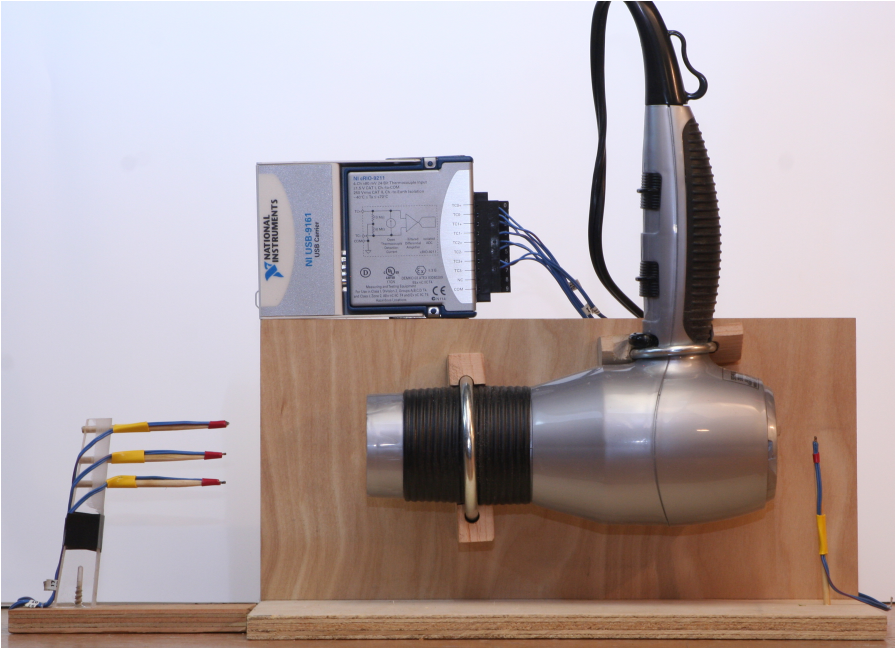
While you are waiting for the thermocouples to stabilize, decide what two blender speeds to use for the energy storage experiment. The goal is to measure the relationship between blender speed and the rate of increase in temperature of the water. Should the two speeds be close or very different? Or should the relationship between the two speed settings not effect the quality of the experimental results?



## 6 Heat Transfer

In Section 4.2, you were advised to use room temperature water when filling the blender. Why does using water at room temperature improve measurements of energy storage or work input effects? What would happen to the results if the experiment was started with very cold water or very warm water?

# Hair Dryer Lab Exercise





# Hair Dryer Lab Exercise

June 27, 2009

Participant Code: \_\_\_\_\_

## 1 Apparatus

Figure 1 shows the equipment for this laboratory exercise. The key components are

1. A hand-held, electric hair dryer.
2. Thermocouples (temperature sensors).
3. A data acquisition device (DAQ) for digitizing the thermocouple output.
4. A computer to record the output of the thermocouples

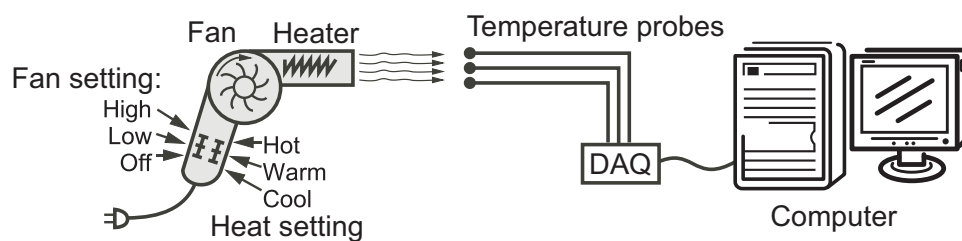


Figure 1: Apparatus for the hair dryer experiment.

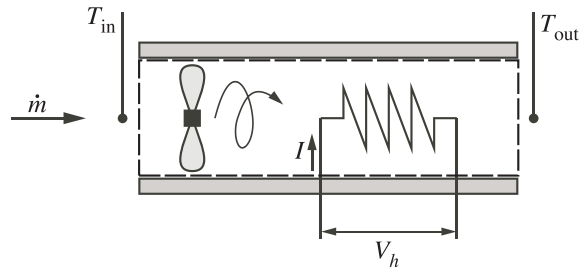


Figure 2: Simplified schematic of the hair dryer experiment. The dashed line is a control volume that may be helpful in developing analytical models.

## 2 Lab Preparation

### 2.1 Learning Objectives

As a result of completing this exercise students will

- Be able to use the steady flow energy equation to explain the performance of a hair dryer.
- Be able to separate the roles of mass flow rate and heat input in the operation of the hair dryer.

### 2.2 The Basic Equations

Figure 2 is a simplified schematic of the hair dryer. A DC-powered fan pulls air from the room and forces it past AC-powered heating coils. The electrical power dissipated as heat is  $\dot{E}_{in} = I^2 R = V_h^2 / R$ , where  $I$  is the current flowing through the heating element,  $R$  is the electrical resistance of the heating element and  $V_h$  is the voltage supplied to the heating element.

The following exercises develop the analytical models that describe the behavior of the hair dryer.

1. Applying the steady flow energy equation to the air flow from the inlet and outlet stations in Figure 2

$$Q = \dot{m}c_p(T_{out} - T_{in}) \quad (1)$$

where  $Q$  is the rate of heat transfer to the air stream,  $\dot{m}$  is the mass flow rate,  $c_p$  is the specific heat of air at constant pressure,  $T_{out}$  is the outlet air temperature, and  $T_{in}$  is the temperature of air entering the hair dryer.

- a. What is the relationship between  $Q$  and  $\dot{E}_{in}$ ?
- b. Use the result of part (a) and algebraically arrange Equation (1) to obtain a formula for  $T_{out} = f(T_{in}, \dot{m}, c_p, \dot{E}_{in})$ .
- c. If  $Q$  and  $T_{in}$  are fixed, how does increasing  $\dot{m}$  affect  $T_{out}$ ?

2. The rate of heat transfer to the air can also be related to the heater temperature by

$$Q = hA_s(T_h - T_{\text{in}}) \quad (2)$$

where  $h$  is the heat transfer coefficient between the heating element and the oncoming air stream,  $A_s$  is the surface area of the heating element, and  $T_h$  is the temperature of the heating element.

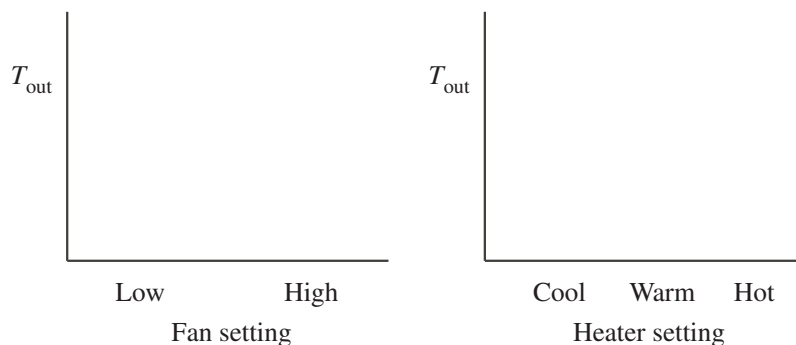
- a. Algebraically rearrange Equation (2) to obtain a formula for  $T_h = f(T_{\text{in}}, h, Q, A_s)$ .
  
- b. If  $Q$  and  $T_{\text{in}}$  are fixed, how does increasing  $\dot{m}$  affect  $T_h$ ?
  
- c. If the fan is running when no current is flowing through the heater, the relationship between  $T_{\text{in}}$  and  $T_{\text{out}}$  must be
  - i.  $T_{\text{out}} = T_{\text{in}}$
  - ii.  $T_{\text{out}} > T_{\text{in}}$
  - iii.  $T_{\text{out}} < T_{\text{in}}$
- d. Which of the formulas derived in this section provides the justification for your answer to part (c)?

### 3 Exit Air Temperature for Unmodified Hair Dryer

1. Plan a set of measurements to quantify the relationship between the outlet air temperature and the settings for the fan and the heater.
  - a. What are the independent variables? Consult Equation (1) and (2)<sup>1</sup>.
  - b. What are the dependent variables?
  - c. If the heater power is held constant and  $\dot{m}$  is increased, will the downstream temperature increase, decrease, or stay the same?
  - d. If  $\dot{m}$  is held constant and the heater power is increased, will the downstream temperature increase, decrease, or stay the same?
2. Use the hair dryer apparatus to perform experiments to fill out the following table. The wattmeter measures  $\dot{E}_{in}$ , the average of the three downstream thermocouples is  $T_{out}$ .

<b>Fan</b>	<b>Heater Setting</b>			
	Cool		Hot	
	$\dot{E}_{in}$ (W)	$T_{out}$ (°C)	$\dot{E}_{in}$ (W)	$T_{out}$ (°C)
Low				
High				

3. Sketch of  $T_{out}$  versus fan speed and  $T_{out}$  versus heater setting.



(Continued on next page)

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<sup>1</sup>An *independent variable* is an input or parameter that is directly controllable by the person performing the experiment. An independent variable is often, though not always, the quantity on the  $x$  axis of a plot. A *dependent variable* is the output or result of changing a system. A dependent variable is often, though not always, the quantity on the  $y$  axis of a plot. In an experiment, both independent and dependent variables are measured.

4. Are the measured trends consistent with your predictions in (1c) and (1d)? (YES or NO)
  
5. Are the measured trends consistent with your rearrangement of Equation (1) and Equation (2)? (YES or NO)
  
6. Suggest an explanation for the agreement or disagreement between the measurements and the theory.



3. Make a sketch of fan speed versus fan voltage. How would you describe the relationship between the applied voltage and the air speed? What simple model of  $\dot{m}$  versus fan voltage is plausible?
4. Suppose that the angular velocity of the fan is directly proportional to the applied voltage. What does the pump similarity scaling laws say about relationship between pump flow rate and impeller speed? How can this information be used to infer the effect of applied voltage and fan flow rate.

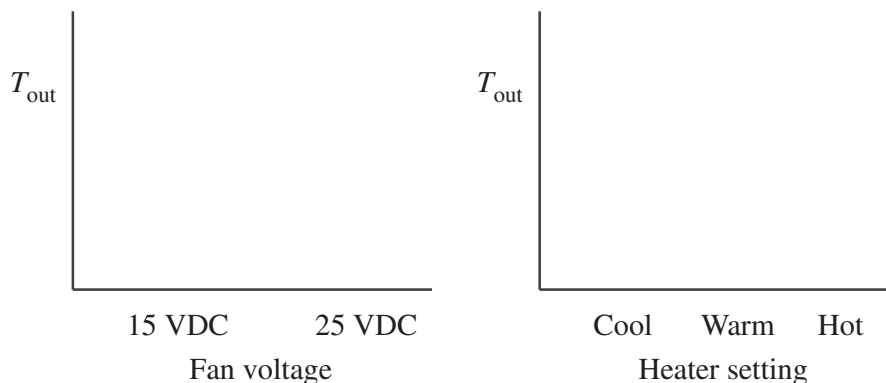
## 5 Exit Air Temperature Versus Fan speed

Devise and carry out an experiment to measure the relationship between the exit air temperature and the fluid velocity. Instead of measuring the fluid velocity directly, what other variables can be used?

1. Connect the modified hair dryer to the wattmeter.
2. With the fan running and the heater turned off, measure the difference between  $T_{\text{out}}$  and  $T_{\text{in}}$ .
  - a. Does the fan motor make measurable change in air temperature?
  - b. If the fan causes a measurable change in air temperature, is that change significant compared to the effect of the heater?
3. With the fan running at two speeds (say 15 and 25 VDC), record the power settings and air exit temperatures in the following table.

Fan Voltage	Heater Setting			
	Cool		Hot	
	$\dot{E}_{\text{in}}$	$T_{\text{out}}$	$\dot{E}_{\text{in}}$	$T_{\text{out}}$
15 VDC	(W)	(°C)	(W)	(°C)
	(W)	(°C)	(W)	(°C)
25 VDC	(W)	(°C)	(W)	(°C)
	(W)	(°C)	(W)	(°C)

4. Make a sketch of  $T_{\text{out}}$  versus fan speed and  $T_{\text{out}}$  versus heater setting.



5. How does the fan speed affect the exit temperature when the heater power is held constant? When the heater power is held constant, does increasing the fan speed cause the air exit temperature to increase, decrease, or stay the same?
6. What could explain the variation of power consumption with the "Fan" setting on the handle?



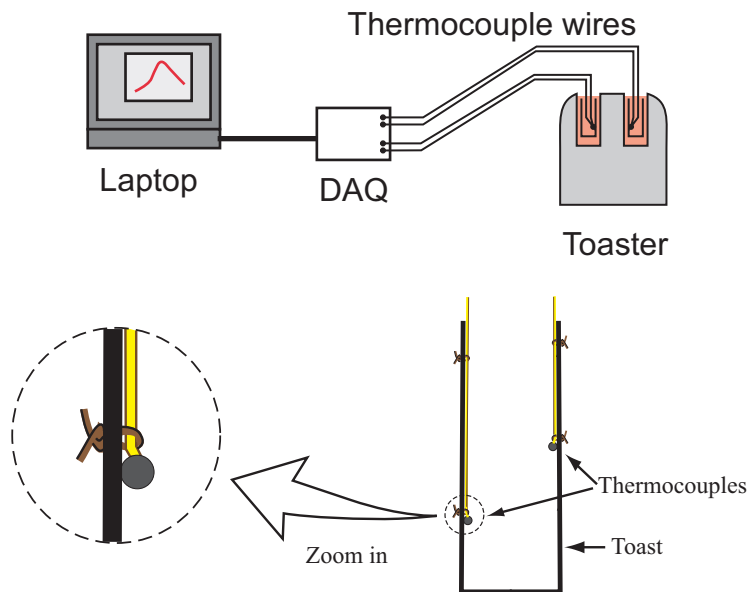
# Toaster In-Class Demonstration



### Apparatus

The sketch shows the equipment for this demonstration. The key components are

1. A toaster.
2. Two pieces of sheet aluminum bent into the shape of a “U”.
3. Four thermocouples: two attached to the inside walls of each of the sheet metal pieces.
4. A data acquisition device (DAQ) for digitizing the thermocouple output.
5. A computer to record the output of the thermocouples



### In-Class Demonstration

1. The “toast” is placed in the room-temperature toaster.
2. The data acquisition software is started, and the temperature of the system in the ambient condition is displayed.
3. The toaster lever is depressed, sending power to the heating elements. The data acquisition records the temperatures. After one or two minutes the toaster lever is raised, turning off the power to the heating elements.
4. After waiting for the toast to cool, the data acquisition system is stopped.

See over

## Predictions

In the following the *heating rate* or *cooling rate* refers to  $dT/dt$ , where  $T$  is some average temperature of the metal “toast”. To answer the questions, neglect the effect of any spatial variation in temperature of toast, i.e., assume that any instant of time  $t$ , all of the metal is at the same temperature  $T$ .

1. If there is any difference in heating and cooling rate for the toast it is most likely due to
  - a. the insulating effect of the black paint layer.
  - b. the difference in energy storage between the two metal pieces
  - c. the difference in surface properties.
  - d. air currents in the toaster cavity.
  - e. uncontrollable variations in temperatures of the heating coils.
2. After 30 seconds the highest temperature achieved by the toast will be approximately
  - a. 30 °C (very warm room temperature)
  - b. 50 °C
  - c. 100 °C
  - d. 500 °C
  - e. 1000 °C
  - f. > 1000 °C
3. When the toaster is turned on, and the sheet metal pieces are lowered into the toaster,
  - a. the two pieces of toast will heat up at the same rate.
  - b. the black toast will heat up much faster than the shiny toast.
  - c. the black toast will heat up a little faster than the shiny toast.
  - d. the black toast will heat up a little slower than the shiny toast.
  - e. the black toast will heat up much slower than the shiny toast.
4. When the toaster is turned off, the two pieces of metal will be removed and suspended in still air. During the cooling phase
  - a. the two pieces of toast will cool down at the same rate.
  - b. the black toast will cool down much faster than the shiny toast.
  - c. the black toast will cool down a little faster than the shiny toast.
  - d. the black toast will cool down a little slower than the shiny toast.
  - e. the black toast will cool down much slower than the shiny toast.
5. Which modes of heat transfer are *significant* (i.e., cannot be neglected) during the heating phase?
6. Which *one mode* of heat transfer is *dominant* during the heating phase?
7. Which modes of heat transfer are *significant* (i.e., cannot be neglected) during the cooling phase?

## Bicycle Pump In-Class Demonstration



## Apparatus

Figure 1 shows the equipment for this demonstration. The key components are

1. A bicycle pump.
2. A pressure transducer replacing the pressure gage.
3. A thermocouple immediately downstream of the discharge valve and a thermocouple attached to the outside wall of the pump cylinder.
4. A string potentiometer to record the instantaneous position of the pump handle, and hence the piston.
5. A data acquisition (DAQ) system for digitizing the pressure transducer, thermocouple, and potentiometer output.
6. A computer to record the output of the digitized signals.

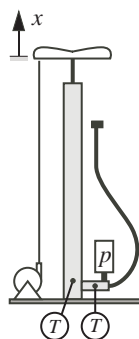


Figure 1: Apparatus for the bicycle pump experiment.

## Single Stroke Experiments

Consider two experiments: one with the discharge hose blocked and the other with the discharge hose connected to a bicycle tire. Before the start of each experiment the pump handle is pulled upward so that the cylinder volume is maximum. The experiment consists of a single stroke of the pump handle: down to compress the gas, and back up to return to the starting position.

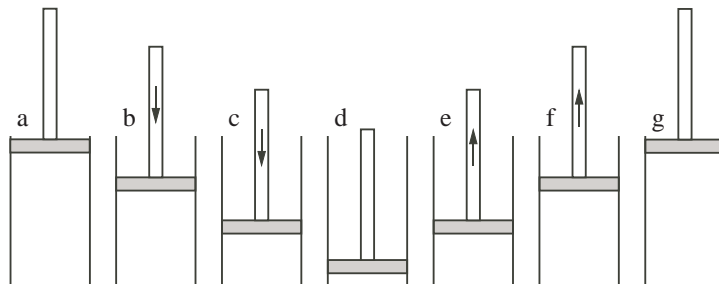
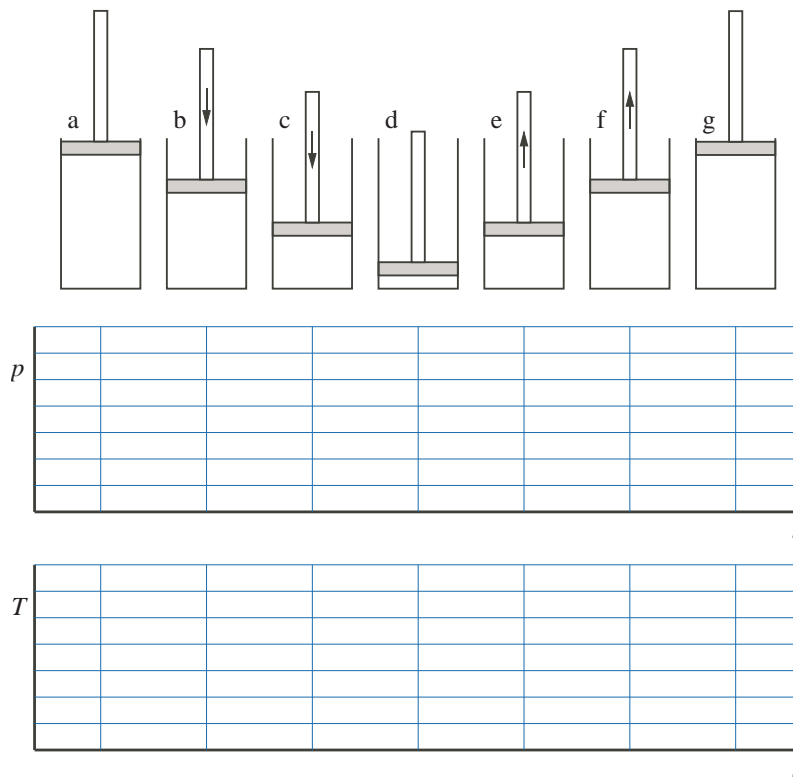


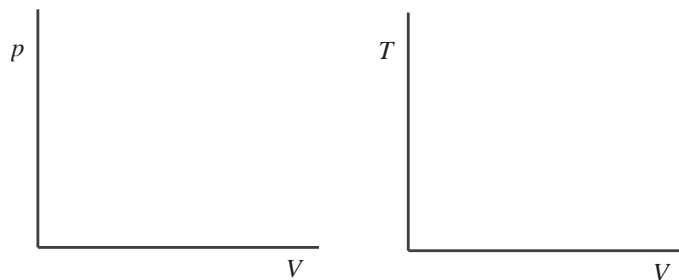
Figure 2: Piston positions during the single-stroke experiment

1. **Closed cylinder experiment:**

- (a) Use the diagram below to sketch how pressure of air in the cylinder,  $p$ , and temperature of the air in the cylinder,  $T$ , vary during the experiment. Use the schematic of piston position to guide your sketch.



- (b) Translate the  $p(t)$  and  $T(t)$  data to the following plots of  $p$  versus  $V$  and  $T$  versus  $V$ , where  $V$  is the cylinder volume.



2. **Open cylinder experiment:**

- (a) When the discharge is connected to the tire, is the peak pressure higher, lower, or roughly the same as when the discharge is blocked?