Introduction to Instrumentation and Data Acquisition

Experiment 1

1 Objective

The objective of this experiment is to introduce some of the basic hardware used in experiments in thermal-fluid sciences and the fundamental physical principles behind their operation. Specifically, you will learn to use and calibrate static, total/pitot, and pitot-static probes with pressure transducers of various types. A brief introduction to the data acquisition hardware and software will also be provided.

2 Background

Pressure, Temperature and Velocity are the most fundamental properties that are most commonly used to describe the state of a fluid. Other properties, such as density, can generally be estimated using these along with appropriate relations. For example, for an ideal gas, the density can be estimated if one knows (measures) the pressure and temperature and uses the ideal gas law. In this experiment, we will learn how to measure the pressure in a wind tunnel and how to use this to calculate the velocity of air; temperature measurement methods are covered in Experiment 5: Temperature Sensors and Calibration.

3 Bernoulli's Equation and Pressure

Pressure is the most common and frequently measured property. This is in large part due to the relative ease with which it can be measured. For a moving fluid, there are two types of pressures are normally measured: the static pressure and total pressure, often also referred to as the stagnation pressure. These two pressures and the relationship between them is best explained in the context of Bernoullis Equation (1). For two points located along a streamline in an *inviscid* flow the equation can be written as

$$p_1 + \frac{1}{2}\rho {u_1}^2 + \rho g h_1 = p_2 + \frac{1}{2}\rho {u_2}^2 + \rho g h_2 \tag{1}$$

where p is the local static pressure, u is the local velocity, ρ is the fluid density, g is gravity, and h is the height. Subscripts 1 and 2 denote property values at each location. For the above statement to hold true, the flow must be *steady* and have a *constant density.* If gravitational effects are neglected, equation 1 can be written as:

$$p_1 + \frac{1}{2}\rho {u_1}^2 = p_2 + \frac{1}{2}\rho {u_2}^2 = p_T \tag{2}$$

where p_T is the total (stagnation) pressure of the fluid. In a frictionless flow the total pressure, p_T, is conserved along a streamline. In equations 1 and 2, the term $\frac{1}{2}\rho u^2$, is commonly referred to as the *dynamic pressure.*

Static Pressure: In equation 1, p_1 and p_2 are referred to as the static pressure. It is the pressure that the moving fluid feels while it is traveling with the velocity of the fluid, u_1 and u_2, respectively.

Total/Stagnation Pressure: Under the frictionless flow assumption that applies to Bernoullis equation, there are no losses as the flow moves from point to 1 to point 2. Hence, if the flow is brought to rest, then the energy associated with the fluid motion, which appears as the dynamic pressure term ($\frac{1}{2}\rho u^2$), is recovered as pressure. The pressure when the fluid is brought to rest is called the total or stagnation pressure. If one examines Bernoullis equation, it becomes clear that under these conditions, the total/stagnation pressure must remain constant. One way to think of the total pressure is to consider it as representing the total available mechanical energy. As the fluid moves, the total pressure (energy) is partitioned into the energy associated with motion, and that associated with the static pressure (p).

4 Estimating Flow Velocity Using Pressure Measurements

If the total and static pressure in a fluid are measured at a given point, equation 2 can be rearranged to estimate the fluid velocity, as shown below.

$$u_1 = \sqrt{\frac{2(p_T - p_1)}{\rho}} \quad \text{and} \quad u_2 = \sqrt{\frac{2(p_T - p_2)}{\rho}} \tag{3}$$

This is how velocity is most commonly estimated in experiments, where static and stagnation pressures are measured using a static pressure probe and stagnation pressure probes, respectively. There are also probes that combine both measurements, and are referred to as *pitot-static* probes. Schematics for the probes used for each measurement are shown in figures 1 and 2 and are briefly discussed next.

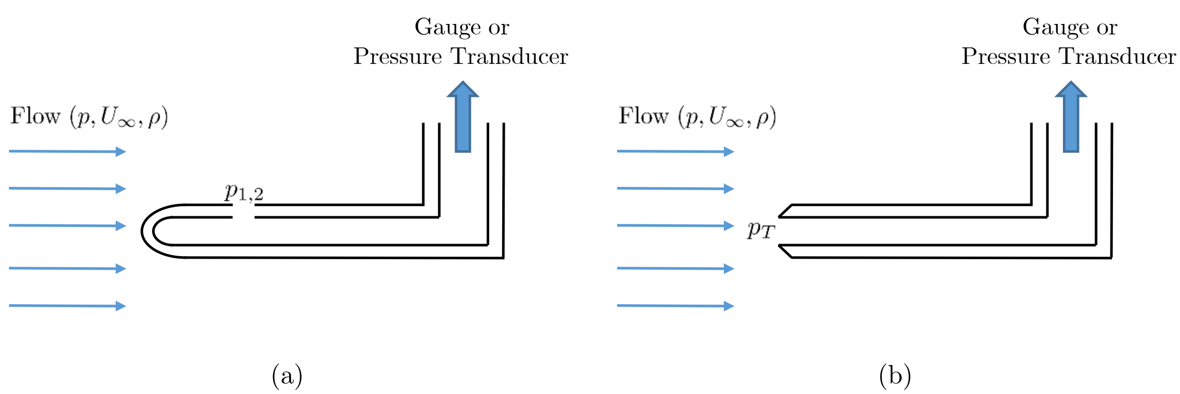

Figure 1: Schematics of (a) static and (b) total pressure probes

Static Pressure Probe: The static pressure probe shown in figure 1, consists of a hollow tube with multiple orifices around the tube displaced a few diameters behind the probe tip. Since the static pressure is the pressure felt by the moving fluid, it is important that the orifices do not interfere with or modify the flow field. Hence, the static pressure ports must be small and free of burrs. Furthermore, the probe must be nearly perfectly aligned with the flow to measure the static pressure accurately. Generally, there are number of static pressure orifices to provide a good spatial average of the static pressure. The back-end of the static probe, or any pressure probe for that matter, is generally connected to a pressure transducer. Sometimes, instead of using a probe, the static pressure in a tunnel is measured using a wall-static port. This is simply a port that is flush mounted in the wind tunnel wall. In this experiment, both a static probe and a wall-static port are used to measure the static pressure.

Total (Stagnation/Pitot) Pressure Probe: The total pressure probe (figure 1b) is a very simple device consisting of a hollow tube with an orifice at its tip. When making total pressure measurements, the probes are aligned so the opening is perpendicular to the flow. This probe is most commonly referred to as a Pitot Probe (pronounced pea-toh) after the French engineer Henri Pitot (1695 – 1771) who first invented it. The prefixes, 'total', 'pitot', and 'stagnation' are used interchangeably.

Pitot-Static Pressure Probe: This probe is a combination of the total and static pressure probe. It consists of two concentric tubes, as shown in Figure 2. The inner tube makes up the pitot probe with the opening at its tip. The outer tube measures the static pressure through the surface ports at the periphery. The image on the right of Figure 2 provides a close-up of a typical probe tip, clearly showing the total and static pressure orifices. The output of each of the tubes (on the back end of the probe) can be connected to separate transducers, or in many cases, to the low and high pressure sides of a single differential pressure transducer. (Question: Which pressure should be connected to the low and high pressure sides, and why might this be beneficial?).

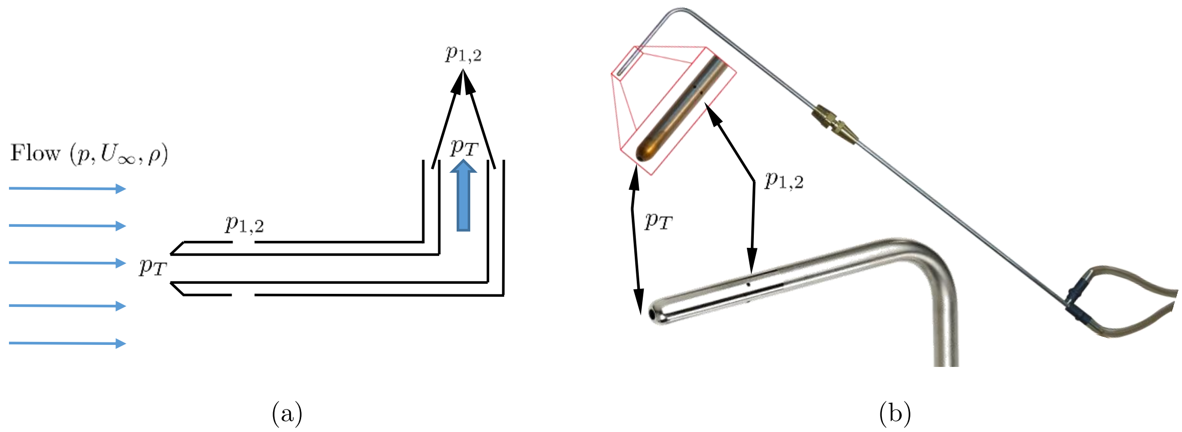

Figure 2: (a)Schematic of a pitot-static probe and (b) photos of example pitot-static probes from Aerolab, LLC and United Sensor Corporation.

Often the total and static pressure in the free stream of a wind tunnel are measured using a total pressure probe and a flush mounted pressure tap in the wind tunnel wall. Figure 3 shows how the setup is similar to a pitot-static probe to estimate the flow velocity in a wind tunnel.

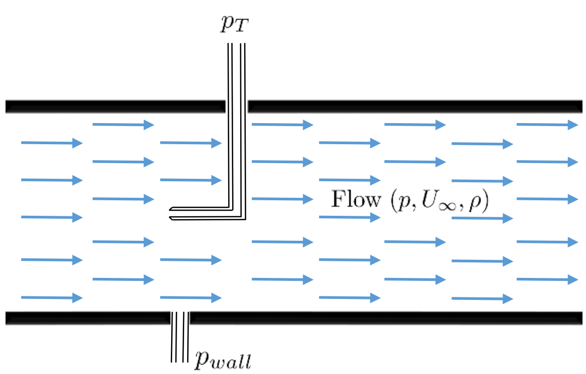

Figure 3: Example of pitot probe and wall mounted pressure tap setup used to estimate velocity

5 Data Acquisition - Software and Hardware

Here we briefly discuss the basics of hardware and software that will be used in these experiments as well in most experiments in this course. Although there may be slight differences in the specifics, the principles of digital data acquisition that you are exposed to in this lab are similar to what is used in industry and in research laboratories.

5.1 Software

LabVIEW is a graphical programming language that was first developed in 1986. It combines data acquisition, analysis, and presentation tools into one software program. LabVIEW is probably the most commonly used software for data acquisition and control. The goal of this exercise is to provide you with what is most likely your first exposure to LabVIEW programming; namely, the construction of a LabVIEW program, or virtual instrument (VI).

5.2 Hardware

The data acquisition module used in this experiment is a National Instruments model NI-USB-6009, which interfaces to the computer through the USB port. It has 8 single ended and 4 differential analog voltage inputs, 14-bit resolution, a maximum voltage range of -10 to 10 volts, and a maximum overall sampling rate of 48 thousand samples per second (48 kHz). It is controlled by LabVIEW, which is also made by National Instruments. The USB device is one of the many different types of data acquisition devices that can be used. Another common interface is a PCI based data acquisition card.

5.3 Digital Data Acquisition Fundamentals

- Instruments can record and/or display data in either analog (continuous) or digital (discrete) formats.
- The main difference between analog and digital data acquisition is that digital systems sample the signal at discrete times only, not continuously.
- In a digital data acquisition system, no information is recorded at times in between the discrete sampling times. Instead the signal is recorded as follows:
  - A continuous signal is sampled discretely at sampling frequency, f_s.
  - The time period t between samples is the inverse of f_s, $\Delta t = 1/f_s$
  - Thus, for a sampling frequency of $f_s = 10\text{Hz}$, the time period is $\Delta t = 0.1\text{s}$
- Most sensors we commonly use, including the pressure transducers and temperature sensors used in this class, are analog. Hence, in order to record the senor values using a digital data acquisition system their output has to be first converted to a discrete/digital format. This is accomplished using Analog to Digital Conversion that is inherent in all digital data acquisition systems, this is discussed next.

5.4 Analog to Digital Conversion (A/D Conversion)

- Digital data acquisition is used in digital multimeters, digital oscilloscopes, computercontrolled data acquisition systems, and many other modern instruments and electronic devices such as computers, tablets, and cell phones.
- In all these examples, the conversion of an analog signal into a digital signal is accomplished with an electronic device called an analog-to-digital converter, which is abbreviated as A/D converter.
- The goal of an A/D converter is to change an analog voltage signal into a digital number (usually in binary form).
- An A/D converter is labeled as N-bit, where the number of bits N represents how many bits (ones and zeroes) are used in the digital output of the A/D converter. For example, an 8-bit converter creates an 8-bit output.
- For simplicity, consider a 2-bit A/D converter (N = 2) with a range of 5 to 5 volts. The voltage range is divided into bins as shown in table 1.
- The assigned voltage for each bin is here defined as half-way between the limits of the bin.

Table 1: Example of 'binning' for a −5 to 5V analog signal on a 2-bit DAQ

Analog Voltage (Volts)	Bin Number	Digital Output (Binary)	Assigned Voltage (Volts)
$-5.0 \leq V < -2.5$	0	00	$V = V_{min} + 0.5\Delta V = -3.75$
$-2.5 \leq V < 0.0$	1	01	$V = V_{min} + 1.5\Delta V = -1.25$
$0.0 \leq V < 2.5$	2	10	$V = V_{min} + 2.5\Delta V = -1.25$
$2.5 \leq V \leq 5.0$	3	11	$V = V_{min} + 3.5\Delta V = -3.75$

- The number of bins = 2N for an N-bit A/D converter. For our example 2-bit converter, there are 2^2 = 4 bins.
- The resolution of the A/D converter is defined as

$$\Delta V = \frac{(V_{max} - V_{min})}{2^N} \tag{4}$$

- If the input resolution and range of the digital data acquisition hardware is not carefully chosen in light of the output of the pressure (or any other) transducer/sensor, very large errors can be introduced in the measurement!

6 Apparatus Used in Experiments

1. Wind Tunnel
2. Pitot-static probe
3. Pressure transducers:
   (a) Hand-held manometer
   (b) Strain-gauge based pressure transducer with an analog voltage output (Omega PX138-0.3D5V)
4. PC-based analog to digital (A/D) device to record the data (NI-USB-6009)
5. Computer/LabVIEW

7 Experimental Procedure

WARNING: The Instructor will explain the procedure to operate the wind tunnel in a safe manner. Please follow the instructions carefully and do not use the wind tunnel prior to being instructed. Always start the wind tunnel at low speeds and vary the speeds slowly.

7.1 Pitot Probe and Wall Static Measurements

1. Insert and mount the pitot probe into the wind tunnel.
2. Split the output of the pitot probe into two tubes.
   (a) Connect one output to the *high pressure* side of the pressure transducer.
   (b) Connect the second output to the *high pressure* side of the hand-held manometer.
3. Connect the wall-static pressure tap to another tube
   (a) Split the output of the wall tap into two tubes.
   (b) Connect one output to the *low pressure* side of the pressure transducer.
   (c) Connect the second output to the *low pressure* side of the hand-held manometer.
4. Connect the analog voltage output of the pressure transducer to the input on the data acquisition card.
5. On the Data Sheet, measure and record the difference between the total pressure and the wall-static pressure (dynamic pressure) in the table for the following:
   (a) Hand-held manometer (in mm of water)
   (b) The mean output from the DAQ, using the LabVIEW Program
6. Repeat steps 1-5 for seven different wind tunnel speeds, increasing from low to high velocity.

7.2 Pitot-Static Probe Measurements

1. Insert and mount the pitot-static probe into the wind tunnel.
2. Split the output of the pitot portion of the probe into two tubes.
   (a) Connect one output to the *high pressure* side of the pressure transducer.
   (b) Connect the second output to the *high pressure* side of the hand-held manometer.
3. Split the output of the static portion of the probe into two tubes.
   (a) Connect one output to the *low pressure* side of the pressure transducer.
   (b) Connect the second output to the *low pressure* side of the hand-held manometer.
4. Connect the analog voltage output of the pressure transducer to the input on the data acquisition card.
5. On the Data Sheet, measure and record the difference between the total pressure and the static pressure in the table for the following:
   (a) Hand-held manometer (in mm of water)
   (b) The mean output from the DAQ, using the LabVIEW Program
6. Repeat steps 1-5 for seven different wind tunnel speeds, increasing from low to high velocity.