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Laboratory to Assess the Effect of Flow Velocity on Temperature Measurements

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Laboratory to Assess the Effect of Flow Velocity on Temperature Measurements

Abstract

Engineering students often struggle to connect the theoretical concepts discussed in class with the practical challenges of measurement and experimentation. This article presents an innovative laboratory experiment for aerospace engineering students, aimed at bridging this educational gap. The laboratory provides them a chance to experiments with measurements of static and stagnation values of two important parameters, namely pressure and temperature, in high-speed flows and to realize that common temperature measurements are not always what they are supposed to represent in theory.

Introduction

A course in experimental methods was previously taught jointly for students in the mechanical engineering and aerospace engineering programs. This second-year course provides an introduction to experimentation in engineering. It aims to develop key skills such as test planning, understanding measurement chains, analyzing the metrological characteristics of instruments, as well as identifying measurement errors and propagating uncertainties. Students also learn to analyze and validate measurement results and to carry out typical measurements in solid mechanics and fluid mechanics. The course also covers the description of the main types of sensors, reading and recording devices, computerized data acquisition systems, and an introduction to LabVIEW software. Laboratories play a central role in this training: 11 experimental sessions are scheduled throughout the term. This course contributes to Quality 3 – Investigation – as defined by the Canadian Engineering Accreditation Board. In response to feedback from the aerospace engineering students, a separate version of this course has recently been developed for their program. This new course introduces three new laboratories, among which is the laboratory discussed in the present paper. These new laboratories will provide aerospace engineering students with the opportunity to develop essential technical skills, such as handling tools, taking measurements, and using sensors and other devices more specific to aerospace applications. This will not only allow them to understand the complexity of these systems but also enhance their critical thinking and skills in this field. All these benefits, widely documented in the scientific literature on pedagogy, have guided our choice toward experiential laboratories, despite the fact that in recent years, many instructors have turned to hybrid or remote formats for their laboratories ([1], [2], [3]).

Aerospace engineers often encounter very high-speed flows, such as those over an airframe or in aircraft engines, where the static and total (stagnation) values of pressure and temperature can differ significantly. Static and total pressures can be measured using pressure ports that are parallel and perpendicular to the flow, respectively, often combined in a device called a Pitot-static tube, which consists of two co-axial tubes, as shown in Figure 1. The flow is slowed to zero speed at the perpendicular hole in the central tube, giving the total pressure measurement, while the side holes on the outer tube measure the static pressure. The difference between these two pressures can be used to obtain the flow velocity. In the vast majority of cases, temperature is measured using a thermocouple. A thermocouple consists of two different metal materials joined at one end to form a junction (see Figure 2). When a temperature variation occurs at the junction, it generates a voltage, which can then be converted into temperature, through calibration. Since part of the flow stagnates at the thermocouple junction, the measured temperature is often assumed to be the total temperature. A laboratory has been developed to allow aerospace engineering students to verify this assumption while teaching them how to measure flow velocity using a Pitot-static tube. This laboratory has not been found in the open literature.

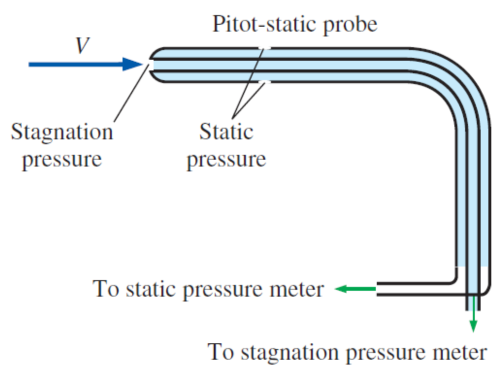

Figure 1: Pitot-static tube [4]

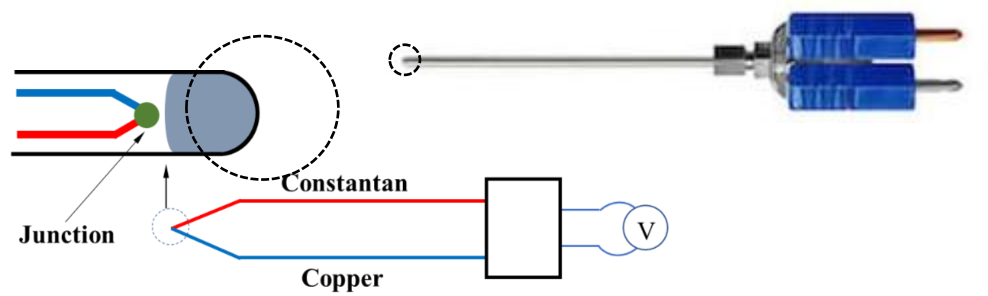

Figure 2: Thermocouple

Experimental Setup

The experimental setup, shown in Figure 3, consists of an 8-gallon reservoir, with one end connected via a valve to a 100 psig compressed air line, and the other end connected to a nozzle to produce a jet with a diameter of 0.25 inches, capable of reaching Mach 0.8. The valve allows for varying pressure in the reservoir and thus the jet velocity. The reservoir creates near-stagnant flow conditions for the gas inside, and a thermocouple is inserted into it at Point 1 to measure the total (stagnation) air temperature associated with the jet. Downstream of the nozzle, there is a Pitot-static tube and a thermocouple at Point 2. Both probes are placed on a laterally sliding platform with two stops: one stop positions the Pitot-static tube at the center of the nozzle to measure the maximum jet velocity, and the other places the thermocouple at the same location to measure the temperature at the center of the jet (see Figure 4). A differential pressure transducer is used to measure the difference between the total and static pressures on the Pitot-static probe. The static pressure is the atmospheric pressure, which is obtained via an electronic barometer. Both thermocouples are of type T.

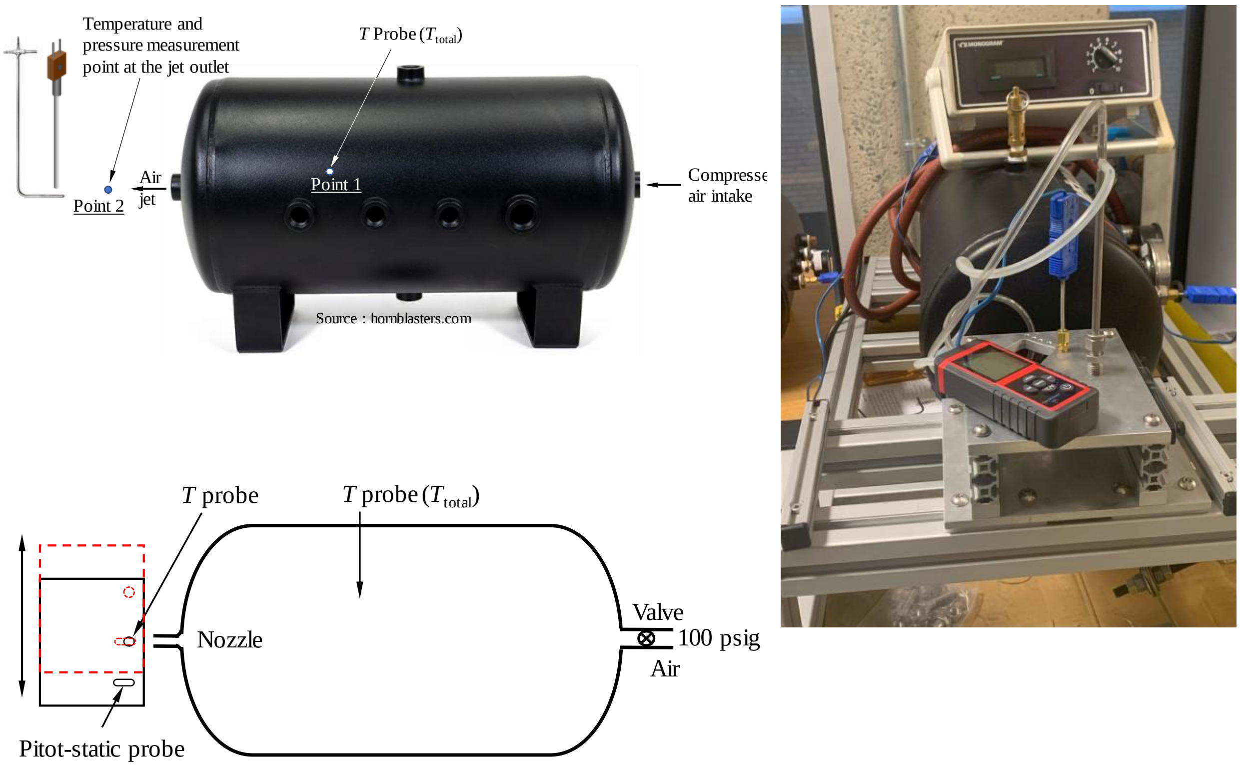

Figure 3: Experimental setup

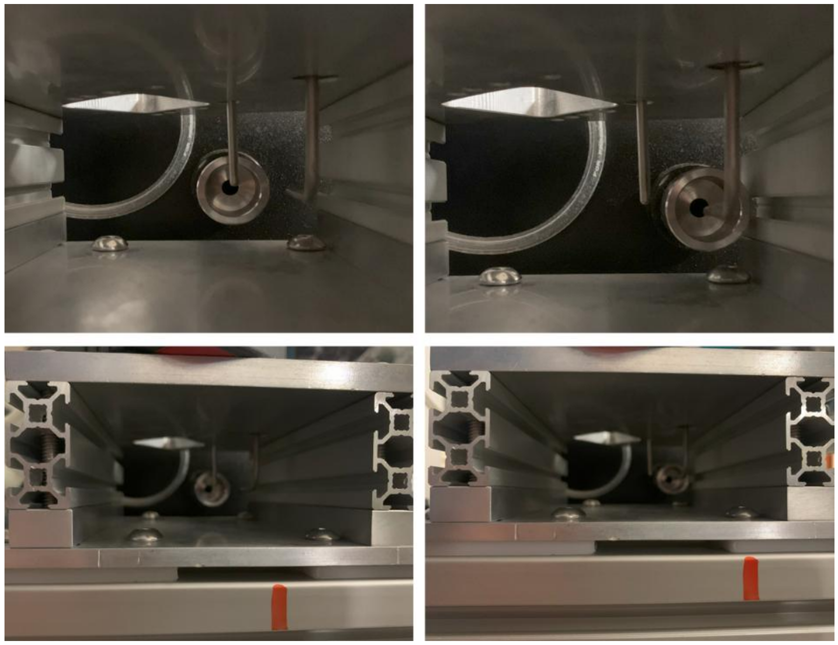

Figure 4: Alignment of thermocouple and static Pitot tube at the center of the nozzle

Test Procedure

First, the students are asked to familiarize themselves with the setup and to align the Pitot-static and the thermocouple probes at Point 2 with the center of the nozzle by moving the sliding platform and securing the stops. The air jet is activated by opening the valve, and the Pitot-static tube is first centered by moving the platform until the measured pressure differential is maximized, corresponding to the maximum velocity that occurs at the center of the jet. Once the first stop is secured, the thermocouple at Point 2 is centered with the jet by finding the two positions where the temperature drops, and returns to, the ambient value marking the lateral boundaries of the jet. The thermocouple is then positioned exactly between these two positions, and the second stop is secured.

In the second phase, the students reset the valve to achieve a low jet velocity and record the values of atmospheric pressure (P_{static}), the temperature at Point 1 (T_{total}), the pressure differential of the Pitot-static tube (ΔP_{Pitot}), and the temperature at Point 2 ($T_{measured}$). The students repeat the exercise about twenty times, increasing the jet velocity (by opening the valve) in increments until reaching the maximum value.

Results

Due to constraints related to the machine shop, the teaching team and technicians were unable to complete all the copies of the experimental setup required for deploying the laboratory in time for the Winter 2025 semester. The first deployment of the laboratory is scheduled for the Fall 2025 semester. Only then will the feedbacks from the students be collected session to allow the teaching staff to gain insight into the positive outcomes and potential shortcomings of this laboratory. For now, only demonstrations of the functional setup has been performed by the staff and the sample data, as shown in Table 1, was provided to the students.

Table 1: Sample of raw test data obtained from experiment

ΔP_{Pitot} (Pa)	P_{static} (Pa)	T_{total} - Point 1 (°C)	$T_{measured}$ - Point 2 (°C)
60	99500	23.0	22.9
220	99500	23.0	22.8
700	99500	23.0	22.6
1600	99500	22.9	22.4
2785	99500	22.8	22.0
4405	99500	22.7	21.7
6375	99500	22.7	21.4
8385	99500	22.6	20.9
11910	99500	22.6	20.6
18000	99500	22.6	20.3
22950	99500	22.6	19.9
28175	99500	22.6	19.5
31815	99500	22.6	19.0
38200	99500	22.6	18.5
41000	99500	22.6	18.0

Based on these results, the students can determine the velocity at the center of the jet (in Mach number) by using the values of the ambient pressure (P_{static}) and the total pressure (P_{total}) measured at Point 2 (P_{static} + ΔP_{Pitot}). By applying their knowledge of thermodynamics and fluid dynamics, and assuming the process is adiabatic and reversible, they calculate the Mach number (M) of the jet using equation (1), where γ is the ratio of specific heats for air (value of *1.4* under typical conditions).

$$\frac{P_{total}}{P_{static}} = \left(1 + \frac{\gamma-1}{\gamma} M^2\right)^{\frac{\gamma}{\gamma-1}} \tag{1}$$

Then, using the total temperature (T_{total}) measured at Point 1, the students calculate the static temperature (T_{static}) of the jet using equation (2).

$$\frac{T_{total}}{T_{static}} = 1 + \frac{\gamma-1}{\gamma} M^2 \tag{2}$$

The temperature measured at Point 2 by a thermocouple subject to air flow is then compared to the total temperature (T_{total}) and the static temperature (T_{static}) of the jet, all in K, for different jet velocities by plotting a graph like that shown in Figure 5. The horizontal line at the value of 1 represents the case where the assumption that the temperature measured by the thermocouple in a flow is the total temperature. The students will find that there is a deviation between the temperature measured by the thermocouple at Point 2 and the total temperature of the jet measured in the reservoir (Point 1). This deviation is very small at low jet speeds (below Mach 0.1) but increases with the jet speed, causing the temperature measured by the thermocouple in the flow to move toward the static temperature.

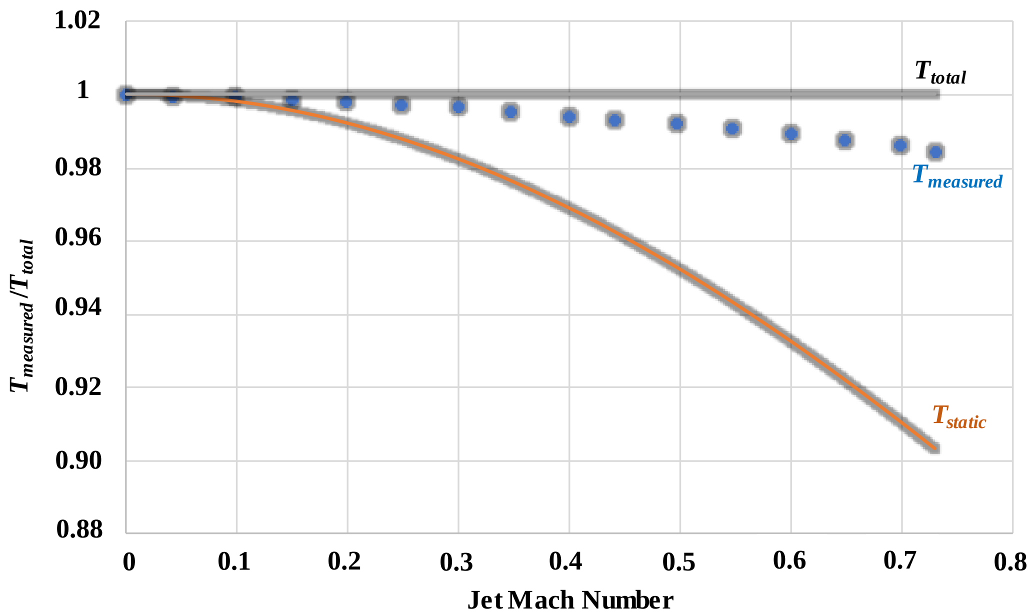

Figure 5: Example of test results

The students are expected to write a laboratory report that contains standard elements such as laboratory objectives, assumptions, a description of the experimental setup including a list of instrumentation and associated range and error margin, test procedure and results. In the results section, the students are asked to show the recorded data in a table similar to Table 1 and a plot as shown in Figure 5. Moreover, detailed error calculations for the temperature and Mach number based on the uncertainties in the pressure and temperature probes will be required with associated errors bars placed on the temperature ratio versus jet Mach number plot. The above elements of the report will account for 60% of the grade associated with this laboratory. The remaining 40% will come from a discussion section, which is the most educationally valuable section as it forces the students to think about what has been done and to interpret the data and, in doing so, better understands the physics associated with the experiment. To guide the students through this thinking process, they are asked to provide elaborate answers with justification to three questions.

The first questions is "*How valid is the assumption of taking the measured temperature by a regular thermocouple as being the total temperature and what could be the physical explanation behind any observed deviation?*" In answering the first part of this question, the students are expected to discuss the limit of this assumption based on the speed of the jet. For the second part, they will have to think about the flow physics, particularly the velocity distribution associated with flow on a bluff body and the extent of the flow stagnation region.

The second question is “*What does the difference between static and total pressure seen during the centering procedure of the Pitot-static tube say about the velocity distribution across the jet and how will this affect the calculated error bars in the temperature ratio versus jet Mach number plot?*” This question helps the students realize that the velocity varies significantly across a jet and that the errors in temperature and jet Mach number calculated solely based on the measurement uncertainties in pressure and temperature probes are incomplete and should, in fact, include the uncertainty in the position of the probes with respect to the jet centre.

Finally, the last question for the students in the discussion is to propose a solution to make thermocouples measure the true total temperature when exposed to a high-speed flow. In answering this question, the students have to reflect upon how the measurement of the total pressure was physically obtained in a Pitot-static tube in order to mimic the same effect in the case of a temperature measurement.

Conclusion

This article presents a laboratory designed for aerospace engineering students, allowing them to connect their theoretical knowledge to a practical experience. By the end of this laboratory, students will understand, for example, that the choice of a thermocouple for measuring fluid temperature is not only based on its measurement range, the type of medium, and the operating conditions specified by the manufacturer. Indeed, in the case of high-speed fluid flow, meaning with a Mach number greater than 0.3, a standard thermocouple does not capture the total temperature because the entire fluid does not stagnate at the thermocouple contact point. On the other hand, for low-speed fluid flow, corresponding to a Mach number below 0.1, the temperature measured by the thermocouple is very close to total temperature. The students are expected to prepare the experiments, analyze the experimental results and perform error calculations. They are then guided through a discussion section with three questions that will not only ask them to come up with the above observation, but force them to think critically about the physics associated with this experiment to explain the results, identify potential error sources, and to propose a solution to more accurately measure the total temperature of a high-speed flow. These elements should satisfy Quality 3 – Investigation – as defined by the Canadian Engineering Accreditation Board.

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