AC 2010-1803: THE AERODYNAMICS OF THE PITOT-STATIC TUBE AND ITS CURRENT ROLE IN NON-IDEAL ENGINEERING APPLICATIONS

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The Aerodynamics of the Pitot-Static Tube and its Current Role in Non-Ideal Engineering Applications

Abstract

The Pitot-static tube is a traditional device for local point-wise measurement of airspeed. It is a typical component used in conjunction with most, if not all, wind tunnels in the undergraduate and graduate engineering laboratory. Depending on the application, the physical size of the probe can range from relatively small on the order of a millimeter in diameter, up to 5-10 mm in diameter for large "field" application devices. The principles of the Pitot-static tube (or Pitot-static probe) are typically introduced as an example application of Bernoulli's equation in most undergraduate courses in fluid mechanics. Yet, in spite of the fact that it has been in use for decades, its use (and sometimes misuse) in non-traditional non-ideal flow situations is still the subject of investigation and uncertainty for important engineering applications. Consequently, it is necessary to acquaint engineering students not only with the normal operation of such instruments, but with their behavior in non-ideal flow situations as well. This is crucial from the standpoint of establishing the limits of applicability and accuracy, and in identifying flow situations where this device should and should not be implemented.

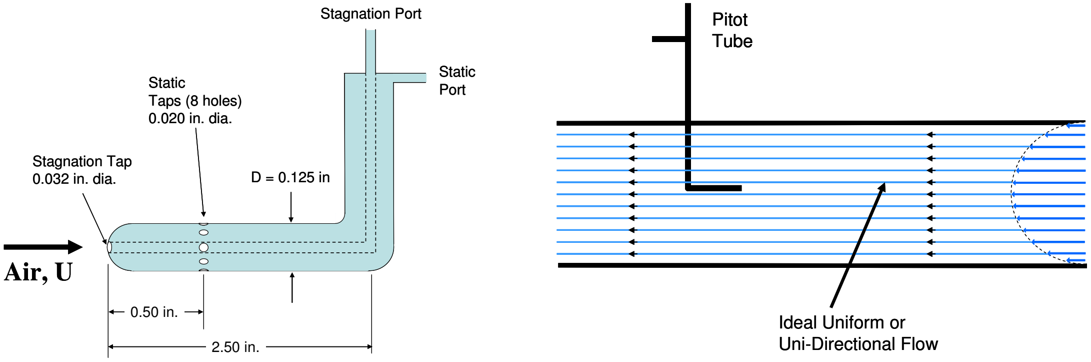
This paper attempts to investigate the non-traditional characteristics of the Pitot-static tube, in conjunction with an engineering laboratory for a senior-level elective introductory course in Aerodynamics. This is a natural place to introduce engineering students to the more detailed physical characteristics of this device, including the concept of pressure coefficient, dimensional analysis, streamlining and boundary layer separation phenomena. Equally important, and not generally given much consideration in a typical introductory fluid mechanics course, are the directional characteristics of the Pitot-static tube. The Pitot-static tube is not a directional device. It is generally well known that the Pitot-static tube is designed for use in relatively ideal parallel or nearly parallel flows. Such flows are typically encountered in a wind tunnel test section free stream, or nearby a smooth aerodynamic surface not encountering boundary layer separation. What may not be generally known, however, is that this device is commonly used by field engineers presently conducting "test and balance" of Heating, Ventilating and Air-Conditioning (HVAC) systems in large commercial buildings, to assess volumetric flow rate. Furthermore, the flows encountered in such applications can be quite far from the ideal parallel flows that the Pitot-static tube is designed to operate in. The focus of this paper is to demonstrate the full-range of Pitot-static tube directional characteristics to students using a simple physical setup in our Aerolab Educational wind tunnel facility. Quantitative measurements of Pitot-static tube pressure coefficient are complemented with flow visualization of the associated boundary layer separation phenomena to provide the students with insight into the measured Pitot-static tube behavior. The practical implications of these observations on the accuracy and reliability of modern field "test and balance" measurements are also investigated. Recommendations are proposed and investigated by the students for dealing with such non-ideal, but very important, field measurement situations.

Introduction

The Pitot-static tube or Pitot-static probe is probably one of the most common instruments used for measurement of local air velocity, and is still an integral part of wind tunnel testing facilities. It is the instrument used for airspeed measurement in commercial aircraft, and is a test instrument for airflow measurement in building duct systems. It functions on a very simple impact pressure principle, based on the application of Bernoulli's equation to relate the local "dynamic pressure" or "velocity pressure" to a measurable pressure difference (assuming approximately incompressible flow) given by

$$p_{dynamic} = \frac{1}{2}\rho U^2 = p_{stagnation} - p_{static} \tag{1}$$

This pressure difference is the difference between the "stagnation pressure" (sensed by the stagnation port) and the "static pressure" (sensed by the static pressure port), as shown in Figure 1(a) below. The probe dimensions shown here are for a relatively small probe, having a diameter of D = 0.125 in. (3.18 mm). The static tap dimension is nominally 0.1D – 0.3D, with the static tap location nominally 8D from the stagnation tap[6]. A commercial probe, such as is typically used for "test and balance" in large commercial buildings, is considerably larger with nominal diameter of 0.313 in (7.94 mm). This small probe is typically used in wind tunnel testing by the authors, while the larger commercial probe is currently in use by the lead author in conjunction with research involving assessment of errors in "test and balance" operations associated with large building duct systems.



(a) Schematic of Pitot-Static Tube **(b) Pitot-Static Tube in Duct Flow**

Figure 1: The Pitot-Static Tube

It is well-known that the Pitot-static tube is designed for use in relatively ideal parallel or nearly parallel flow, such as the duct flow shown in Figure 1(b). When the inclination of the flow exceeds about 15-20 degrees, significant errors will result due to the friction and boundary layer separation effects that occur. In these situations, the pressures sensed at the Pitot-static tube ports do not represent the desired stagnation pressure and static pressure. This is due to the fact that the Pitot-static probe is not a directional device, and so in unknown flow situations, a departure from the ideal uni-directional flow in Figure 1(b) can result in very significant errors—errors which may be unknown to the observer due to lack of knowledge of the true flow direction.

The purpose of this paper is not so much to address the "known" characteristics of the Pitot-Static probe, but rather to focus mainly on the characteristics that are not so well-known. Typical undergraduate fluids texts[9,10,11,12] describe the basic operation of the Pitot-Static probe.

Some also typically show a portion of the directional behavior, usually expressed in terms of the measurement error as a function of yaw angle[9], and others describe further details about the accompanying pressure distribution on the surface of the probe during normal operation[11]. This more detailed pressure distribution is primarily to justify the location of the static pressure taps. Because the normal operation of the Pitot-static probe is with the probe aligned with the flow (i.e., zero yaw angle), the associated yaw angles associated with error investigations are commonly limited to about ± 20 degrees and the resulting measurement errors are only a few percent. The objective of this work is to demonstrate focus more on the non-ideal behavior of the Pitot-static probe using a simple physical setup in our Aerolab Educational wind tunnel facility, and to acquaint engineering students with some of the current important measurement issues. The "full-range" of Pitot-static tube directional characteristics was investigated as part of an engineering laboratory for a senior-level elective introductory course in Aerodynamics. This is a natural place to introduce engineering students to the more detailed physical characteristics of this device, including the concept of pressure coefficient, dimensional analysis, streamlining and boundary layer separation phenomena. In addition to the measurements of the directional characteristics of the pressure coefficient for the Pitot-static tube, flow visualization can show the associated boundary layer separation phenomena to provide the students with further insight into the measured Pitot-static tube behavior. The practical implications of the probe characteristics on the accuracy and reliability of modern field "test and balance" measurements are also discussed, along with some of the student observations and interpretations of the quantitative Pitot-static probe test results.

Wind Tunnel Facility

Figure 2 shows the existing Educational Wind Tunnel associated with the current Pitot-static probe testing. A photograph of the overall facility is shown in Figure 2(a), and a longitudinal view of the wind tunnel showing the test section and instrumentation for data acquisition is shown in Figure 2(b).

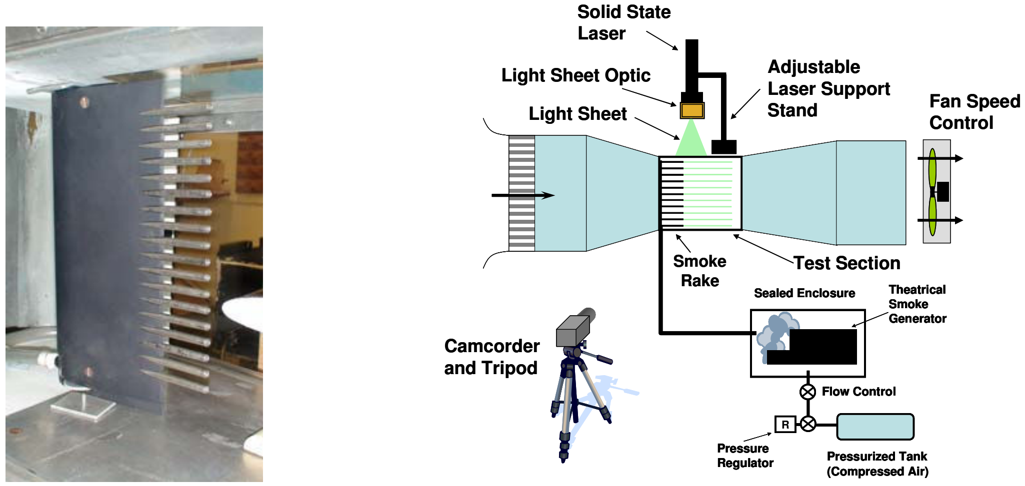
(a) Wind Tunnel Facility **(b) Test Section and Instrumentation**

Figure 2: Educational Wind Tunnel Facility

While relatively inexpensive in comparison to some wind tunnels, this facility has been demonstrated to be capable of investigating a wide variety of phenomena of interest to fluid mechanics and aerodynamic courses.[1-5,8] A more detailed description of the wind tunnel features and specifications are addressed elsewhere[1-5,8]; however, those features related to the current work are described below. The wind tunnel has a test section measuring approximately 12 in x 12 in x 24 in (305mm x 305mm x 610mm), and has a maximum air speed of approximately 140 mph (63 m/s). It is instrumented with an electronic strain-gage based balance for measurements of normal force, axial force, pitching moment, and pressure distribution as a function of air speed and angle of attack. Both manual as well as electronic pressure sensing is available on this facility. An electronic pressure scanning unit containing 32 individual electronic pressure sensors is also used in conjunction with this facility. This latter unit can be used to provide real-time visualization of the pressure distribution in the wind tunnel, in much the same manner as it has been used to visualize the pressure distribution associated with airfoils and wings.[3,5] Manual measurements are accessible from a front panel digital display shown in Figure 2(b), and electronic data acquisition is also available for remote access and real-time measurements. A recently developed flow visualization setup, with general-purpose smoke rake system, will be used with the current Pitot-static probe investigation.

Smoke Rake System

Figure 4(a) shows a photograph of the smoke rake[8] used with the current investigation. The rake is modular and can support a variable number of tubes by adjusting the housing. In the current version used for testing presented below, the rake has a total of eighteen ¼-inch (6.4 mm) O.D stainless steel tubes. Smaller or larger tubes can be used, depending on the size of the test model. This size provides reasonable resolution of the flow fields associated with the morphing wing wake flows currently under investigation. Additional single stream smoke injection was also used, for simplicity, during the current testing.



(a) Smoke Rake Assembly **(b) Overall Smoke Distribution System**

Figure 4: Flow Visualization System

To provide good flow visualization and streamline definition, laminar flow in the rake tubes is highly desirable. Otherwise, the smoke streams will break up very quickly after exiting the tubes, which will "wash out" the desired streamlines. Well defined streams on the order of 12 inches (30 cm) or more are possible with careful attention to this laminar flow requirement, and with proper balancing of the flow streams. The diameter and length (in external flow direction) of the flow injection tubes also limits the tube spacing. Too close and the external boundary layers from adjacent tubes will interfere, and also tend to block off the flow around the entire rake assembly. The current rake has a symmetrical airfoil design, and the airfoil housing was constructed from ABS plastic using an in-house rapid prototyping facility. This rapid prototyping facility was also used to construct a simplified large-scale Pitot-static probe test model for flow visualization purposes.

Smoke Generation System

In addition to the rake itself, a smoke generation and smoke distribution system is required to supply smoke at a constant rate to the rake assembly. A schematic diagram of the current smoke distribution system is shown in Figure 4(b). Flow must also be provided through the test section. The flow velocities required to provide well-defined streamlines are considerable below the normal wind tunnel airspeeds. Hence, an external box-fan was positioned at the discharge end of the wind tunnel to suck air and provide the flow.

A Variac (variable transformer) was used to regulate the speed of this fan, and the relative spacing between the fan and the exit plane of the wind tunnel also provided some speed adjustment. In practice, a spacing of about 6-12 inches (15-30 cm) was sufficient for flow visualization in conjunction with the current Pitot-static tube test model. Another issue of importance to more quantitative evaluation of the flow visualization is the determination of the airspeed or flow rate in the duct model. The airspeeds are too small for the normal wind tunnel measurement system which makes use of the pressure drop in the wind tunnel converging section resulting from the Bernoulli effect. An indirect method is possible, by measuring the volumetric flow rate supplied to the rake manifold from the smoke generation system. If the total volumetric flow rate of air containing smoke is Q, then the average discharge velocity from N identical rake tubes will be $U = Q/(NA)$, where A is the internal cross-sectional area of a single typical rake tube. Since the exit tube flow must be properly balanced with the external airspeed for so-called iso-kinetic injection, U will be approximately the airspeed in the tunnel test section at the point of the smoke rake exit. Alternatively, a small rotating vane anemometer could possibly be placed in a neutral location, depending on the type of test section model configuration. For the current testing, and as is typical for such low speed testing in this wind tunnel, the volumetric flow rate was less than about 10 SCFH (280 liters/hour). The ¼-inch 18-tube stainless steel rake tubes have an inside diameter of about 0.200 inches (0.508 cm), which yields a nominal airspeed of about 1 ft/sec (0.4 m/sec).

Streamline Illumination and Image Acquisition System

For clear visualization of the smoke streams, an illumination system is also needed. A laser-based illumination setup was used for the current testing. This light source consists of a 500mW solid state laser mounted vertically on an adjustable support platform above the wind tunnel test section. The adjustable platform provided lateral displacement adjustment and tilt adjustment degrees of freedom for aligning the light sheet with the plane of the smoke streams. A simple cylindrical lens optic produced the desired sheet of light for illumination of a section of the test section. The top of the test section, as well as the side-walls, are of Plexiglas for optical access. Not all of the flow field could be viewed at the same time with the current optical setup due to the spreading of the laser light sheet. For safety reasons, precautions were taken to minimize stray laser reflections. It is also important to instruct students about the safe use of lasers. A generic camcorder with tripod mount was used to capture both video and single frame images of the streamline flow. The camcorder was positioned about 10 ft (3 m) from the image plane to minimize parallax effects and to also provide large depth of field to keep everything in focus.

Small Pitot-static Probe Directional Measurements

Figure 5 shows the simple setup used for investigation of the directional characteristics of the small-scale Pitot-static tube. The probe was inserted in a special-purpose side mount fitting specifically made for Pitot-static probe access. A simple 360-degree protractor facilitated the angular positioning of the probe relative to the approximately airflow in the test section. In figure 5(a) the probe is shown properly aligned with the flow. Figure 5(b) shows the probe tilted about 30° relative to the airflow. Under ideal conditions, the probe directional characteristics should be symmetrical about the 0° (properly aligned) orientation. Only rotations about the main support stem were investigated here. Slightly different characteristics might be expected for combined pitching of the probe support stem, owing to different flow interference with the stem axis. However, the current directional characteristics are the dominant ones associated with typical duct flow applications.

(a) Probe In-Line with Flow **(b) Probe Alignment Tilted**

Figure 5: Pitot-Static Probe Angular Positioning Setup

Figure 6 shows the results of directional measurements of the pressure coefficient for the small Pitot-static probe. The pressure coefficient for the Pitot-static tube is defined as

$$C_p \equiv \frac{p_{stagnation} - p_{static}}{\frac{1}{2}\rho U_\infty^2} \tag{2}$$

Two different airspeeds (80 mph and 100 mph) are shown superimposed on the Figure, illustrating that the pressure coefficient is approximately independent of airspeed (or alternatively, Reynolds number $Re = UD/\nu$).

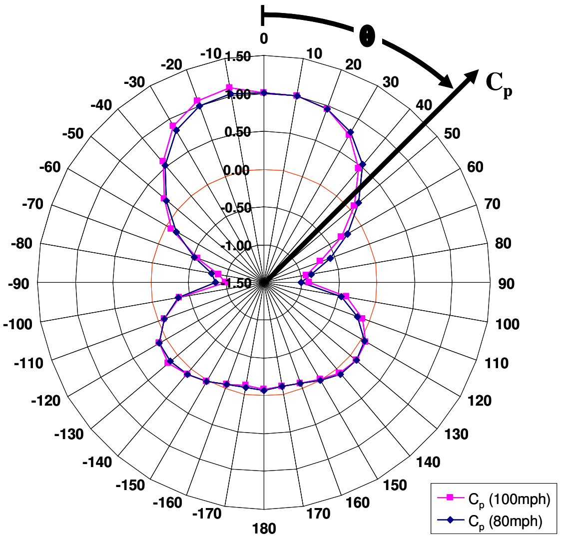
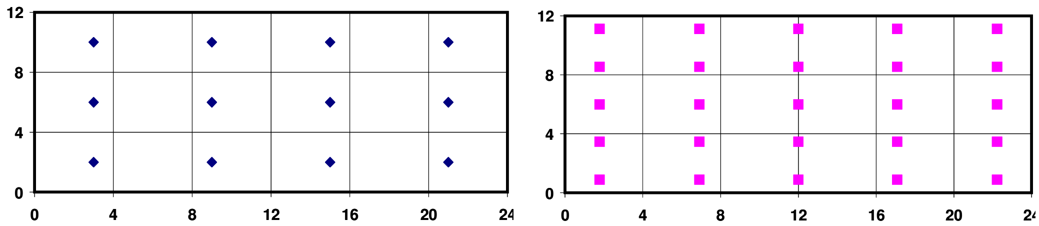


Figure 6: Pitot-Static Probe Pressure Coefficient Tilt Characteristics

When properly aligned with the flow, the pressure coefficient should be very close to $C_p = 1$. It is clear from Figure 6 that there is considerable variation in the pressure coefficient, C_p , if the probe axis is tilted more than a nominal 15-20 degrees out of alignment with the flow. Furthermore, the pressure coefficient reaches a minimum value close to $C_p = -1$ when the probe alignment is nearly perpendicular to the flow, and is close to zero and slightly negative when the probe is completely reversed (180 degrees out of alignment). At the 90^o position (perpendicular to the flow) it would appear that the static and stagnation ports are acting approximately in reverse, with the stagnation port sensing the local static pressure and the static port effectively sensing the stagnation pressure.

Large Pitot-Static Probe Testing in HVAC Duct Flows

Large-scale Pitot-static tube probes[7] with diameter D = 0.313 in (7.94 mm) are typically used in "test and balance" operations by field engineers in large airflow duct systems. In an effort to determine the volumetric airflow at a given location, discrete measurements of local air velocity are made across the duct cross-section, by drilling carefully positioned access holes in the sheet duct wall and inserting the probe. The average of the discretely measured velocities gives an estimate of the average air flow velocity through the duct at the given location. Two common traversing methods have been employed for this purpose—the co-called Equal Area (EA) method, and the Log-Tchebychev (Log-T) method[7]. The measurement locations associated with a 12 in. x 24 in. (30 cm x 60 cm) commercial rectangular duct are shown in Figure 7. For the typical turbulent flow situations encountered in practice, the velocity profiles are fairly uniform accept near the walls. With the EA positioning, the measurement positions are equally spaced, and as such may not give proper influence of the attenuation of air velocity near the side walls. The Log-T method attempts to more accurately account for these near wall effects.



(a) Equal Area (EA) Positions (b) Log-Tchebychev (Log-T) Positions

Duct Size	Traverse Algorithm	Horizontal Locations	Vertical Locations
inch x inch		(inches) from side of duct	(inches) from bottom of duct
24 x 12	Log-T	1.8, 6.9, 12, 17.1, 22.2	0.9, 3.5, 6, 8.5, 11.1
	Equal Area	3, 9, 15, 21	2, 6, 10

(c) Summary of EA and Log-T Traverse Positions

Figure 7: Traversing Methods for 12 in x 24 in Rectangular Duct

In these field application situations, it is often necessary for engineers or field technicians to make measurements close to a fitting, where the flow can be very non-uniform and highly directional, as suggested by the flow in the branch of the tee shown in Figure 8. Even reverse flow can take place near the walls, making the associated Pitot-static probe readings highly suspect. Since the true flow direction is not known, and because of the directional characteristics of the Pitot-static probe, it is generally not possible to make accurate measurements in this important situation. A sample of some actual duct flow measurements taken with the large Pitot-static probe is shown in Figure 9. These measurements were taken just downstream of a tee branch entrance, and within the region of highly non-uniform flow. The rectangular grid values shown in Figure 9 are for an orientation looking downstream from the branch of the fitting shown schematically in Figure 8. Hence, the negative values likely occur within the separation region illustrated in Figure 8. The probe insertion shown in Figure 8 is for simplified 2D schematic purposes only, and the yaw angle of the probe is actually about an axis normal to the plane of the Figure. Due to the nature of the flow near duct fittings used in commercial buildings, such yaw angular deviations can be as high as 180 degrees. Moreover, even at smaller angular deviations of around 45 degrees, the resulting errors can be extreme and even negative "apparent" velocity pressure readings can take place. It is important to recognize that during

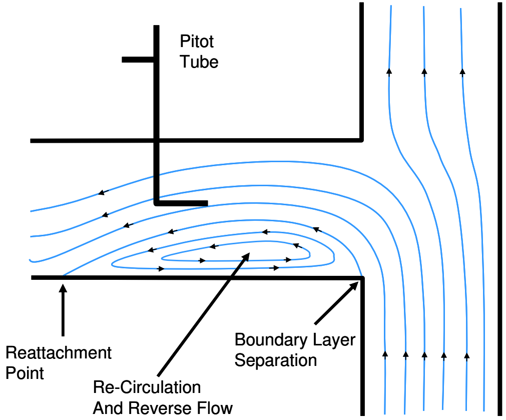


Figure 8: Non-Uniform Flows in the Branch of a Rectangular Duct Tee Fitting

such field testing, the true flow direction is unknown. Furthermore, technicians do not have sufficient time to attempt assess the flow direction by other manipulations of the probe, which would require further corrections for yaw angle to properly determine volumetric flow rate. Clearly, the presence of negative readings, resulting from the unknown flow direction, presents a problem in interpreting the measurements. A negative result suggests a major departure from the normal velocity pressure relationship given by Equation (1). Current ASHRAE Fundamentals Handbook recommendations for use of Pitot-static probe measurements in assessing duct volumetric flow rate are that “if negative velocity pressure readings are encountered, they are considered a measurement value of zero and calculated in the average velocity pressure[7].” Even though it is clear that this “zeroing out” procedure likely introduces some type of bias in the measurement, there are currently no generally accepted alternative procedures for this type of situation.

	3	9	15	21
2	-204	263	364	641
6	-206	-130	64	560
10	-199	225	351	607

(a) EA Velocity Measurements

	0.9	3.5	6	8.5	11.1
0.9	-210	95	439	609	712
3.5	-207	-45	263	293	671
6	-202	-193	-4	187	671
8.5	-207	-183	317	282	653
11.1	-207	-100	414	533	701

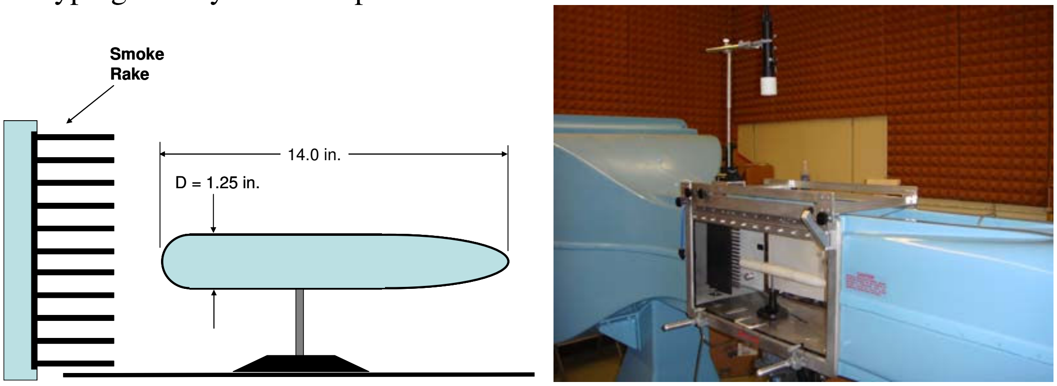
(b) Log-T Velocity Measurements

Figure 9: Pitot-Static Probe Measurements Downstream of Tee Branch

This is still an unsolved problem, and a consequence of this laboratory work is to illustrate this important issue to students. Even if no obvious negative pressure reading occurs, it should be clear from Figure 6 that even positive readings in the highly separated flows near a fitting can lead to very unreliable velocity measurements.

Flow Visualization using Simplified Pitot-Static Tube Model

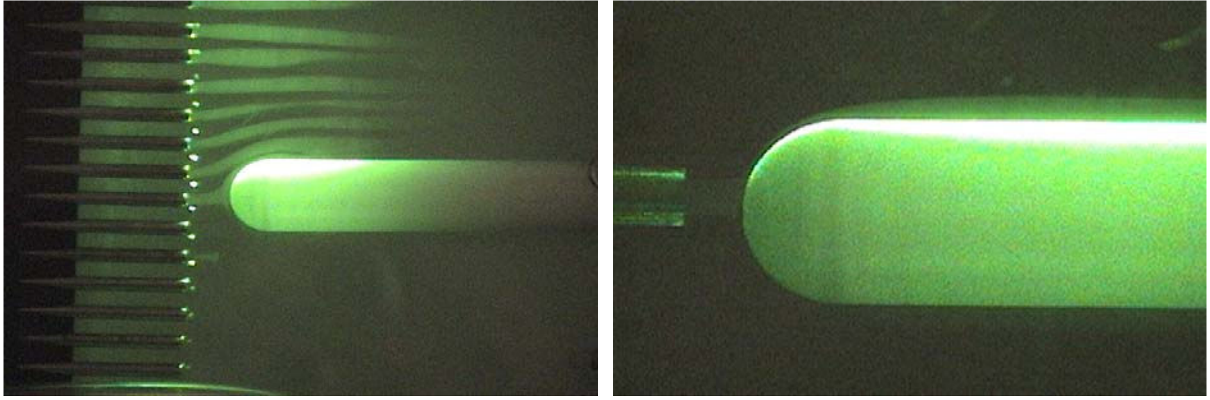
In an attempt to provide some qualitative explanation for the variation in the Pitot-static probe pressure coefficient, a large-scale simplified model Pitot-static probe was constructed using the rapid prototyping facility in our Department.



(a) Simplified Pitot-Static Tube Model **(b) Model in Wind Tunnel Test Section**

Figure 10: Simplified Pitot-Static Probe Model for Flow Visualization

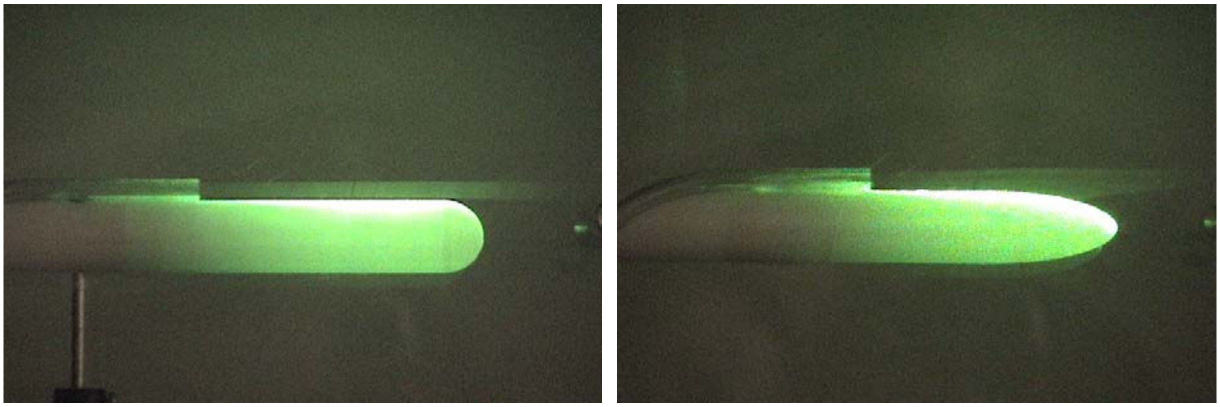
The main purpose of this model is to illustrate some of the flow separation characteristics of the Pitot-static probe. For simplicity, only angles of zero degrees and 180 degrees are shown here. A more complete large scale Pitot-static probe is planned for future implementation, which would provide better control of orientation and viewing of other yaw angles. A simplified schematic of the current large-scale Pitot-static probe test model is shown in Figure 10. The model was constructed from ABS Plastic, and had a diameter of about D = 1.25 in. (31.8 mm), and an overall length of about 14.0 in. (356 mm). One end was hemispherical with a diameter D, and the other end was elliptical in shape.



(a) Leading Edge Smoke Streams **(b) Close-up Leading Edge Flow**

Figure 11: Simplified Pitot-Static Probe Flow Visualization—Normal Orientation

Figure 11(b) shows the streamline behavior near the leading edge of the simplified Pitot-static probe using the smoke rake system, representing the flow near the stagnation pressure tap of the Pitot-static probe for normally aligned operation. An enlarged view of this flow is shown in Figure 11(b), where a single smoke stream is used instead of the rake. It is clear from the photographs that the flow follows the contour of the surface, with a stagnation point at the leading edge, and that boundary layer separation effects along the side walls are negligible. Hence, the probe output should be a good representation of the dynamic pressure of the air stream.



(a) Reverse Flow Smoke Streams **(b) Reverse Flow with Elliptical Shape**

Figure 12: Simplified Pitot-Static Probe Flow Visualization—Reverse Orientation

Figure 12 illustrates the approximate behavior of the flow expected at the leading edge (stagnation tap location) when the flow orientation is out of alignment by 180 degrees (reverse flow orientation). Clearly boundary layer separation is seen to occur very close to the start of curvature on the back surface, as shown in Figure 12(a). In Figure 12(b), the elliptical edge is used instead of the more hemispherical Pitot-static tube shape, and the boundary layer separation is seen to be delayed slightly. The pressure downstream sensed by the stagnation pressure tap in this separated region is typically below atmospheric pressure, and this contributes significantly to the negative Pitot-static tube output in reverse flow orientation.

Student Experience with Pitot-Static Probe Investigation

The quantitative Pitot-static probe measurements illustrated above formed part of a new addition to a student laboratory exercise associated with a senior level 3-credit hour introductory course in aerodynamics[5]. This introductory aerodynamics course currently does not have a separate laboratory associated with it. As a result, laboratory exercises such as the current one are integrated into the course 50-minute lecture sequence. There are typically a total of three to four main 50-minute laboratories used in conjunction with this course, along with a semester design project which usually takes the form of a group glider design project with detailed flight testing at the end of the semester. Some significant outside time is required of the students for analysis and evaluation of results. These laboratories cover topics such as (1) Basic Wing Lift, Drag, and Pitching Moment Characteristics, (2) Airfoil Pressure Distribution, (3) A Mini-Design Build Test Lab focused on Streamlining and Drag Reduction, and (4) Airplane Stability and Flight. The number of students in this senior elective course also puts a practical limits to the number of laboratories.

The current Pitot-static probe laboratory was motivated by a desire to introduce students to the pressure coefficient concept as part of an existing lab associated with airfoil pressure distributions, as well as to a simple investigation of the directional characteristics of the Pitot-static probe—an important tool used in experimental aerodynamics as well as in HVAC applications. After being shown the pressure characteristics associated with an airfoil at increasing angles of attack, and the onset of boundary layer separation and stall, the students were confronted with the Pitot-static probe testing. The attempt here was to at least partially relate the boundary layer and stall phenomenon associated with the wing to that of the airflow over the Pitot-static probe. The associated boundary layer separation phenomenon also becomes important in relation to a subsequent streaming and drag reduction design/build/test laboratory. As part of the testing, students were shown the typical output of the Pitot-static probe for normal orientation with the airflow. This output (which is essentially the dynamic or velocity pressure) was then compared to the measured pressure ring output (see blue plastic tubing in Figure 5) relative to the ambient pressure. The pressure ring is used by the wind tunnel instrument panel to provide an average indicated airspeed at the entrance of the test section region, and this was shown to compare quite close to the Pitot-static probe results. Next the probe was rotated from 0 degrees yaw angle to 180 degrees. Separate stagnation and static pressure tap measurements were also observed so that the students could see more detail associated with the physical behavior of the Pitot-static probe. For consistency of results, all students were provided with a set of common experimental results for later individual analysis.

Some of the general conclusions reached by students in this beginning attempt to incorporate some of the unusual physics and applications of the Pitot-static probe, as well as difficulties they had in evaluating and interpreting the lab, are summarized below. For this initial attempt, only qualitative evaluations of student performance and results are presented. The number of students in this course ranges from about 25 to 35 students.

1. Most students were able to correctly obtain plots of the pressure coefficient, C_p , as a function of tilt angle for the two assigned airspeeds of 80 mph and 100 mph. For the most part, students correctly noted that the effect of airspeed was relatively small, although students tend to overestimate the significance of small differences in results. This clearly underscores the importance of emphasizing uncertainty in measured results, and it's role in correctly interpreting relative comparisons. It should be noted that while the larger airspeed represents only a 25 percent increase, the associated dynamic pressure of the free stream increases by about 56 percent due to the fact that the dynamic pressure varies as the square of the airspeed. Thus, the scaling of results for the two different airspeeds to nearly the same C_p distribution is indeed significant.
2. Some students had difficulty in working with the polar plot, and in interpreting results from the polar plot. This is probably due to their limited experience in using this mode of graphical results, and so this exercise was probably a good one in this respect as well as for the aerodynamic characteristics.
3. Students usually recognized the clear need to have knowledge of the flow direction for accurate Pitot-static tube measurements of airspeed. The probe needs to be aligned within about 15-20^o to achieve reasonable accuracy. Outside of this range, the probe output (as normally defined) does not provide an indication of the dynamic pressure, and hence cannot correctly assess the flow due to ambiguity of the flow direction.
4. The pressure coefficient, C_p , in reverse flow is negative. It is also negative for other selected orientation angles. The magnitude of this coefficient is also very small for the 180 degree orientation, indicating that a large measurement uncertainty may result due to the decreased level of pressure difference.
5. Clearly Bernoulli's equation is not valid when calculating the pressure difference in reverse flow, or for that matter, even at other angles significantly different from inline with the flow. The pressure indicated by the stagnation pressure tap is below atmospheric pressure when the tilt angle is 180^o (reverse flow). This can be observed by separately measuring the stagnation pressure tap output and the static pressure tap output. Students generally recognize that use of Bernoulli's equation is suspect when significant friction effects are present. However, students entering this course have typically only had an introductory fluid mechanics course, and they are not yet acquainted with the detailed physics of boundary layer separation prior to taking this course. Bringing the boundary layer separation phenomenon to further light is one of the purposes of this overall laboratory.
6. Some students had minor difficulties in dealing with units. Since our wind tunnel instrumentation provides output pressures in units of "inches of H_2O," it is necessary to relate this "head or length" unit to the appropriate pressure from hydrostatics. Some students tend to approach this as a unit conversion, when it really is an elementary application of the hydrostatic equation $p = \rho g h$, where p is the associated gage (or relative) pressure measured at the pressure tap, and h is the associated "head" that a column of water having density ρ would produce. The issue of clarification here is that the fluid density, and also the local acceleration of gravity, both affect the hydrostatic pressure. The density of pure water varies about 0.6% over the temperature range from 10C to 35C. The acceleration of gravity depends on latitude and varies at sea level as much as 0.5% from the poles to the equator. Hence, the liquid column height alone does not give a precise definition for pressure. It is true, however, that "conversion factors" are commonly given in handbooks in terms of water

(or mercury) column height. These conversions imply a specific "fixed standard" fluid density, such as the density of water at 4C. As long as high precision measurements are not required, accepting the water (or mercury) column height as a unit of pressure is convenient. The intent here, however, is to indicate to the students some caution in that there are situations (associated with precision instrument calibration for example) where not giving proper consideration to the density and acceleration of gravity affects, may result in unacceptable errors. Some manometer fluids are designed to provide a "fixed" specific gravity fluid over a large temperature range. Use of distilled water in a water manometer to calibrate a precision electronic pressure transducer, however, can lead to significant errors without properly addressing the temperature dependence.

7. Some students clearly noted that there was a range of angle which yielded negative C_p values, and not just at the 180^o reverse flow situation.
8. Students did not have significant recommendations for dealing with the observed negative Pitot-static probe observations, as far as improved interpretation of results or recommendations related to field measurements. This is not surprising since this is likely their first encounter with the field measurement issue.

In addition to illustrating the more detailed directional characteristics of the Pitot-static probe device, these test results, and the simple methods presented here, should also be very useful in providing physical insight in undergraduate fluid mechanics courses which typically introduce the Pitot-static tube as an application of Bernoulli's equation, and in more advanced courses dealing with boundary layer separation and boundary layer control. Because of the still unsolved nature of the duct flow measurement problem—a problem faced currently by field engineers and technicians—these results may also provide a practical laboratory experience associated with more advanced graduate level boundary layer theory courses. Some of the important learning objectives associated with this type of laboratory experience include the following:

1. Introduce students to practical optical fluid flow visualization techniques.
2. Introduce students to practical flow measurement issues of current importance.
3. Illustrate the important directional nature of the Pitot-static probe.
4. Develop understanding of engineering fluid mechanics principles associated with wind tunnel smoke rake design.
5. Develop experimental understanding of laminar and turbulent jet flows associated with smoke injection into an airstream.
6. Introduce students to characteristics of flow over various geometries, and the principles behind streamlining.
7. Develop understanding of engineering fluid mechanics principles associated with boundary layer separation.
8. Foster an important hands-on wind tunnel laboratory experience.

Summary and Conclusions

This paper investigates the common as well as the non-traditional characteristics of the Pitot-static tube, in conjunction with an engineering laboratory for a senior-level elective introductory course in Aerodynamics. The focus of this paper was to demonstrate Pitot-static tube directional characteristics to students by means of a simple physical setup in our Aerolab Educational wind tunnel facility. Quantitative measurements of Pitot-static tube pressure coefficient were made and interpreted by students as part of an additional application of pressure coefficient concepts associated with airfoil pressure distribution. These quantitative measurements can be complemented with flow visualization of the associated boundary layer separation phenomena to provide the students with insight into the measured Pitot-static tube behavior. The practical implications of these observations on the accuracy and reliability of modern field "test and balance" measurements are discussed in conjunction with actual large-scale duct traversing tests taken in the branch flow of a commercial rectangular duct tee fitting. The implications of the Pitot-static tube directional characteristics on the difficulty and as yet unsolved problem faced by field engineers of interpreting Pitot-static tube measurements in highly non-ideal flows is also discussed. It should again be noted that one of the important issues brought out by this lab is the practical limitations of field measurements in comparison to laboratory measurements. In the field, technicians do not have sufficient time to attempt assess the flow direction by other manipulations of the probe, which would require further corrections for yaw angle to properly determine volumetric flow rate. The extension of this experimental setup to include more quantitative interpretation of the results is a logical next step. The question remains as to whether there is a simple easy-to-apply procedure that field engineers could use to rapidly and efficiently get useful data from Pitot-static probe measurements in these extreme flow situations. Additional visualization at other tilt angles may also be a valuable exercise, and may help to further illustrate these issues to students. The yaw angles shown in this paper were the easiest to implement with the simplified test model and associated mounting and visualization hardware. This will likely require a more detailed physical model of the Pitot-static probe, which includes more details of the physical characteristics including the pressure tap openings and the typical L-bend configuration. More detailed scaling issues will need to be addressed with this enlarged test model.

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