Averaging Pitot Tubes; Fact and Fiction

Abstract

An experimental investigation has been undertaken to elucidate effects of averaging stagnation pressures on estimated velocities for pressure averaging instruments such as averaging Pitot tubes or velocity grids. The data from this study suggests that although an averaging Pitot tube does accurately measure the average stagnation and dynamic pressure, errors in the average of the velocity or volumetric flux (which are over-predicted) can be significant if large velocity gradients are present. The data indicates that if an averaging instrument is to be used, the installation location should be surveyed with a Pitot tube or other point velocity-measuring device, such that the values from these measurements may be compared to the averaging instruments estimates.

Introduction

Averaging velocity probes are widely used to estimate volumetric flow through ductwork, while various averaging velocity grids are used to estimate flow from HVAC grids. These devices offer the benefit of simplicity and cost effectiveness. Averaging Pitot's work by averaging the stagnation (or total) pressure measured at various pressure ports along the length of the probe. In combination with a static measurement, the dynamic (or velocity) pressure, and thus the "average" gas velocity may be estimated. Mathematically, however, averaging the stagnation pressures is incorrect, individual velocities, not pressures should be averaged. This is shown clearly by example. The relevant equation describing the velocity (at low speed) measured by a Pitot tube is (Barlow and Pope, 1999):

$$Velocity = \sqrt{\frac{2 \times \Delta P_{dynamic}}{\rho}} \quad (1)$$

If we were averaging just two readings (at location 1 and 2) we may write:

$$VelocityAverage_{1,2} = \frac{1}{2}\left(\sqrt{\frac{2 \times \Delta P_{dynamic1}}{\rho}} + \sqrt{\frac{2 \times \Delta P_{dynamic2}}{\rho}}\right) \quad \text{Pitot survey}$$

$$Velocity(Average\,\mathrm{Pr}essure_{1,2}) = \sqrt{\frac{2 \times \left(\frac{1}{2}\left(\Delta P_{dynamic1} + \Delta P_{dynamic2}\right)\right)}{\rho}} \quad \text{Averaging Pitot}$$

$\Delta P_{dynamic}$ is the differential pressure at either Port 1 or 2 and ρ is the air density. These two relations are clearly not equivalent and show that differential pressures cannot be averaged. As a simple mathematical example, assume we are averaging just two numbers, namely the number 10 using a square root relationship;

$\sqrt{100}+\sqrt{100}=20\neq\sqrt{100+100}=14.14$. The first answer (20) corresponds to that of a Pitot tube, while the second answer (14.14) corresponds to an averaging Pitot tube.

To account for these averaging errors, manufacturers of averaging Pitot probes often include some form of correction factor. However, an implicit assumption in the use of these probes is that the velocity profile conforms to certain criteria. These are usually assumed satisfied through location of the probe, e.g. a certain number of duct diameters upstream and downstream of a potential flow disturbance. Even when satisfied (which is not always practical), this does not guarantee that the flow profile conforms, especially in the less then ideal systems that are typical.

In this article, an experimental study into the effects of velocity profile on the accuracy of a simple averaging Pitot tube is discussed. Data from the averaging Pitot tube is compared to data from a standard two row, eight points per row traverse of the same duct using a Log-Tchebycheff point distribution. The ports on the averaging Pitot were located so as to match the Log-Tchebycheff distribution. The data presented in this study is not intended as an absolute, but used to identify and clarify the behavior of these instruments.

Equipment and Procedure

Tests were undertaken in a small blow down wind tunnel as shown in Figure 1. The tunnel consists of a 6” diameter acrylic tube attached to a 330cfm tube-axial ac fan. A simple notched inlet is used instead of a bell mouth. Inlet flow conditioning is achieved using a 1/8” cell honeycomb to remove cross-flow velocity gradients and to a lesser extent axial velocity gradients. Measurements of the turbulence intensity (the root mean square of the instantaneous velocities divided by the average free stream velocity) indicated levels less then 2%. The turbulence intensity was measured using a TSI IFA 300 hot wire anemometer system with output voltages acquired at 5kHz using a 16 bit A/D board. The Pitot static tube used had a 1/8" diameter and a unity calibration coefficient. The averaging Pitot tube was also of 1/8" diameter and was manufactured from brass tubing. As mentioned, holes were drilled into the brass tubing to form the averaging Pitot. Holes were positioned at locations defined for a Log-Tchebycheff distribution (8 points/row). The holes were carefully inspected for burrs. Pressure data from the survey was acquired using a FlowKinetics™ LLC FKT 1DP1A-SV Series instrument. Prior to use, the FKT was calibrated against a primary standard.

To simulate flow profiles that may be seen in industry, velocity gradients across the duct were created using a porous sponge and a fine steel mesh. These materials were placed across the forty-five degree diagonal of the tunnel inlet. During a test, the Pitot was positioned at the eight pre-determined locations for each of the two perpendicular surveys. The data was acquired using the FKT 1DP1A-SV in duct survey mode. Additionally, the standard deviation of the measured velocity of each data point was calculated by the instrument (using 36 samples). No correction for atmospheric pressure, temperature or water vapor were necessary as the instrument measures all of these parameters directly and uses them to calculate the gas density and then velocity. After completion of a survey, the FKT 1DP1A-SV calculated the average volumetric flux (i.e. the volumetric flow rate divided by the cross sectional area of the duct) and mass flow rate flux as well as the standard deviation of the volumetric flux directly. After the Pitot survey, the averaging Pitot was inserted using the same access ports; the pressure, velocity and standard deviation of the pressure and velocity was then recorded.

Results and Discussion

Figure 2 shows the velocity profile across the duct with honeycomb, honeycomb + foam and honeycomb + foam + mesh present at the tunnel inlet. Each data point represents thirty-six data averages calculated by the instrument. Uncertainty intervals (Holman, 1989), estimated using the standard deviations calculated by the FKT 1DP1A-SV are shown on the plot. The middle inset figure (2b) shows the velocity profile across the duct for a placement of porous foam (k_{loss} = 0.37, where k_{loss} is the loss of stagnation pressure reduced by the dynamic pressure) along the forty-five degree diagonal as shown by the shaded region in the inset figure. The foam was positioned in front of the honeycomb. Figure 2c shows similar data except for a fine mesh placed in concert with the foam (k_{loss} = 1.42). A summary of estimated volumetric flux determined using the Pitot surveys and the averaging Pitot tube are presented in Table 1. The presented data is the average of the two surveys. Note that all data conforms to ASHRAE (1988) guidelines in that more then 75% of the measurements are greater then 10% of the maximum measured velocity, in fact, the present measurements would be considered ideal.

The increasing asymmetric pressure loss due to the foam and mesh is reflected in an increasingly asymmetric velocity distribution. Although manufacturers of averaging Pitot’s specify distances from disturbances, bends, valves, etc, these distances are not always possible, and may not guaranty flow conformity. The profiles in Fig. 2 may be representative of profiles seen after an obstruction, asymmetric expansion, damper, etc. The data in Table 1 shows that the averaging Pitot consistently over-estimates the volumetric flux. For the mesh + foam, the error is 19%. Interestingly, the averaging Pitot tube has a smaller uncertainty indicating smaller standard deviations and thus velocity fluctuations around the mean. This is presumably due to the damping effect of the internal volume of the tube.

Table 1 Survey Data Summary

Survey Method	Volumetric flux, ft/m	99.7% Uncertainty interval, ft/m	Volumetric flux difference, %	Tunnel inlet Condition
Pitot	1378	19.5	5	Honeycomb
Averaging Pitot	1447	12.8		
Pitot	1279	22.6	2.4	Honeycomb + foam
Averaging Pitot	1309	18.7		
Pitot	1181	42.3	19	Honeycomb + foam + wire mesh
Averaging Pitot	1407	20.7		

Table 2 Two Port Data Summary

Port configuration	Static pressure, inH_2O	Stagnation pressure, inH_2O	Dynamic pressure, inH_2O	Average volumetric flux, ft/m
Top port (Pitot)	-0.4	-0.02	0.38	1259
Bottom port (Pitot)	-0.4	-0.4	0	
Averaging Pitot tube (two ports)	-0.4	-0.2	0.2	1826

To gain a better insight into the effects of averaging pressures, an averaging Pitot was manufactured with two holes. Prior to use, the honeycomb was removed from the inlet. The averaging Pitot was positioned such that the lower hole was behind a combination of the foam and mesh while the upper hole was in the undisturbed air stream. This puts a large stagnation pressure gradient across the two ports. Table 2 shows a data summary. The Pitot tube was subsequently positioned at the same locations as the two ports to determine the “reference” values for each location. For the test facility geometry, the static pressure is a constant, while the stagnation and dynamic pressure vary. The data in Table 2 shows that even for this extreme gradient of stagnation pressure, the averaging Pitot accurately estimates the average of the stagnation pressure (-0.201 inH_2O from the Pitot) or dynamic pressure (0.19 inH_2O from the Pitot). However, the average velocity (or volumetric flux) is not correct, it’s over-estimated by 45%. Interestingly, an often-held opinion is that having multiple holes fused together incurs additional errors due to flow between the holes from higher to lower regions of stagnation pressure. The present experiments do not support this concept, as the loss of stagnation pressure that would be associated with air flowing through the ports would culminate in erroneous estimates of the average stagnation pressure, which for the present setup at least, is not the case.

Conclusions and Recommendations

An investigation has been undertaken to clarify the effects of averaging pressures on estimated velocities for pressure averaging instruments such as averaging Pitot tubes or velocity grids. The data suggests that although an averaging Pitot tube does accurately measure the average stagnation and dynamic pressure, errors in the average of the velocity or volumetric flux (which are over-predicted) can be significant if large velocity gradients are present. It is suggested that if an averaging instrument is to be used, the manufacturers suggested positioning guidelines should be heeded. However, the installation location should be surveyed with a Pitot tube or other point velocity-measuring device, such that the values from these measurements may be compared to the averaging instruments estimates. Surveys should be conducted over the turn down ratio of the averaging Pitot tube to determine if any Reynolds number sensitivity is present. From these comparisons, the engineer or consultant can establish if the averaging Pitot accuracy falls within acceptable bounds.

References

ASHRAE, 1988. *Practices for measurement, testing, adjusting and balancing of building heating, ventilation, air-conditioning and refrigeration systems*. Standard 111-1988.

American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., Atlanta, GA

Barlow, J. B, Rae, W. H. and Pope, A. 1999, *Low-Speed Wind Tunnel Testing*, New York, John Wiley and Sons, Inc.

Holman, T. P. 1989 *Experimental Methods for Engineers*, New York, McGraw-Hill.

Figure 1 Wind tunnel test facility

c)

b)

a)

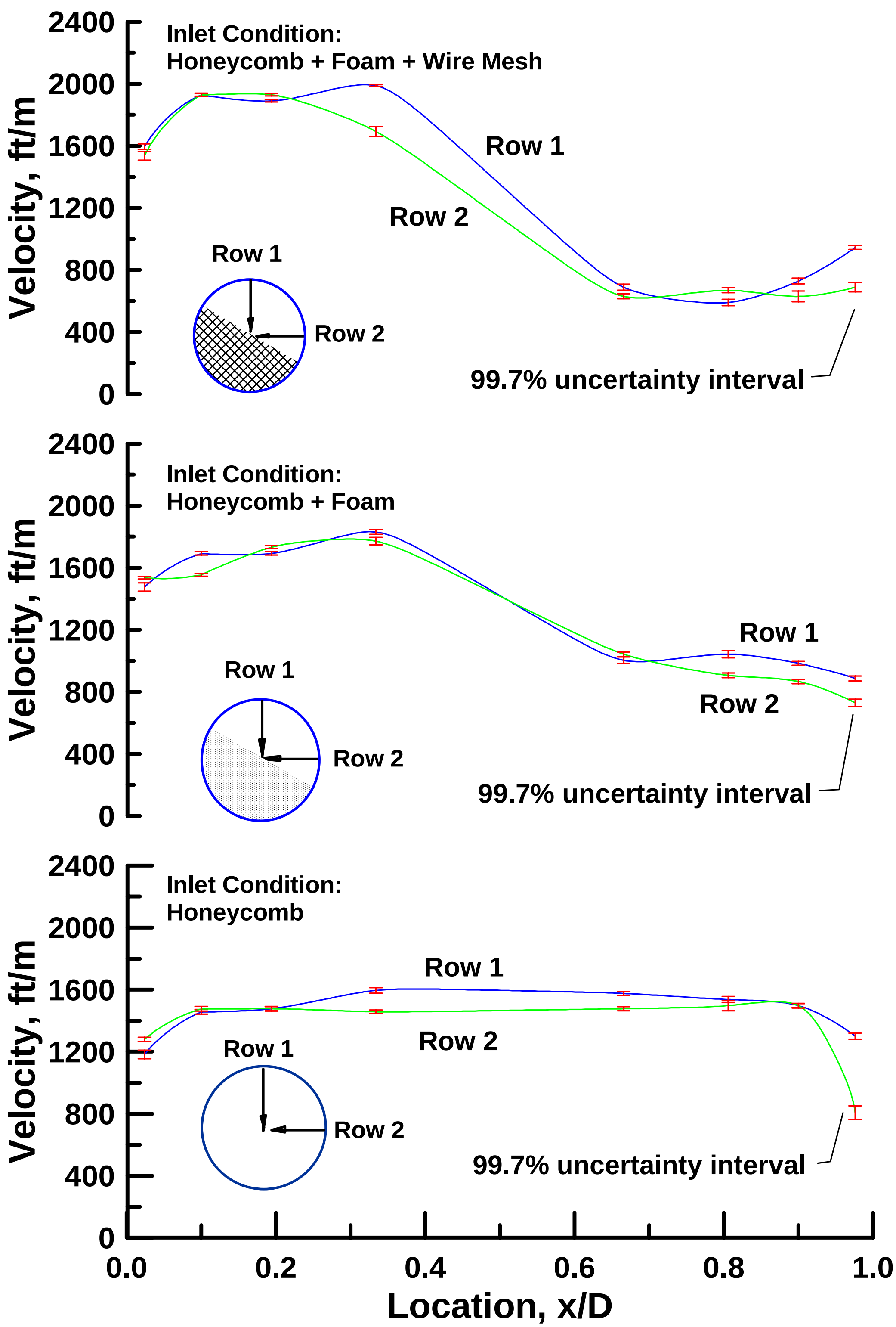

Figure 2 Pitot tube survey velocity profiles. x is the distance from Pitot tube insertion point.