EFFECT OF INTERNAL FLOW CIRCULATION ON SELF-AVERAGING PITOT TUBE ARRAYS

By: Dr. Jerry Kurz

I. INTRODUCTION:

For years people have used various types of multi-sensor Pitot tube arrays to measure volumetric flow rate in large ducts and stacks. The device is constructed to measure the average area weighted differential pressure and from this signal infer the average velocity within the duct or stack. From a mathematical point of view, it can be shown that this assumption is in error, and furthermore, that the entire method is suspect because of internal flow circulation within the inter-connecting tube structure between total pressure ports, and is only accurate under conditions in which the velocity profiles within the duct are highly uniform.

II. BASIC PRINCIPLES:

The basic equation governing the output of a Pitot tube device is Bernoulli's theorem which relates the kinetic energy to the potential energy in a flow streamline. By decelerating the flow, kinetic energy (velocity) is converted to potential energy (pressure). Thus a standard Pitot tube senses the impact or total pressure caused by stopping the flow. If the static pressure in the duct is measured and subtracted from the total pressure, the result is related to the density and velocity of the flowing fluid.

The basic equation is:

Equation (1): $\Delta P = 1/2 K_{\rho} V^2$

Where:

ΔP = Differential Pressure

K = Calibration Factor

ρ = Gas Density

V = Actual Velocity

In a multi-point Pitot tube array, all of the total pressure tubes (or impact tubes) are connected together; and all of the static pressure sensing ports are connected together. The differences between these two pressure outputs is measured by a sensitive differential pressure transducer. The basic concept of the pneumatically inter-connected array is to generate an average differential pressure over the cross-section of the duct and relate it to the average velocity.

The basic question is "How does this device generate the average differential pressure?" The answer is "By allowing flow circulation between the various total pressure tubes to dissipate and to hopefully equalize the pressure within the array by virtue of fluid friction." Therefore, a sizeable flow rate circulates from impact tubes having high velocities to those having lower velocities. This means that air flows into impact tubes having high velocity and out of impact tubes having low velocity. Generally, the static pressure array is not affected. The amount of such flow circulation is dependent on the following considerations:

1) The size and geometry of the inter-connecting array tubing.

2) Tubing roughness factor.

3) Effect of dirt accumulation on internal walls.

4) The velocity profile to be measured.

Because of this flow circulation, the basic physical principle of the Pitot tube has been violated. Equation (1) is based on total stoppage of the oncoming flow at the impact tube, but in fact, there is a considerable outward or inward circulation flow rate. We suggest that the multi-point Pitot tube array does not obey the simple relation of Equation (1) and that this devise suffers greatly in accuracy under non-uniform velocity profile conditions (the original conditions it was designed for!).

Another substantial error is the commonly made assumption that the "average" pressure generated by the Pitot array is governed by Equation (2) to give the mathematically correct average velocity.

Equation (2): $\Delta P_{ave} = 1/2 K_{\rho} V^2_{ave}$

Where:

ΔP_{ave} = Average Differential Pressure

V_{ave} = Average Velocity

Even if we assume that the Pitot device generates the proper average differential pressure, elementary mathematics shows that the average velocity can be in serious error because of the non-linear relationship between ΔP_{ave} and V_{ave}. In other words, the average of a non-linear variable does not give the proper average of that variable. Let's use an example:

Assume we have an array which has only two interconnected Pitot tube sensors and that the velocity at one sensor is 2,000 FPM and the velocity at the second sensor is 6,000 FPM. In engineering terms, Equation (1) can be reduced to a handy formula (good only at ambient conditions) as follows:

$$\Delta P \ (inches\ of\ water) = \left[\frac{Velocity(FPM)}{4000}\right]^2$$

The output of the sensor at the 2,000 FPM location is 0.25" w.g. and the output of the 6,000 FPM location is 2.25" w.g., assuming that the circulation effect is not present. The average ΔP for the sample is:

$$\frac{0.25 + 2.25}{2} = 1.25'' w.g.$$

Substituting this value to Equation (3) and solving for the average velocity, we obtain:

$$V_{ave} = 4472\ FPM$$

However, we know that the true average velocity in our example is:

$$\frac{2000 + 6000}{2} = 4000\ FPM$$

Thus, the effect of nonlinear averaging shows up as an 11.8% error.

It seems apparent the main reason that manufacturers of Pitot tube equipment use flow straightener's, profiler's and other velocity profile modification hardware is to eliminate this mathematical source of error; and to minimize the effect of internal flow circulation, which can exhibit a very large and unpredictable error in the measurements. If one can modify the flow profile to be perfectly uniform, than there is no need to put a large number of sensors in the duct; one would suffice! Because the flow circulation is dependent on the velocity profile, it is very difficult to properly calibrate Pitot arrays. The velocity profile may not be known, and changes frequently with varying turndown ratios and due to other effects.

III. COMPARISON TO KURZ EVA SYSTEM:

The sensors of a Pitot tube array have been shown to have outputs dependent on each other and strongly influenced by non-uniform velocity profiles within a duct. The Kurz Electronic Velocity Array (EVA) uses thermal mass flow sensors, each of which are operated independently of each other, eliminating the effect analogous to flow circulation in Pitot tube systems. Since each thermal sensor is calibrated separately in an NBS traceable wind tunnel and then assembled into an array, and electronically averaged, the EVA system calibration is not dependent on the velocity profile.

Dirt accumulation in a Pitot tube array can also change its calibration. Pitot tube devices are "perfect" implactors of suspended particulates because of the principle of operation. Because of their larger momentum, dirt particles tend to continue straight ahead into the Pitot tube inlet, while many air molecules go around the inlet tube. Thus, most Pitot tubes are "DIRT TRAPS" and can clog up rapidly in dirty flow streams. Flow circulation allows the dirt to accumulate inside the inter-connecting tubing of the array and change the magnitude of the flow circulation, which in turn affects the calibration of the overall device. Conversely, a large properly designed thermal sensor has far less sensitivity to dirt, because the air passes around the sensor. The thermal sensor offers a flow-thru design rather than a design based on stopping the flow and entrained particles.

IV. CONCLUSION:

Multi-sensor Pitot tube arrays operated in ducts having non-uniform velocity profiles can have substantial errors due to non-linear averaging and internal flow circulation. The physical basis for the measurement is therefore violated. Since these devices are nearly identical particulate collectors, they can change calibration over time under variable velocity and profile conditions. The Kurz EVA system eliminates the equivalent effect of flow circulation since it is based on independent velocity sensors instead of dependent sensors. Furthermore, the Kurz large thermal sensors are much less sensitive to dirt accumulation and its effects.