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Angular Flow Insensitive Pitot Tube Suitable for Use with Standard Stack Testing Equipment

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ANGULAR FLOW INSENSITIVE PITOT TUBE SUITABLE FOR USE WITH STANDARD STACK TESTING EQUIPMENT

by

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ABSTRACT

Existing pitot tube designs were tested under various gas flow conditions for accuracy in measuring static and total pressure. Then the static- and impact-pressure measuring tubes least affected by angular flow were combined and evaluated in the presence of particulate sampling nozzles. Tests were performed on "S" pitot tubes, "L" pitot tubes, Kiel pitot tubes, cylinder pitot tubes and a shielded static-pressure pitot tube. The percent error of each pitot tube was determined against an ASME "L" pitot tube as a function of yaw, pitch, orifice size, orifice location, pitot tube size, and velocity. Secondary factors considered in determining the acceptability of a pitot tube were: construction cost, ability to align with gas flow, ease of insertion into small ports, tolerance to flow disturbance by a sampling nozzle, suitability for use with a variety of in-stack and out-of-stack filter assemblies popular in stack testing, and ability to be used in particulate and moisture laden gas streams without plugging. The latter point was tested during field tests at a sewage sludge incinerator, a clay crushing plant, and a power plant. The Kiel pitot tube was found to be essentially error free (<5%) when yawed and pitched ±30° even while attached to a standard EPA Method 5 sampling assembly. Also included are: a summary of the present state-of-the-art in sampling a stack with cyclonic flow, the errors involved in such sampling, a recommendation for straightening cyclonic flow by insertion of a venturi throat, and the effect of Reynold's Number on pitot tube accuracy.

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FIGURES

(continued)

FIGURES

(continued)

TABLES

SECTION 1

LITERATURE REVIEW

The pitot tube, a device used to measure the velocity of fluids, operates on the principle that a moving fluid exerts pressure on any object placed in its path. This pressure, which is termed impact pressure or total pressure (P_T) is the sum of the dynamic pressure (P_d) and the static pressure (P_s). Dynamic pressure is a measure of the momentum of the molecules in the fluid resulting from their movement in the overall direction of fluid flow, while static pressure is a measure of the random motion of molecules that exists in all fluids whether moving or at rest. By determining P_s and P_T of a flowing fluid using orifices located on the pitot tube, it is possible to determine the velocity (V) of a fluid:

$$P_T = P_s + P_d$$

$$P_d = P_T - P_s = \tfrac{1}{2}\rho\, V^2$$

$$V = [\tfrac{2}{\rho}\,(P_T - P_s)]^{\frac{1}{2}}$$

The first reported use of the pitot tube is credited to Henri Pitot, who used it in 1732 to determine river flow as a function of water depth.[1] Little additional development work was done on the pitot tube until 1925 when Ower and Johansen studied the effect of pitot tube shape and orifice location on the measurement of velocity.[2] Parts of their work were checked by Merriam and Spaulding during a more extensive, but similar study reported in 1935.[3]

Merriam and Spaulding used their results and the results of Ower and Johansen to design and evaluate a pitot/static tube that had a predictable degree of error under most flow conditions. This pitot tube, shown in Figure 1, became the basis for the ASME, ASTM and AVA pitot tubes. Unfortunately, they limited their study to pitot tubes that were very similar in design to that shown in Figure 1 and because of its long tip and small static orifices, this tube is not generally applicable for stack testing.

Several other types of pitot tubes have been developed and studied extensively. Perhaps the most unusual one is the Kiel total impact pitot tube (Figure 2) which was developed and studied extensively by G. Kiel in 1935.[4] An outstanding feature of Kiel's tube is that it is accurate to within one percent for yaw and pitch angles up to 40° over a wide velocity range. This tube has since been modified by United Sensors, a commercial supplier of pitot tubes (Figure 3), and is essentially error free for yaw and pitch angles up to 64°. (For our purposes, pitot tube yaw and pitch are defined as shown in Figure 3.)

Another pitot tube that has been evaluated extensively is the cylinder pitot tube[5] in which the impact and static pressure orifices are located on the same side of a cylindrical tube (Figure 4). One advantage of this pitot tube is its easy insertion through small port holes. However, a major disadvantage is that the exact location of the static pressure orifice with respect to the impact pressure orifice must be determined with previous knowledge of the viscosity, density, and approximate velocity of the fluid to be measured. Also, this pitot tube is extremely inaccurate under conditions of angular flow, that is, yaw, pitch and swirl (a combination of yaw and pitch). Like the Kiel tube, pitot tubes of this type are commercially available.

Hemke[6] studied the pressure distribution on the circumference of cylinder type pitot tubes and determined that the pressure on the back half of the tube is essentially constant (Figure 5). This observation suggests that if an orifice is located on the back of a cylinder, the pressure measured will be insensitive to yaw angles of ±80° when the pitch error is zero. Hemke did not evaluate the effect of pitch on this type of pitot tube.

The Staubscheibe or "S" pitot tube (Figure 6) has been studied extensively. This tube has received wide application in stack testing for the following reasons: 1) the distance between the two orifices can be as small as 21 mm allowing easy insertion through small port holes, 2) it is easy to construct; and 3) the large orifice size allows it to be used in a stack with high particulate loading. Unfortunately, the design of the tube is not standardized in relation to orifice spacing, orifice shape or the angle of the bend (θ in Figure 6). Vollaro[7,8] and Williams and De Jarnette[9] have shown that these parameters do not affect the accuracy of an isolated "S" pitot tube when the pitot tube is perfectly aligned with the flow, i.e., when pitch and yaw are both zero. However, Williams and De Jarnette[9] have shown that the orifice spacing can significantly affect the accuracy of this pitot tube when it is not perfectly aligned with the flow (Figures 7 and 8). The downstream-facing orifice measures a flowing stream experiencing disturbances from the upstream-facing orifice. Thus, increasing the orifice spacing reduces this disturbance, making this pitot tube less sensitive to angular flow[9] and to misalignment of the orifices. Vollaro[8] has shown that misalignment of the two pitot tube legs can be a significant source of error for pitot tubes having an orifice spacing of 21 mm when the tube is perfectly aligned with stack gas flow. The turbulent effect of the sampling assembly was not considered in these studies.

Vollaro[7], Williams and De Jarnette[9], and Gnyp[10] have shown that the pitot calibration coefficient of the "S" pitot tube is affected if the spacing between either the adjacent edges of the nozzle and "S" pitot tube or the thermocouple and "S" pitot tube is less than 18 mm. Vollaro's work was used to establish construction guidelines for the EPA Reference "S" pitot tube (Figure 9). De Jarnette and Williams have shown that this pitot tube is very sensitive to error from pitot misalignment with respect to stack flow.[9] They recommend: 1) that the spacing between the orifices be expanded to the widest practical limit, 2) that the "S" pitot tube be inserted approximately 20 to 25 mm further into the stack than the sampling nozzle (Figure 10), and 3) that the thermocouple be inserted approximately 20 mm behind the pitot tube orifices. Besides making the velocity measurement less sensitive to interference from the nozzle and the thermocouple, their sampling configuration allows the sampling assembly to be inserted through the 76 mm (3 inch) diameter sampling ports frequently encountered in stack testing.

As indicated, comprehensive studies have been done to characterize the behavior of several pitot tubes under conditions of angular flow. However, only in the study by De Jarnette and Williams[9] was an attempt made to characterize the behavior of a specific pitot tube under conditions of swirling flow, that is, a flow that has non-zero components of both yaw and pitch. (In the other studies involving angular flow, the error curve for pitch was determined under conditions of zero yaw and vice-versa.) Yet, recent work done by Phoenix[11], Peeler[12] and Lundgren[13] shows that (1) angular flow in stacks has non-zero components of both yaw and pitch; and (2) the percent contribution that each component makes to the overall direction of flow changes with distance from the wall (Figures 11 and 12). In circular stacks, for example, both the yaw and pitch components of flow increase as the distance from the wall increases.

Consequently, unless its error curves for yaw and pitch are identical or completely independent of each other, a pitot tube cannot be used to measure the velocity in field situations where cyclonic flow is encountered. For example, Williams and De Jarnette[9] have shown that the error curve for "S" pitot tubes under conditions of cyclonic flow (a combination of yaw and pitch error) are different from those obtained when only yaw or pitch is present, even in the absence of a sampling nozzle. Thus, unless the true direction of flow is known and the "S" pitot tube is perfectly aligned with this flow, it cannot accurately measure the velocity. For this reason, the USEPA limits the use of the "S" pitot tube to conditions of angular flow less than 10° from the stack axis.

SECTION 2

INTRODUCTION

Reported here are the results of a study that was done to evaluate the behavior of different types of pitot tubes as a function of orifice size, orifice location, velocity, angle of flow (yaw only, pitch only, yaw and pitch combined), and presence of sampling nozzle. The following types of pitot tubes were studied: Kiel total pressure pitot tube, "S" pitot tube, "L" pitot tube, cylindrical pitot tube similar to that of Hemke and a shielded static-pressure pitot tube. The primary objective of this study was to yield a pitot tube design that would have exceptional tolerance to flow misalignment and nozzle and thermocouple interference effects when used with a stack sampling assembly. Each tube's behavior was studied as a function of yaw, pitch, and combined conditions of yaw and pitch.

This study resulted in the development of an improved pitot design that will measure the stack velocity within 5% accuracy under conditions as extreme as a combination of 30° yaw and 30° pitch, even when attached to a stack sampling probe. After development, this pitot tube was tested at three stationary sources to determine its ability to function in dust laden stack gases.

SECTION 3

EXPERIMENTAL

TRANSIT ASSEMBLY

A standard theodolite (surveyor's transit) was used to generate the yaw, pitch, and combined yaw and pitch error curves. The yaw and pitch functions on the theodolite were graduated in 0.1 degree increments.

WIND TUNNELS

Two wind tunnels having similar characteristics, that is, test sections approximately one meter square, each capable of generating a laminar flow profile in the velocity range of 1 to 21 m/sec (3 to 70 fps) were used in this study. Both wind tunnels used an ASME standard "L" pitot tube installed in the test section to determine the true velocity in the test section. One wind tunnel was equipped with a door that permitted the entire transit assembly to be placed in the tunnel. Access to the test section at the other wind tunnel was through 15 cm (6 inch) portholes. Therefore, it was necessary to locate the body of the transit assembly outside this wind tunnel and insert the pitot tube through the porthole.

FIELD TEST SITES

Power Plant (Coal-fired, equipped with an undersized electrostatic precipitator)

The pitot tube was inserted downstream of the ESP where stack conditions were as follows: 5% moisture, 150°C, particulate concentration between 400 and 1100 mg/m^3.

Municipal Incinerator (sewage sludge, equipped with a wet scrubber)

The pitot tube was inserted downstream of the scrubber where stack conditions were: 8% moisture, 42°C, particulate concentration approximately 200 mg/m^3.

Clay Crushing Plant (equipped with baghouse)

The pitot tube was inserted downstream of the baghouse where stack conditions were: 2% moisture, 35°C, particulate concentration approximately 100 mg/m^3.

Source Simulator with Provisions for Cyclonic Flow

A 46 cm diameter experimental test stack equipped with turning vanes to produce a cyclonic flow velocity profile in the test section was used to evaluate the applicability of various pitot tubes for measuring flow direction and velocity in stacks that have a cyclonic flow pattern.

PRESSURE MEASUREMENT SYSTEM

Inclined Manometer

A Dwyer Series 424 inclined manometer was used to measure pressure head in all field tests.

Electric Manometer

A Datametrics Barocel Model 1023A Electronic manometer was used to measure the pressure head in the wind tunnel studies.

Voltmeter

The output of the Model 1023A manometer was measured using a Thermo-Systems Model 1076 RMS voltmeter equipped with 0.1, 1, 10 and 100 second time constant functions. The 10 second time constant function was used here.

PITOT TUBE DIMENSIONS

S-Pitot Tubes

As noted in the Literature Review Section the design of the "S" pitot tube has not been standardized with respect to θ, β, and x (Figure 6). Thus, a study was done to evaluate the effect of θ, β, and x on the measurement of impact and wake pressure. To achieve this, sets of "S" pitot tube legs were constructed having the dimensions shown in Table 1. These pitot tube legs were individually evaluated as a function of yaw and pitch error in an attempt to explain the varying calibration coefficients reported for "S" pitot tubes in the literature.

"L" (Standard) Pitot Tubes

Eight "L"-shaped hemispherical tip pitot tubes having the dimensions shown in Table 2 were studied. These tubes were obtained from United Sensor and Control Corp., Watertown, MA.

Kiel Pitot Tubes

Three Kiel pitot tubes having the dimensions shown in Table 3 were obtained from United Sensor and Control Corp., Watertown, MA, and their applicability for measuring static and impact pressure was evaluated.

Shielded Static Pitot Tube

A shielded pitot tube having the dimensions shown in Figure 13 was obtained from United Sensor and Control Corp., Watertown, MA, and its accuracy in measuring static-pressure was evaluated.

Cylinder Pitot Tubes

Cylinder pitot tubes having the dimensions shown in Table 4 were evaluated for their applicability in measuring both impact and static pressure.

SECTION 4

RESULTS AND DISCUSSION

In the first part of this program, the impact-pressure and static-pressure error curves for the five types of pressure sensing tubes described in the Experimental Section of this report were constructed. The static- and impact-pressure error curves were studied separately to determine the factors that affected each type of pressure measurement. A major deficiency with most previous studies to develop and evaluate pitot tubes for stack testing is the fact that they studied only the pressure difference between the static- and impact- pressure and thus combined the two error curves.

The results from the laboratory evaluation were used to select the best pitot tube for further evaluation. In this latter phase, the ability of the pitot tube to measure velocity when attached to a sampling probe was evaluated as a function of nozzle/pitot separation, yaw and pitch. Also, the ability of this pitot tube to measure the velocity in particulate- and moisture-laden stacks was evaluated.

The results from both phases of this study are described below as a function of the individual types of pressure sensing tubes.

SHIELDED STATIC PRESSURE TUBE (FIGURE 13)

This particular tube has two static-pressure sensing orifices, one located further upstream than the other. Under conditions of zero yaw and zero pitch, the absolute static-pressures measured by the two orifices were significantly different from each other and from the ASME "L" pitot tube used as a reference. For example, at 8 m/sec, the upstream orifice measured a static pressure 17% more negative than the "L" pitot tube and the downstream orifice measured a pressure reading 7% more negative than the "L" pitot tube. Further, the % difference between the static pressure measured by these two orifices and the "L" pitot tube varied widely when testing with velocities between 21 and 2 m/sec.

Figure 14 presents the relative error curve for pitch for each orifice in relation to the pressure measured by that orifice at zero pitch and yaw at a velocity of 8 m/sec. From Figure 14 it is obvious that the downstream orifice is less sensitive to pitch, however, an acceptable reason for this has not been determined.

"S" PITOT TUBES (TABLE 1)

Two "S" tubes, 5 S (θ = 45°, X = 25 mm, β = 45°) and 10 S (θ = 90°, X = 25 mm, β = 0) were evaluated extensively as a function of yaw angle (Figures 15 and 16). In addition, the effect of yaw and pitch on the impact-pressure measurement was determined for all tubes under the following conditions: yaw = 0°, pitch = 20, 0°, -20°; yaw = 10°, pitch = 20°, 0°, -20°; and yaw = 20°, pitch = 20°, 0°, -20°. The accuracy of the static-pressure measurement was determined for all tubes under the following conditions: pitch = 0°, yaw = ±90°, 180°. The results are summarized in Table 5. For comparative purposes, the corresponding impact and static pressures measured by the ASME "L" pitot tube installed in the wind tunnel are also presented in Table 5. (The actual pressures measured are presented in Table 5 to portray the differences in impact- and static-pressure measured by different "S" tubes under identical flow conditions. For example, compare the impact-pressure measured at zero yaw and pitch for each "S" tube to the impact-pressure measured by the Reference "L" Pitot Tube.)

Based on the results in Table 5 and in Figures 15 and 16, the following conclusions can be made concerning the use of the "S" pitot tube for pressure measurement: (1) decreasing X increases the magnitude of the wake pressure measured by an "S" pitot leg; (2) changing θ from 45° to 90° and β from 0° to 45° does not significantly affect the wake pressure measurement; (3) no definite correlation exists between either X, β, or θ and the accuracy of the impact measurement (compared to the "L" pitot); and (4) the "S" pitot tube cannot be used to give an accurate measurement of static pressure (compare the static pressure measured by the "S" pitot tube legs at 90° and -90° with the corresponding pressure measured by the "L" pitot tube).

These results suggest that subtle differences in the construction of "S" pitot tubes can significantly affect the calibration coefficient, which may explain why calibration coefficients of 0.9 to 0.7 have been reported for isolated "S" pitot tubes. In addition, these results may explain why some "S" pitot tubes meeting the specifications in EPA Reference Method 2[14] do not have the predicted coefficient of 0.84 when "properly" attached to a sampling probe.[15,16] This is why all "S" pitot tubes should be calibrated with the sampling nozzle in place.

"L" PITOT TUBES (TABLE 2)

The eight "L" pitot tubes studied differed in relation to stem diameter, static orifice size and spacing, but had similar static orifice locations, all between 2.6 and 3.3 tube diameters from the tip and the stem. Based on the results of Merriam and Spaulding,[3] these pitot tubes should read the static pressure within 2% of true static, and as expected, all tubes were found to have an error of less than 2% in the static pressure under conditions of zero yaw and zero pitch. Also as expected from Merriam and Spaulding's work,[(3)]

the three pitot tubes with both impact- and static-pressure orifices (1L, 2L, 3L) were found to have coefficients (Cp) between 0.99 and 1.00 when properly aligned with the flow. (These coefficients were calculated on the assumption that the coefficient for the ASME "L" pitot in the windtunnel test section was 0.99.) The effect of velocity on the coefficient for tube 1L is presented in Figure 17. As expected, the coefficient varied only slightly with velocity.

Merriam and Spaulding designed their pitot-static tube to minimize the effect of stem and tip on the static pressure measurement. Decreasing the spacing between the static orifice and the stem and the tip to 3 tube diameters should destroy this symmetry — a fact confirmed through yaw and pitch studies on tubes 3L, 7L and 8L. Since the results from the three tubes were similar, only those for tube 8L are presented in Figure 18.

Within the experimental error of 1%, varying either the number of static orifices in a row or the number of rows of static orifices did not significantly affect the yaw and pitch error curves in the static pressure measurement in the range ± 20°. However, as expected, tube 3L, which had only four static orifices separated by 90°, was more sensitive to angular flow in excess of 20° than were tubes 7L and 8L (Figure 19).

Merriam and Spaulding also designed their pitot tube to have offsetting error curves for static- and impact-pressure measurement under conditions of moderate angular flow. Thus, as their tube is yawed or pitched, the positive error in the static pressure is somewhat offset by the negative error in the impact pressure, so the pitot coefficient varies no more than ± 2% for yaw and pitch errors as large as ± 30°.[3] Figure 20 demonstrates that the pitot-static tubes in Table 2 also have offsetting error curves for impact and static pressure; but as expected, the deviation from the true value is larger for these shortened "L" pitot-static tubes.

KIEL TOTAL PRESSURE PITOT TUBES (TABLE 3)

Three Kiel tubes were evaluated in velocities ranging from 1 to 21 m/sec to determine their suitability for measuring static as well as impact pressure. The three tubes were found to measure the impact pressure to within ± 5% under a condition as extreme as 40° yaw and 30° pitch. However, their ability to measure the static pressure (in reality a wake pressure), which was evaluated by facing the tube downstream, was not as good. For example, Kiel tubes 1K and 2K, which had a venturi exit and entrance, measured the wake pressure within 5% of the pressure measured by the tube when properly aligned with the flow but only up to yaw and pitch angles of ± 15°. At yaw angles of ± 40° and pitch angles of ± 30°, the relative error was as large as 10%. As expected, tube 3K (which did not have a venturi entrance when faced downstream) was even more sensitive to yaw and pitch effects.

Figure 21 presents the results of pitch on the static- and impact-pressure measurement for tube 1K. The curves for yaw error were essentially the same and thus are not presented. Neither error curve was significantly affected by velocity in the range 8 to 21 m/sec.

CYLINDER PITOT TUBES (TABLE 4)

The cylinder pitot tubes were evaluated for yaw and pitch error at velocities of 1, 8 and 21 m/sec and found independent of velocity and orifice size. The effect of yaw was evaluated by aligning the pitot tube in the wind tunnel to obtain the maximum impact pressure (0°) and then measuring the absolute pressure at 5° intervals as the tube was rotated through a 180° arc. Analogous to Hempke's results[6], the absolute pressure was found to vary less than 1% from 100° to 180°, but changed rapidly from 0° to 70°. Some representative results are presented in Table 6.

The effect of pitch on the impact- and static-pressure measurement was determined as follows: The pitot tube was aligned to obtain the maximum impact pressure, the absolute pressure was then measured at 10° intervals from ± 40°, the pitot tube was then returned to 0° pitch, rotated 180° and again pitched ± 40°. As expected, increasing the distance between the orifice and the tube edge dramatically reduced the effect of pitch on the pressure measurement until the orifice was located at least three tube diameters from the edge (Tables 4 and 7).

KIEL/CYLINDER PITOT-STATIC TUBE

Based on the above study, the Kiel pitot tube was selected as the best for measuring impact pressure and the cylinder pitot tube was selected as the best for measuring static pressure and for determining direction of gas flow. Since these two tubes were essentially error free (<5%) when yawed and pitched ± 30°, an attempt was made to combine them into one pitot-static tube. The first approach involved simply piggybacking a cylinder pitot tube onto the sheath (stem) of the Kiel tube. However, the presence of the Kiel tube stem made the cylinder pitot tube much more sensitive to both yaw and pitch error — much like the impact leg of the "S" pitot tube significantly affects the error curve for the wake-pressure leg.

The next attempt to combine these two pressure sensing tubes involved placing a series of 3.2 mm orifices on the downstream side of Kiel tube 1K at points 19, 29, 38, 48, 57, and 66 mm from the center of the Kiel impact orifice. The optimum location for the static orifice was then determined by plugging all but one orifice and establishing the yaw and pitch error curves for that orifice location. As expected, the results were similar to those received for the isolated cylinder pitot tubes. i.e., increasing the distance between this and the Kiel tube shield dramatically improved the tolerance of the tube to pitch effects until a point 38 mm from the impact orifice was reached. After 38 mm the improvement was modest. Based on this study, it was decided to locate the wake pressure orifice on the stem of the Kiel tube approximately 38 mm from the center of the impact orifice.

Figure 22 presents the calibration curve (calculated relative to the ASME "L" pitot tube) for tube 1K when the wake pressure orifice is located 38 mm from the center of the impact orifice and the tube is properly aligned with the direction of gas flow. The double hump in the curve between 2 and 5 m/sec is not an artifact of the wind tunnel because it was observed at both wind tunnels. Similar fluctuations in the pitot tube curve have been reported for "S" pitot tubes (Figure 23) by Williams and De Jarnette[9], Gnyp[10], and Brooks and Williams[17].

This Kiel/cylinder pitot-static tube was then studied to evaluate the effect of pitch on the tube when it is used to detect gas flow direction when the wake pressure orifice is faced downstream and used as an impact-pressure orifice. Three orifice positions were evaluated, i.e., 19, 38, and 57 mm from the center of the impact orifice. (All orifices were 3.2 mm in diameter.) The results, which are presented in Table 8, show that the effect of pitch was small up to ± 20° for all three positions.

The suitability of the Kiel/cylinder pitot tube for use with a stack sampling probe was then evaluated using EPA Reference Method 5 sampling probes[18] equipped with 4.6 mm ID x 12.5 mm OD and 12.5 mm ID x 15 mm OD gooseneck-shaped nozzles, and an EPA Reference Method 5 sampling probe equipped with a 12.5 ID x 15 mm OD, 90°-bend sampling nozzle. The effect of yaw on the velocity measurement in the velocity range 1-20 m/sec was evaluated as a function of probe sheath to pitot sheath distance. During this study, the entrances to the Kiel head and to the nozzle were in the same horizontal plane and the centerline of the impact orifice was approximately 15 mm in front of the vertical plane containing the centerline of the nozzle tip (Figure 24). Also, the static orifice was located 38 mm behind the impact orifice. Probe sheath to pitot sheath spacings (X in Figure 24) of 5, 8, 18, and 22 mm were evaluated. The results for the two gooseneck-shaped nozzles are summarized in Table 9. Results for the 90°-bend nozzle were similar to these and are therefore not presented. (Pitch studies were not done because pitch is not a significant source of error until combined with yaw).

Based on the results in Table 9, a probe/pitot sheath spacing of 18 mm was selected as the best spacing and the combined effects of yaw and pitch on sampling assemblies having this dimension were evaluated for the two gooseneck-shaped nozzles and the 90°-bend nozzles described in Figure 24. The results for the 12.5 mm ID x 15 mm gooseneck-shaped nozzle at 8 m/sec are summarized in Table 10 and in Figure 25. The results for the gooseneck nozzle at 1.3 and 21 m/sec were similar to those in Table 10 and are not presented. Similarly, the results for the 90°-bend nozzle differed only by a few percent from the results for the gooseneck nozzle so only selected results are presented (Figure 25). All results dramatically demonstrate how tolerant this sampling assembly is to angular flow.

After completing the studies with the Method 5 probe, the suitability of the Kiel/cylinder pitot tube for use with an Alundum in-stack filter holder was compared to that of the "S" pitot. First, the effect of thimble blockage on the velocity measurement was evaluated by locating the impact orifice of the pitot tube 25 mm in front of the nozzle centerline, a distance 225 mm in front of the leading edge of the thimble, and monitoring the impact and wake pressure reading as the pitot was moved toward the thimble. As shown in Table 11, the Kiel/ cylinder pitot tube could be positioned much closer to the leading edge of the thimble than could the "S" pitot tube before the velocity reading would be affected. The pitot tube was then located at a point 15 mm in front of the nozzle centerline (Figure 26) and the effect of velocity on the "S" pitot and Kiel/cylinder pitot tube coefficients determined (Figure 27). In this latter study no attempt was made to determine the effect of yaw or pitch on the Kiel/ cylinder pitot tube/Alundum thimble assembly because: (1) the thimble and the pitot were located far enough away from each other that blockage effects were not present, and (2) the spacing between the nozzle and the pitot tube was similar to that encountered when the Method 5 probe with 90° bend nozzle was studied.)

In the present EPA recommended sampling methods for particulate[18,19] the orifices of the "S" pitot tube are located in the plane containing the centerline of the nozzle (Figure 28). In contrast, the impact orifice for all sampling configurations studied here was located approximately 15 mm in front of this plane to accomplish the following: (1) reduce the chance for the Kiel shield to perturb the particulate flow to the nozzle, (2) allow the pitot sheath to be located closer to the probe sheath to decrease the overall width of the sampling assembly, (3) reduce the chance for the nozzle to strike the stack wall while testing a stack but still permit sampling in the area near the wall, and (4) reduce the chance for the nozzle to affect the flow of gas to the pitot tube.

Field Evaluation of the Kiel/Cylinder Pitot Tube

The performance of the Kiel/cylinder pitot tube under actual sampling conditions was evaluated by inserting it along with an "S" pitot-static tube in stacks at a coal-fired power plant, a clay crushing plant calciner, and a sewage sluge incinerator. Both pitot-static tubes operated without plugging for the length of the test — 16 hours at the incinerator, 15 hours at the calciner, and three hours at the power plant. The actual stack conditions during the field tests are described in the Experimental Section of this report.

Inclusion of a Thermocouple in the Sampling Assembly

Since the Kiel/cylinder pitot tube evaluated was not equipped with a thermocouple, the best thermocouple location had to be selected on the basis of the flow profile about the nozzle and pitot tube. Due to the insensitivity of the pitot tube to flow disturbance, almost any position that does not interfere with the flow in the vicinity of the wake orifice is acceptable. Four such positions are:

1) Run the thermocouple inside the pitot sheath into the Kiel shield directly behind the impact tube. This is the best location from the view of thermocouple protection and measuring temperature of the stack gas at the point of velocity measurement. Kiel pitot tubes with the thermocouple inside the shield are commercially available, but cost approximately $20 more than those without the thermocouple.

2) Run the thermocouple down the side of the probe sheath opposite the pitot tube to a point about 25 mm behind the nozzle. (This location may make it difficult to attach the nozzle to the sampling probe.)

3) Run the thermocouple through the 12 mm space between the probe and pitot sheath to a point 25 mm behind the wake orifice and angle it toward the nozzle.

4) Run the thermocouple along the pitot's sheath to a point 25 mm behind the wake orifice and angle it toward the nozzle.

USING PITOT TUBES TO DETERMINE FLOW DIERECTION AND VELOCITY IN ANGULAR FLOW SITUATIONS

The "S" and cylinder pitots were mounted in the surveyor's transit and used to determine the direction of flow in a circular stack with cyclonic flow. Fifteen points located at distances of 1.2, 3.8, 5.3, 7.8, 11.4, 16.5, 20.3, 22.9, 25.4, 29.2, 34.3, 37.6, 40.1, 42.6, and 44.7 cm along the stack's 46-cm in diameter were surveyed. Flow direction was determined with the "S" pitot using the standard null technique and with the cylinder pitot tube 2C (orifice two tube diameters from end) by rotating it until the maximum impact pressure with respect to barometric pressure was obtained.

In general, the two pitot tubes agreed in flow direction within 10° at each of the six points nearest the walls of the stack, but differed by as much as 40° for the three points in the center — the region where the radial (pitch) component of flow is largest. For example, the average angle of flow with respect to the longitudinal axis was 36° and 50° for the cylinder and "S" pitot tubes, respectively, based on a survey of all fifteen points. In contrast, the respective values for the twelve points nearest the wall (the points that would be surveyed if the stack were divided into six concentric zones of equal area) were 56° and 51°.

A comparative test was also done to determine how the impact-pressure measured by the Kiel pitot tube would compare to that measured by the "S" and cylinder pitot tubes. Impact-pressure was determined at the 15 survey points used in the flow direction study using the flow angles previously determined by that pitot tube. (The Kiel pitot tube was rotated to the flow angle determined by the cylinder pitot.) The results were as expected, i.e., all three tubes compared favorably at the four points nearest the wall, but disagreed markedly the closer the survey point was to the center of the stack —— the points where radial component of flow was significant.

SECTION 5

SUMMARY AND CONCLUSIONS

The primary objective of this study was to develop a pitot-static tube possessing certain characteristics:

1. It should have a high tolerance to angular flow and to flow disturbance;

2. It should be suitable for routine use with the variety of in-stack and out-of-stack filter assemblies now used in stack testing;

3. The error curve should be predictable as a function of angular flow, i.e., the error curve should not be affected by minor differences in pitot construction parameters;

4. It must be able to establish the direction of gas flow;

5. It should be inexpensive to construct; and

6. Like the conventional "S" tube now being routinely used in stack testing, it should not rapidly plug when being used in particulate- and moisture-laden gas streams.

Different types of pitot tubes were evaluated according to the above criteria. (The results are summarized below.) On the basis of these findings, a tube was developed and field tested that met the performance specifications: the Kiel/cylinder pitot tube.

SHIELDED STATIC PRESSURE TUBE

The static pressure measured was inaccurate and varied with gas velocity even when properly aligned with the direction of gas flow.

SHORTENED "L" PITOT TUBE

Decreasing the distance between the static holes and the tip and stem allowed this type pitot to be inserted through standard size portholes. It measured velocity accurately under ideal flow conditions of zero yaw and pitch, but the symmetry in the error curves for yaw and pitch, present in the standard size "L" pitot, was lost when the pitot was shortened. Compared to the standard "L" pitot tube, the magnitude of the error curve for the shortened "L" pitot tube was five times larger in the range ± 30° yaw and pitch. However, these results do show that the shortened "L" pitot-static tube can be used in source testing when parallel flow situations are encountered. It will also measure velocity accurately in the range of 1 to 3 m/sec and can be used to yield an accurate static pressure.

"S" PITOT TUBE

Found to be highly sensitive to angular flow. Subtle differences in construction between two "S" pitot tubes can radically alter the behavior of this pitot tube. It does not give an accurate static pressure when the orifice face is placed parallel to the direction of stack gas flow.

CYLINDER PITOT TUBE

Found to be useful for determining stack gas flow direction when used as an impact-pressure tube. When used to measure static pressure, in terms of a wake pressure, the tube is essentially error free for yaw angles up to ± 90° and pitch angles up to ± 20°. When used to measure static pressure it has a coefficient of 0.74.

KIEL IMPACT-PRESSURE TUBE

Found to accurately measure impact-pressure within ± 2% under a condition as extreme as a combination of 40° yaw and 40° pitch. The Kiel tubes studied had coefficients of 0.99 ± 0.01. These tubes can also be used to measure static pressure, in terms of a wake pressure, when properly constructed.

KIEL/CYLINDER PITOT-STATIC TUBE

This tube combines the best features of the Kiel and cylinder pitot tubes and meets all the performance characteristics specified above.

(1) Its coefficient varies less than 5% when attached to a standard particulate sampling probe and the entire assembly is rotated and tilted to yield conditions as extreme as ± 30 yaw and pitch.

(2) Its coefficient is unchanged when switched from an in-stack filter probe equipped with a right angle bend nozzle to a standard Method 5 probe equipped with a gooseneck-shaped nozzle. The in-stack filter assembly can be located closer to this pitot tube than to the "S" pitot tube before a velocity disturbance is observed.

(3) It will pass through 2-inch diameter sampling ports even when attached to a standard Method 5 sampling probe.

(4) It can be used to establish direction of gas flow, has a larger coefficient than the "S" pitot tube (0.74 compared to 0.85 for the "S" pitot) and its performance in stacks with a high moisture and particulate concentration is equivalent to that of the "S" pitot.

(5) It is relatively inexpensive to construct —— the 0.7 meter long Kiel/cylinder pitot tubes used in this study were procured commercially for $50.00 each.

(6) It can be used to accurately measure static pressure, in terms of a wake pressure, in a stack, i.e., multiply the wake pressure reading by 0.74.

This tube was evaluated only in the velocity range 1 to 22 m/sec, but it should perform well up to at least 40 m/sec, based on the reported performance of the individual Kiel and cylinder pitot tubes. Like all pitot tubes, this pitot tube should be checked before each use to be sure that the welds are intact as improper welds may cause erroneous pressure measurements.

SECTION 6

RECOMMENDATIONS

Based on the experiments conducted during this study, the Kiel/cylinder pitot tube should be suitable for use in stack testing. It is more accurate than the "S" pitot under conditions of moderate and severe angular flow and is less sensitive to interference by the sampling nozzle. The suitability of the Kiel/cylinder pitot-static tube should be evaluated further by routine users of stack testing equipment to confirm that the conclusions of this study are correct.

Recommended sampling assembly dimensions are shown in Figures 24a, 24b, and 26 for gooseneck nozzle, 90° bend nozzle and in-stack thimble, respectively. For all assemblies the edge to edge spacing between the probe sheath and the pitot sheath (X in Figures 24a and 24b) should be at least 18 mm and the wake orifice should be located at least 25 mm behind the impact orifice. Suggested positions for the thermocouple are presented in the text of this report.

If desired, a small Kiel head can be used, e.g., the Kiel head on Tube 2K in Table 3 performed the same as Tube 1K in the laboratory study. Use of this smaller Kiel tube would decrease the overall length and width of the sampling assembly, but at the same time, it would increase the chance for the pitot tube impact orifice to be plugged by particulate. Of course, pitot tube to nozzle spacings different from those in Figures 24 and 26 may also be acceptable provided care is taken to ensure that the pitot shield does not interfere with the pollutant flow to the nozzle.

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APPENDIX A

SUMMARY OF THE EXISTING DATA ON "L" PITOT-STATIC TUBES

The Merriam and Spaulding "L" pitot-static tube is not generally suitable for stack testing because (1) its small static orifice holes plug easily, and (2) its long head makes its insertion difficult in many stacks. However, this study as well as other studies show that there may be applications where a scaled-down or otherwise modified Merriam and Spaulding type "L" pitot-static tube may be the best choice. Fortunately, there is an extensive body of data available that allows one to predict the approximate effect of many design modifications on an ISOLATED "L" pitot-static tube, i.e., one not attached to a sampling probe. The existing body of data on the "L" pitot-static tube is summarized below as an aid to those interested in possibly using this type of pitot-static tube.

STATIC PRESSURE ORIFICE

1) At the velocities encountered in source testing the shape (hemispherical, square, tapered, ellipsoidal) of the tip does not significantly affect the static pressure measurement as long as the static orifice is greater than two tube diameters from the tip.

2) Under conditions of zero angular flow, increasing the orifice size from the standard of 1.0 mm (0.04 inches) up to 2.0 mm (0.08 inches) does not decrease the accuracy of the static error measurement, at least up to tube diameter to orifice diameter ratios of 10. However, as the orifice size

increases the magnitude of the error for yaw and pitch increases, probably due to increased gas circulation through the static holes.

3) The distance of the orifice from the stem and from the tip can be used in conjunction with the work of Merriam and Spaulding to estimate the absolute error in the static pressure measurement at zero angular flow. (Figures A-1, A-2)

4) If static orifices are symmetrically located at a maximum spacing of 90° on the circumference of the tube, and the stem is at least five tube diameters from the static orifices, the yaw and pitch error curves should be similar.

5) If the static orifice holes are asymmetrically distributed on the circumference of the tube, the yaw and pitch error curves will not be similar.

6) The ratio of the orifice depth to orifice diameter can be varied from 0.5 to 6 without a significant error in the static pressure measurement at conditions of zero angular flow. However, some data available indicates that the sensitivity of the static orifice to angular flow error is decreased as the depth to diameter ratio increases, possibly because flow through the orifice is reduced. (This same effect could possibly be obtained by making the angular spacing between the inner and outer tube as small as possible for the combined pitot/static tube, but this would also increase the time lag in the static pressure measurement.)

IMPACT-PRESSURE ORIFICE

1) The sensitivity of the impact orifice to yaw and pitch is lessened when the orifice size is made as large as the tube will allow.

2) Cylindrical probes with square ends seem to have the same relative error as tubes with tapered and hemispherical ends under conditions of zero angular flow.

3) The impact orifice should remain unchanged for at least three tube diameters if an accurate pressure is to be measured, i.e., the orifice opening cannot change in size for a depth of at least three tube diameters from the opening.

4) The impact orifice diameter should be at least 3.17 mm (0.125 in.) to avoid excessively long time constants in the pressure measurement.

5) Reynolds Number effects may be evaluated more accurately, if the impact orifice size and not the tubing size is used in the equation for R_e.

SPECIAL NOTES ABOUT USE OF "L" PITOT STATIC TUBES

The above data applies to isolated "L" pitot-static tubes, that is, those not attached to any sampling probe. If an "L" pitot-static tube will be used with a sampling nozzle attached, extreme care should be taken to ensure that turbulence between the nozzle edge and the pitot-static tube edge does not cause an erroneous static pressure measurement. This situation would be particularly serious under conditions of angular flow, subisokinetic sampling, and superisokinetic sampling. To avoid this potential error simply attach the pitot-static tube tip to the probe so that it is at least 15 mm further into the stack than the sampling nozzle.

Also, the "L" pitot-static tube is sensitive to instrument vibration. If a small diameter "L" pitot tube is to be used in a stack containing high velocities or turbulence, extreme care should be taken to ensure that the "L" pitot tube does not vibrate. This can easily be achieved by using large diameter tubing for the pitot stem or by attaching the pitot tube directly to the sampling probe.

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APPENDIX B

REVIEW OF PRESENT METHODS FOR SAMPLING STACKS WITH CYCLONIC FLOW

INTRODUCTION

Ideally, stack sampling should only be done where the gas flow is parallel to the stack's longitudinal axis. (Under these conditions, it is assumed that the pollutant profile is similarly aligned.) Most recently constructed stationary sources have parallel flow downstream of their control device, but it is not uncommon to find non-parallel flow upstream of the control device. Also, at many old and/or small sources non-parallel flow is encountered both upstream and downstream of the control device. There are several common reasons why non-parallel flow is encountered at these latter sources. First, they have been retrofitted with a pollution control device that was installed using short lengths of duct and sudden changes in direction to accommodate space restrictions. Second, for space and economic reasons, these plants use inertial demisters, cyclones, and common stacks as part of their pollution control system.

As more and more of these older and smaller sources come under emission regulations with revisions of State Implementation Plans, non-parallel flow is being encountered more frequently in compliance testing. This fact may explain why articles suggesting how to sample in stacks with cyclonic (non-parallel) flow are starting to appear in the literature.[1-7]

During the development of the angular flow insensitive pitot tube described in the body of this report, numerous articles on angular flow were reviewed. This appendix describes the present state-of-the-art in sampling cyclonic flow and THE AUTHORS' VIEWS ABOUT THE ERRORS PRESENT when measuring velocity, volumetric flow, and pollutant emission rate in cyclonic flow situations. The three major areas that will be discussed are: selecting sampling points, determining flow direction and volumetric flow, and measuring pollutant concentration. The possibility of using a venturi to straighten cyclonic flow is also proposed.

SELECTING SAMPLING POINTS IN STACK TESTING

The customary approach to determine stack gas velocity and volumetric flow in stacks is to divide the stack into a number of equal area zones.[8-10] For circular stacks, this involves dividing the stack into equal area zones and measuring the velocity at the centroid of each zone. Consequently, the sampling points are unequally spaced on the traverse diameter, i.e., skewed toward the wall. Rectangular-shaped stacks are divided into several equal area zones that are geometrically similar in shape to the full stack. The velocity is then measured at the center of each rectangular-shaped zone. In both cases, the volumetric flow is determined by multiplying the average velocity for all zones across the stack by the stack cross-sectional area.

Underlying this stack sectioning technique is the assumption that the velocity at the centroid of each zone is a measure of the average velocity in that zone. But as Ower and Pankhurst point out, there is no a priori reason why this assumption should be valid,[9] particularly when the flow is not parallel to the stack axis.

When angular flow is encountered, particularly cyclonic flow, studies show that it will contain radial (pitch) and tangential (yaw) flow components that change with distance from the wall[3,5,6,11-14] For example, Phoenix[3] has found that in circular stacks with tangential gas flow inlets, the yaw angle (yaw component of flow) increased from 30° near the wall to 90° at the center, and the pitch angle (pitch component of flow) varied from 0° near the wall to 30° near the center. Since the true direction of gas flow changes rapidly across the stack, it is less likely that the velocity in the centroid of the zone represents the average velocity across that zone. This source of error can be reduced by narrowing the size of each zone, but this increases the number of points that must be sampled, thus increasing the time and effort required to sample the stack.

One common compromise made for the sake of time is to sample 48 velocity points, but only 16 or 24 pollutant points. While this improves the reliability in the volumetric flow measurement, it does nothing to improve the reliability of the pollutant concentration measurement. Further, in cyclonic flow there are reasons why non-gaseous pollutants may not follow the velocity distribution in the stack (see discussion below).

IN SUMMARY, SELECTION OF SAMPLING POINTS IN CYCLONIC FLOW IS A TENUOUS SITUATION AND THE MAGNITUDE AND SIGN (POSITIVE OR NEGATIVE BIAS) OF THE ERROR IS NOT PREDICTABLE.

DETERMINING VELOCITY AND VOLUMETRIC FLOW IN CYCLONIC FLOW SITUATIONS

As mentioned, cyclonic flow is characterized by three flow vectors — axial, radial, and tangential — and its direction can only be accurately measured using direction-sensing pitot tubes.[11,12,13,15] However, these pitot tubes are fragile, employ small, easily-plugged orifices and use a tedious null technique to establish flow direction. Consequently, they generally are not suitable for measuring flow in stack testing. Because of this, it is now customary to use the non-directional "S" pitot tube to establish stack gas flow direction and volumetric flow in angular flow situations. Flow direction is determined by rotating (yawing) the "S" pitot until a null reading is obtained and then determining the angle, θ, between the pitot tube and the stack longitudinal axis. The volumetric flow is then determined after first multiplying the velocity component in the direction of stack gas flow by the cos θ (to yield the axial flow component). It is incorrect to determine flow direction by rotating the "S" pitot until the maximum pressure drop is obtained as was done by Lundgren.[7]

Velocity and volumetric flow measurements may be seriously in error when determined by the null technique because the radial (pitch) flow component is ignored. Obviously, if the angle and magnitude of flow are measured incorrectly, the true volumetric flow will also be in error. Since "S" pitot tubes with different orifice spacing are affected to a different extent by pitch error,[16] it is difficult to generalize whether the measurements will be biased high or low.

In contrast, the Kiel/cylinder pitot tube measures the true velocity head when aligned within ± 40° of the true direction of flow. It also gives a better estimate of the true flow direction because it is less sensitive to yaw and pitch error than the "S" pitot. However, it does not measure the actual pitch component and because of this the volumetric flow measurement will be in error.

The Kiel/cylinder tube should be used to determine flow direction as follows:

1) Invert the pitot tube to use the wake pressure orifice as an impact orifice.

2) Connect this orifice to the appropriate leg of a manometer and vent the other side of the manometer to the atmosphere. (Although the velocity head is always positive, impact pressure may be negative or positive with respect to barometric pressure depending on the location of the fan relative to the measuring point.)

3) Rotate the pitot tube at each sampling point until the Maximum pressure (versus atmospheric pressure) is obtained and the angle, θ, recorded.

4) After completing the above flow-direction traverse, use the Kiel/cylinder pitot tube to obtain the true velocity head at each point.

5) Calculate the volumetric flow using the appropriate value of cos θ and the average velocity across the stack. (Obviously this volumetric flow would be in error to the extent that the true θ was not measured and the selection of velocity sampling points was erroneous.)

Another common approach in dealing with cyclonic flow is to straighten the flow using straightening vanes and stack extensions before measuring the velocity.[6,8] Although this may not straighten the flow completely, it can make the flow significantly more unidirectional. However, straightening vanes can accidently bias the sampling results by removing particulate through impaction or agglomeration[7] and by changing the efficiency (performance) of the control device.

ANALOGOUS TO THE SITUATION OF SELECTING THE SAMPLING POINTS, THE MAGNITUDE AND SIGN OF THE ERROR ARE NOT PREDICTABLE WHEN MEASURING VELOCITY AND VOLUMETRIC

FLOW IN A CYCLONIC FLOW SITUATION. Through care in instrument selection and use of a tedious procedure, the relative error can be reduced, but its magnitude and sign may still not be certain.

MEASURING POLLUTANT EMISSION RATES IN CYCLONIC FLOW SITUATIONS

When measuring pollutant concentration and emission rate in cyclonic flow situations two general approaches are used: 1) straighten the flow mechanically and hope that this also straightens the pollutant flow; and 2) attempt to adapt existing sampling equipment to the character of cyclonic flow. Standard sampling equipment changes include: 1) using special probes;[2] 2) rotating (yawing) the probe to align the nozzle with the tangential vector of flow;[6] and 3) aligning the nozzle with the longitudinal axis of the stack and correcting the nozzle area for the reduction in area caused by the angular flow.[1,4] As described below, both approaches bias the test results in an unpredictable way. But in general, straightening the stack flow whenever possible may be superior to attempting to make existing equipment function satisfactorily in a cyclonic flow situation.

The three techniques generally used to straighten flow (straightening vanes, stack extensions equipped with straightening vanes, installing a duct on the side of the existing stack at the angle the gas is exiting the stack) have the following disadvantages associated with their use. First, they can be expensive to install, particularly for a single test. Second, they may change the performance of an inertial device such as a cyclone by causing re-entrainment of particles or droplets near the wall or by removing them through impaction or agglomeratio.[7] Third, there is no a priori reason why the pollutant flow should follow the same path as the straightened flow, so alignment of the nozzle with the straightened flow may still yield erroneous results. Fourth, space restrictions may make it difficult to sample the modified stack, particularly when a stack extension is used.

The three techniques now generally used to sample in cyclonic flow situations without employing flow straightening devices have been described in detail elsewhere[3,4,6] and will only be summarized here. The simplest approach, termed the Blindman's Approach, involves ignoring all angular flow components and sampling with the nozzle and pitot aligned with the longitudinal axis of the stack. The second approach, the Compensation Approach, also involves aligning the pitot and nozzle with the stack longitudinal axis, but the sampling rate is corrected for the reduction in nozzle area that is caused by the angular flow, i.e., the nozzle is multiplied by the cos θ. In the third approach, termed the Alignment Approach, the nozzle and pitot are aligned with the direction of stack gas flow, which is determined either from a previous traverse of the stack or by rotating the sampling assembly to obtain the minimum pressure head. Although more complex than the other approaches, this latter approach will still be in error to the degree that the direction of pollutant flow deviates from the direction of stack gas flow. All three approaches will be in error to the extent that the radial (pitch) component of flow affects the velocity measurement and thus the isokinetic sampling rate. Both the Blindman's Approach and Compensation Approach will also be biased to the extent the misaligned nozzle perturbs the velocity and pollutant flow upstream of the sampling assembly.[17] For example, this disturbed flow may cause particulate to move toward or away from the nozzle entrance.

One further problem in attempting to sample cyclonic flow without first straightening the flow is caused by the fact that nongaseous pollutants will tend to move toward and concentrate at the wall.[4,7,14] This requires sampling in a turbulent region, which will further aggravate the problem of obtaining a representative pollutant sample.

IN SUMMARY, IN CYCLONIC FLOW SITUATIONS IT IS IMPOSSIBLE TO PREDICT THE MAGNITUDE AND SIGN OF THE ERROR ASSOCIATED WITH EACH POLLUTANT SAMPLING APPROACH because the sources of error are confounded, i.e. not independent of each other. Thus, attempting to say that one approach will yield a positive bias and another a negative bias is tenuous.

USING A VENTURI TO STRAIGHTEN CYCLONIC FLOW

As discussed above, the size and sign of the error associated with standard approaches to sampling cyclonic flow are unpredictable. However, it is still necessary to sample stacks with cyclonic flow and although other more exotic sampling approaches can be used,[11,17] the improvement in the reliability of the result may be insignificant with respect to the additional cost involved.

However, there is one simple, practical, well-characterized device that may straighten cyclonic flow at low cost without also causing a severe pressure drop. In addition, this device — a venturi installed in the stack or in a stack extension — may allow stacks with very low velocity to be sampled using standard sampling equipment. The practicality of using an in-stack installed venturi has been demonstrated by Thompson on alfalfa dehydrators.[18]

Although it does not seem to have been evaluated outside the alfalfa industry, the available literature[19,20,21] indicates that the in-stack venturi would have the following advantages:

1) Easy and flexible design criteria.[19]

2) Ability to straighten the flow to meet EPA Method 1 specifications within one duct diameter after the diffusion section.[18]

3) Would permit a decrease in the number of sampling points required compared to sampling the unstraightened flow. This would decrease the time required for a test run and at the same time improve the reliability of the velocity and volumetric flow measurement. It would also allow standard test equipment to be used without modification.

4) Would permit flow in a rectangular duct to be converted to laminar flow in a circular duct in a very short distance.

5) Can increase the velocity in a stack if size of the diffuser cone is reduced compared to the entrance cone (most pitot tubes are inaccurate below 3 m/sec).

6) Can cause particulate concentrated near the wall to redistribute itself more evenly across the stack without loss of particulate through impaction.

Thus, it would seem prudent for researchers to start evaluating the use of the venturi for straightening cyclonic flow. The following areas should be investigated:

1) The effect on particulate distribution and concentration.

2) The maximum angle that can be tolerated in the diffusion section before the onset of turbulance. (Gibson[21] has found that in liquids this angle can be as large as 40° if the inlet to the diffuser is curved. This alone is a significant improvement over the original venturi design limitation of 7°.)

3) The variation in the convergent section angle that can be tolerated before the onset of turbulent flow in the venturi throat.

4) The development of adjustable (in length and angle) convergent and diffuser sections for use with several standard sized venturi throats.

5) The effect of venturi design on the volumetric flow exiting the stack.

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APPENDIX C

PITOT TUBE ACCURACY AT LOW REYNOLD'S NUMBER

INTRODUCTION

Reynold's Number, Re, is an important dimensionless number that describes the relationship between the inertial and frictional forces present in a fluid and indicates both the nature of fluid motion, i.e., laminar, transitional or turbulent and the energy distribution associated with these stages. It is represented by the relation

$$Re \; \alpha \; \frac{\text{inertial forces}}{\text{frictional forces}}$$

More specifically:

$$Re = \frac{\rho V D}{\mu} \qquad \text{Eq. C-1}$$

where:

- ρ: density, a function of temperature
- V: velocity of the fluid
- D: diameter
- μ: dynamic or absolute viscosity, a function of temperature

Temperature affects the Re because both density and viscosity change with temperature. For gases, under isobaric conditions, as temperature increases density decreases but viscosity increases. Therefore, an increase in temperature under isobaric conditions results in a decrease in the inertial forces (density) and an increase in the frictional forces (viscosity), for an overall decrease in Re.

HOW RE DETERMINES FLUID CHARACTERISTICS

The frictional force (viscosity) of a fluid inhibits the onset of turbulence while the inertial force promotes the propagation of turbulence. These two opposing forces influence the character of the fluid which is indicated by Reynold's number, Re, a dimensionless ratio of inertial to frictional forces. The magnitude of this value reflects which force dominates and therefore the stage of flow development. At low Re the frictional forces dominate and inhibit turbulent propagation thus forming a laminar regime. At high values of Re, the inertial forces dominate over the frictional forces and promote turbulent propagation and the formation of a turbulent regime.

A critical Reynold's number (Re_c) is associated with the onset of turbulence, i.e., the point where the inertial forces start to dominate. This critical ratio of inertial to frictional forces, Re_c, is also the critical minimum for amplification and propogation of oscillatory motion with energy transferring wave characteristics. At values greater than Re_c, viscosity effects which are associated with the frictional forces (the resistance of movement of one layer of fluid over another) become negligible. The transference of energy by inertial effects causes interaction of eddies of different wave numbers and the associated convective spread of energy. The smaller eddies form concentrated but weak vortex sheets, superimposed as perturbations on the main vorticity field of the larger eddies. The system is in energy equilibrium because of the balance between eddy stretching and viscosity effects. Therefore, the total energy of the fluid is constant and evenly distributed throughout the fluid when inertial forces dominate over frictional forces, i.e., at a Re greater than Re_c. At values of Re less than Re_c, the fluid has a non-uniform energy distribution concentrated in pockets of eddy turbulence.

A fluid can be divided into an infinite number of layers, each representing a streamline (See Figure. C-1). If layers B, C, and D encounter an obstruction in their path, the molecules in these layers are reflected by the obstruction and bombarded by the oncoming molecules in the fluid creating excess kinetic energy in the system. Eventually, the molecules in layers B, C, and D are refracted into the unobstructed layers, A and E, to which they transfer some of their additional kinetic energy creating a system that is no longer in equilibrium. At high Re, where viscosity is small there is little resistance of movement of one layer over another so layers B, C, and D are easily joined and separated from layers A and E with a limited energy loss. High energy swirls form downstream at a distance, d, from the obstacle. This distance is a factor of the separation time, T_s. At low Re, where viscosity is greater, there is more resistance of movement of one layer over another and more energy is required for one layer to join another layer. Since it takes more energy for the layers to join, it also takes more to separate them.

If we consider a constant energy gain and a constant energy release value in two systems, i.e. System I with a high Re and System II with a low Re, we conclude

Energy of the System: $E_s^{II} > E_s^{I}$

Release Value: $\frac{dE_s^{II}}{dt} = \frac{dE_s^{I}}{dt}$

Separation Time: $T_s^{II} > T_s^{I}$

Distance from Obstruction to Swirls: $d^{II} > d^{I}$

where: $d = T_s V$

V = fluid velocity

Energy of Swirls: $E_{sw}^{II} < E_{sw}^{I}$

where: $E_{sw} = E_s - \frac{dE_s}{dt} \cdot T_s$

Thus, at low Re, the swirls or eddies, will form further downstream with less intensity and lower energy than for high Re. These results are portrayed graphically in Figure C-1.

HOW REYNOLD'S NUMBER AFFECTS PITOT ACCURACY

The Reynolds number has been found to characterize the type of boundary layer and correspondingly, the frictional losses in the flow around a pitot tube in a flow stream.[1] The Reynold's number in question is not the one that describes the stack flow across the stack but rather, the Reynold's number that characterizes the flow over the pitot tube. Therefore, the value for the parameter D in equation C-1 should be the diameter of the pitot not the diameter of the stack when considering Re effect of the pitot tube.[1]

At low Re, streamline flow will curve around the pitot tube (Fig. C-2a). Small eddies or pockets of energy form downstream from the obstruction out of the range of detection of the impact orifice. The viscosity effects dominate and resist redistribution of this energy causing a lower than true energy to exist in the vicinity of the impact orifice. Since pressure is by definition a force per unit area and in fluid mechanics is used to denote energy per unit volume of fluid, the lower energy in the orifice region results in a lower pressure and a high pitot coefficient. This has been confirmed experimentally by MacMillan, who reported on the accuracy of flat-nosed and hemispherical-nosed impact-pressure pitot tubes at Re from 15 to 1,000. His results (Figure C-3) showed that the pitot coefficients, Cp, were greater than 1.0 at Re less than 1000. For example, the coefficient for a hemispherical-nosed pitot tube (Curve B in Figure C-3) was 1.35 at a Re of 15, but 1.01 at a Re of 1000. The differences between the curves were attributed to the shape of the pitot tube nose by MacMillan.[1]

Although analogous data for Reynold's number less than 1000 is not available for the "S" and Kiel/cylinder pitot tubes, they also seem to experience a shift in Cp in the lower ranges of Reynold's number (Figure C-4). The sinusoidal pattern evident in both curves between Reynold's numbers of 1000 and 3500 has been observed by Williams and De Jarnette[3], Leland[4], Smith[5], and in this study; and therefore, should be considered a real effect and should not be dismissed as a result of data scatter. The two local maxima in both curves may be associated with separate Reynold's number effects on the impact- and the static-pressure sensing orifices but at present this is pure conjecture and the need for more precise studies is indicated.

Figure C-5 shows that low Reynold's numbers can be encountered when sampling stacks with low flows and high temperatures and demonstrates that care should be used in this sampling situation. Quite possibly, the higher flow sometimes measured downstream from a control device compared to that measured upstream may be due to a Reynold's number effect and not to air in-leakage as is usually assumed.

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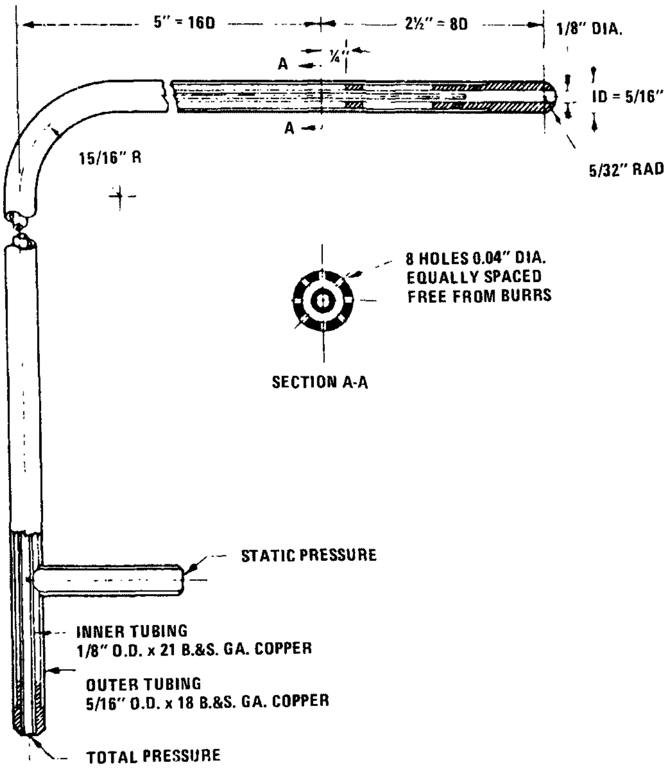


Figure 1. Merriam and Spaulding standard "L" pitot tube.

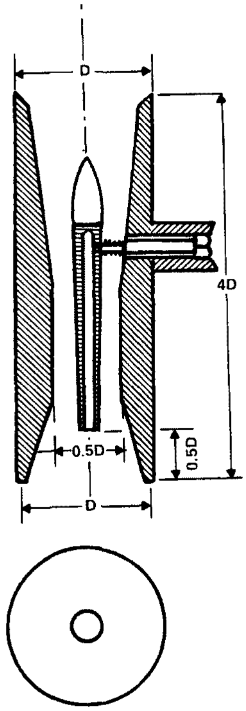


Figure 2. Kiel total pressure tube.

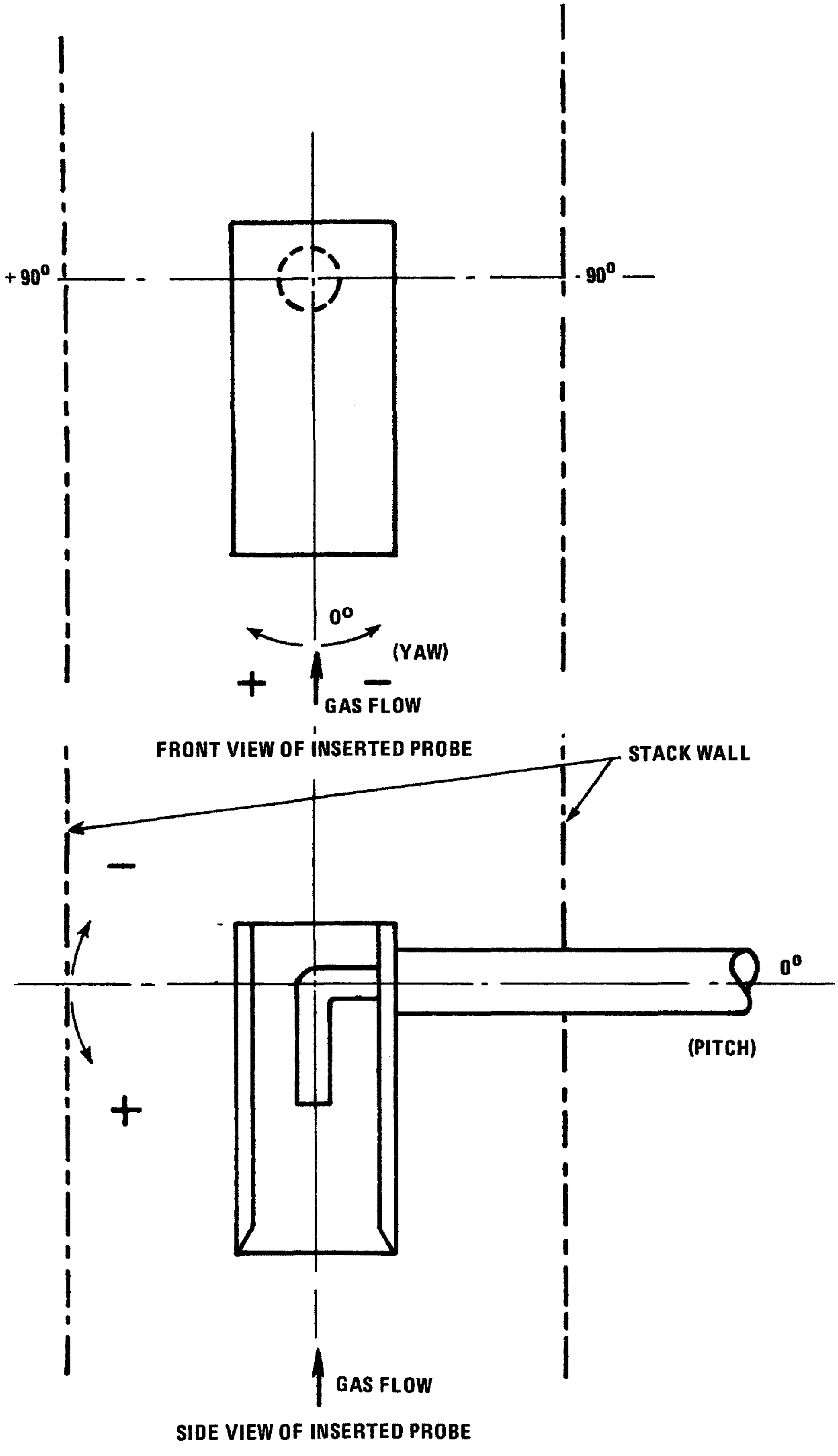


Figure 3. Representation of yaw and pitch.

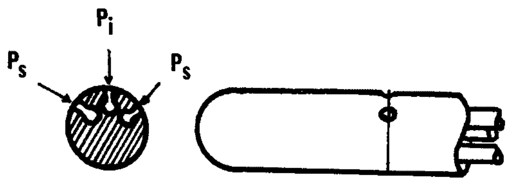


Figure 4. Cylinder pitot tube.

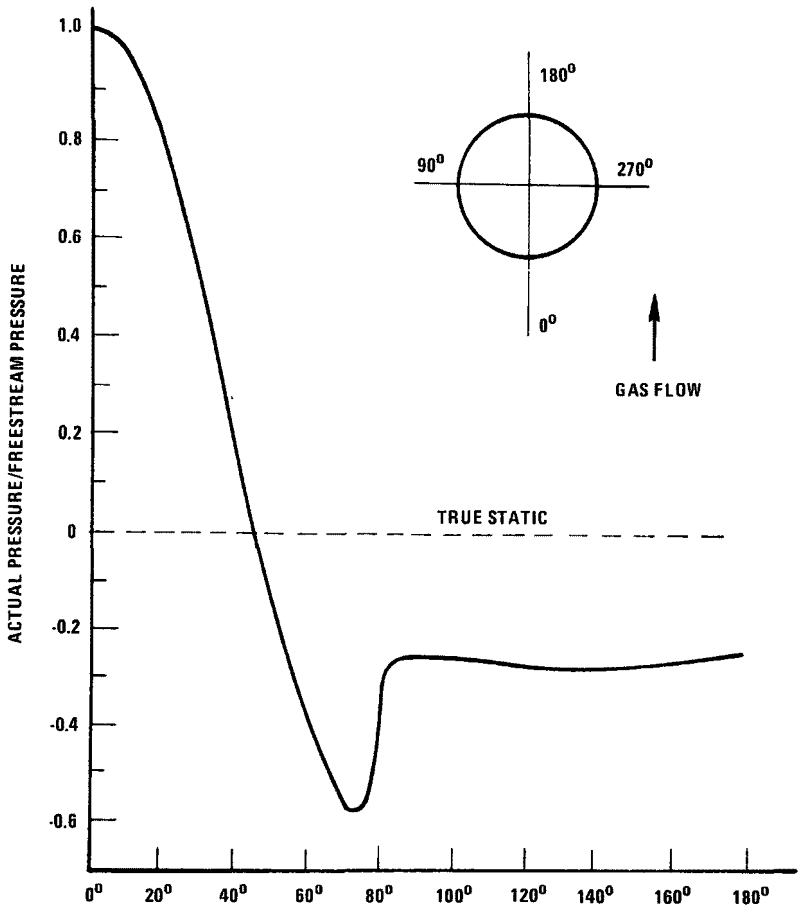


Figure 5. Pressure distribution about a 25 mm diameter cylinder.

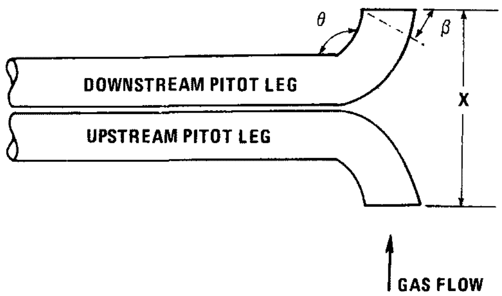


Figure 6. Standard "S" pitot tube.

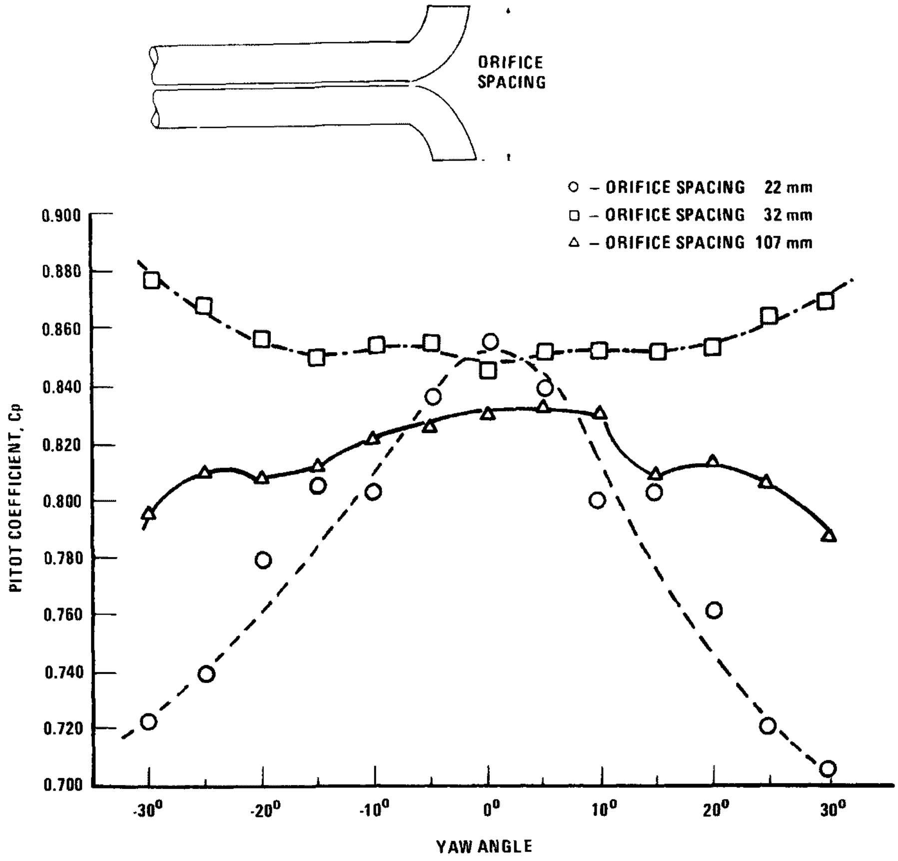


Figure 7. Effect of yaw on different "S" pitot tubes[9].

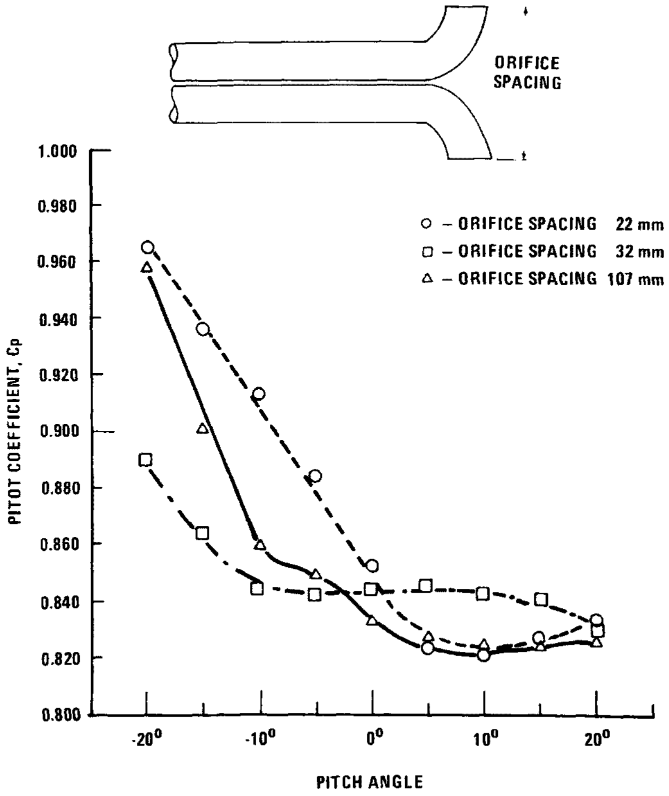


Figure 8. Effect of pitch on different "S" pitot tube[9].

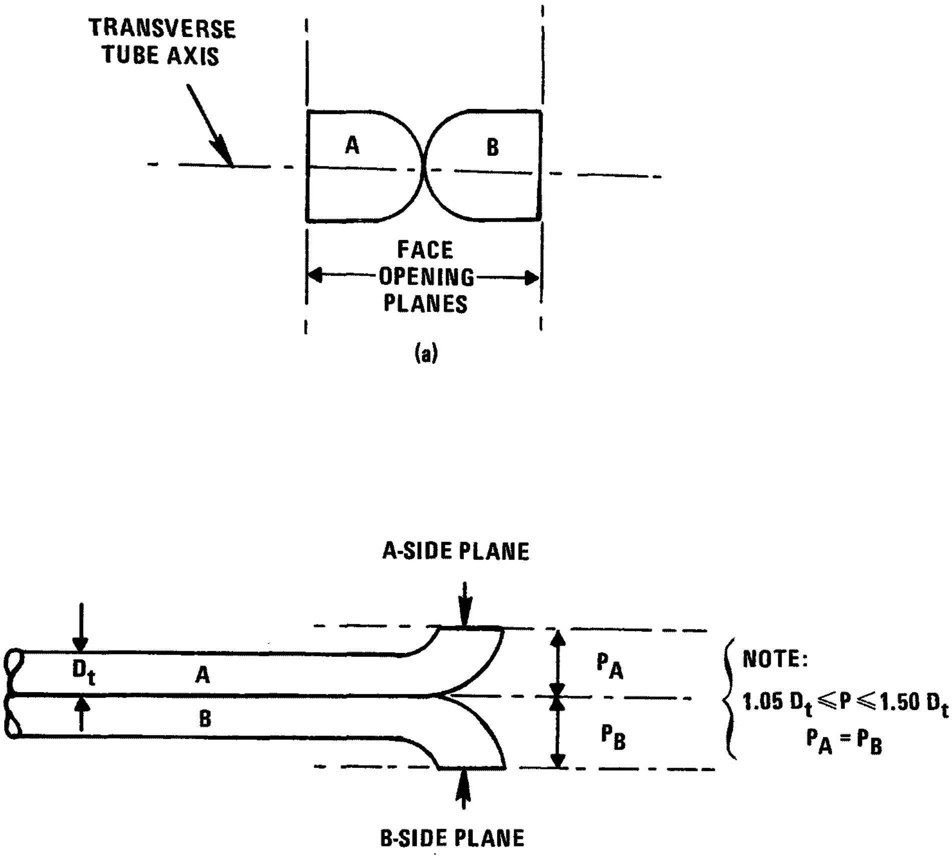


Figure 9. Design specification for "S" pitot tube after Vollaro[8].

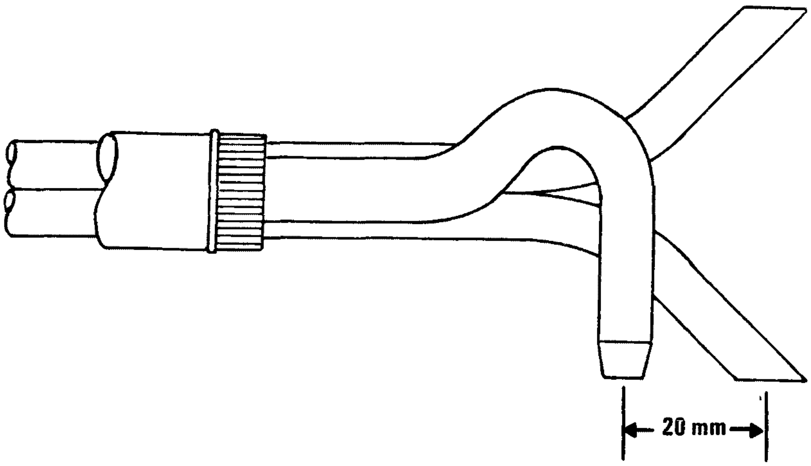


Figure 10. Relative position of pitot and sampling nozzle as recommended by Williams and De Jarnette[9].

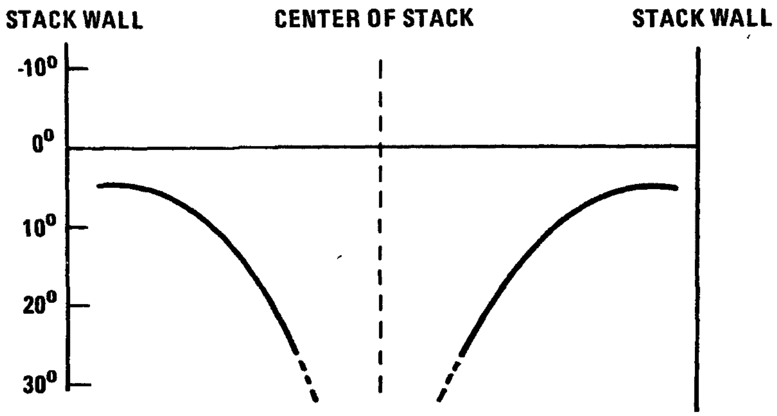


Figure 11. Sample of pitch angle profile in stack with cyclonic flow. (Data near walls and at center is unreliable(11)).

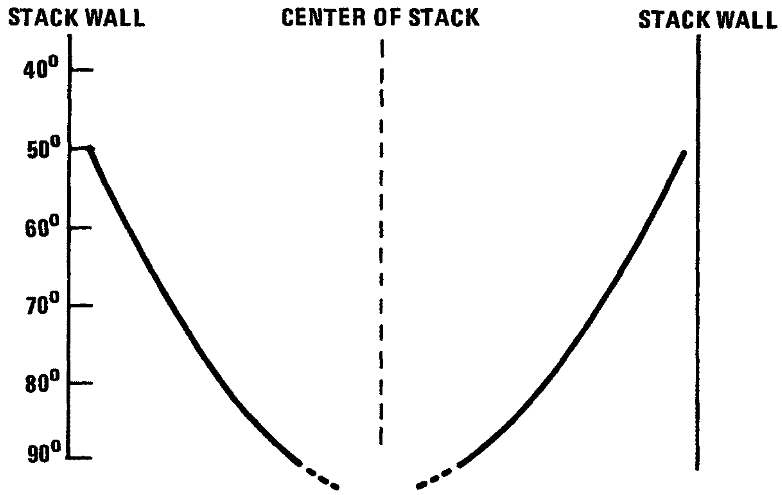


Figure 12. Sample of yaw angle profile in stack with cyclonic flow. (Data near walls and at center is unreliable(11)).

Table 1. DIMENSIONS OF "S" PITOT TUBE LEGS STUDIED

TUBE NO.	θ	X, mm	β
1S	45°	12	0°
2S	45°	25	0°
3S	45°	12	20°
4S	45°	25	20°
5S	45°	25	45°
6S	60°	12	0°
7S	60°	25	0°
8S	60°	12	20°
9S	60°	25	20°
10S	90°	25	0°
11S	90°	12	20°
12S	90°	25	20°
13S	90°	25	45°

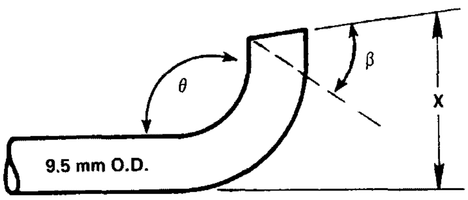


Table 2. DIMENSIONS (IN mm) OF "L" PITOT TUBES STUDIED

TUBE NO.	D	a	b	IMPACT ORIFICE ID	STATIC ORIFICE DIMENSIONS: NO. ROWS	ORIFICES ROW	c	OFFSET OF ADJ. ROWS	ORIFICE ID
1L	8	20	24	4.6	1	6	–	–	1.01
2L	8	20	26	4.6	1	4	–	–	1.60
3L	9.5	24	29	6.4	1	4	–	–	2.05
4L	4.8	13	16	–	1	4	–	–	1.01
5L	4.8	16	16	–	2	3	5	60°	1.60
6L	6.4	20	18	–	1	4	–	–	1.60
7L	6.4	20	18	–	2	3	5	60°	2.05
8L	9.5	30	25	–	1	6	–	–	2.05

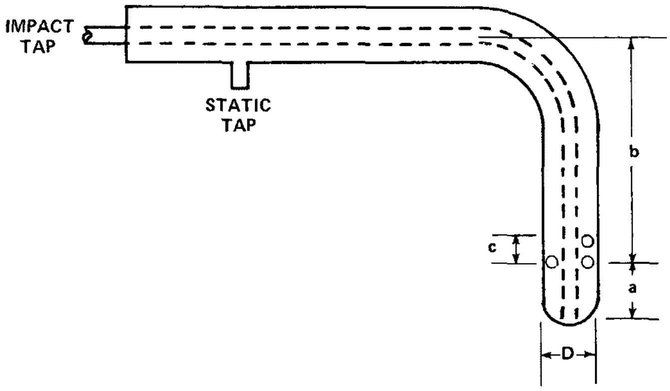
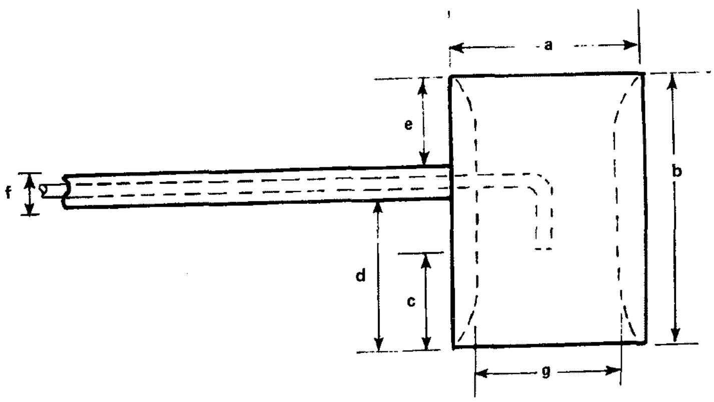


Table 3. DIMENSIONS (IN mm) OF KIEL PITOT TUBES STUDIED

TUBE NO.	MODEL[a]	IMPACT ORIFICE	DIMENSIONS: a	b	c	d	e	f	g
1K	KFF	3.3 (ID) x 5.0 (OD)	19	38	12.5	23	5.0	10	9.5
2K	KFF	2.3 (ID) x 3.3 (OD)	13	27	10.0	15	1.5	10	6.2
3K	KRF	3.3 (ID) x 5.0 (OD)	19	38	12.5	23	5.0	10	9.5

[a]KFF TYPE HAS VENTURI EXIT AND ENTRANCE. KRF TYPE HAS VENTURI ONLY AT ENTRANCE.



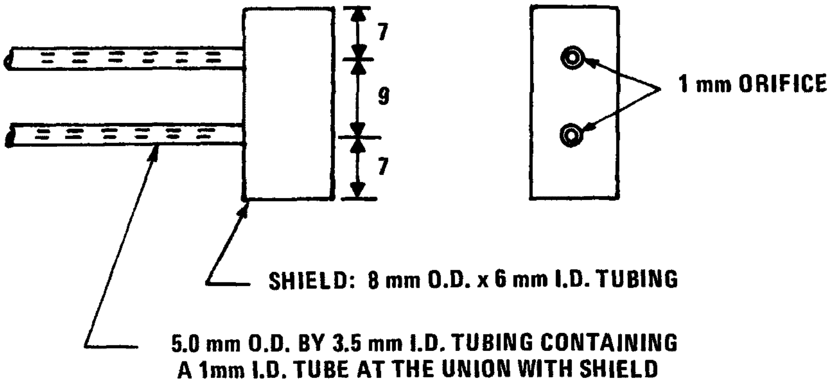
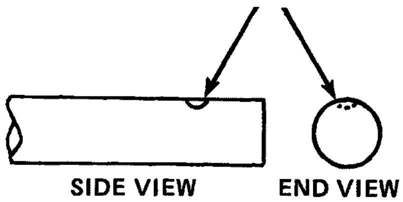


Figure 13. Shielded static pitot tube.

Table 4. DIMENSIONS (IN mm) OF CYLINDER PITOT TUBES STUDIED

NO.	ORIFICE SIZE, mm	ORIFICE LOCATION, TD[a]
1C	2.60	3
2C	2.60	2
3C	2.60	1
4C	1.58	3
5C	1.58	2
6C	1.00	3
7C	2.75	5
8C	2.75	4
9C	3.20	5

[a]TD=TUBE DIAMETERS FROM END OF TUBE.
ALL TUBES WERE 9.5 mm IN DIAMETER.



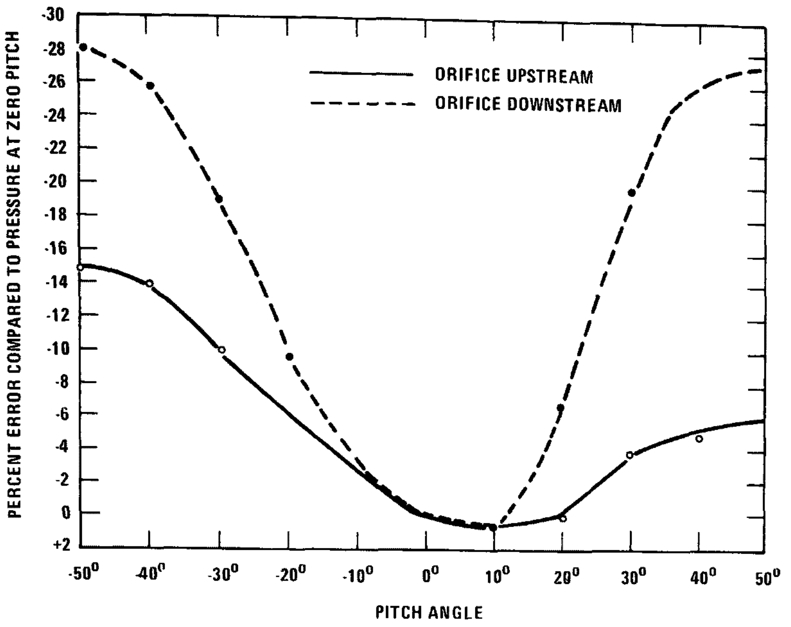


Figure 14. Shielded static pitot tube error curve for pitch at 8 m/sec.

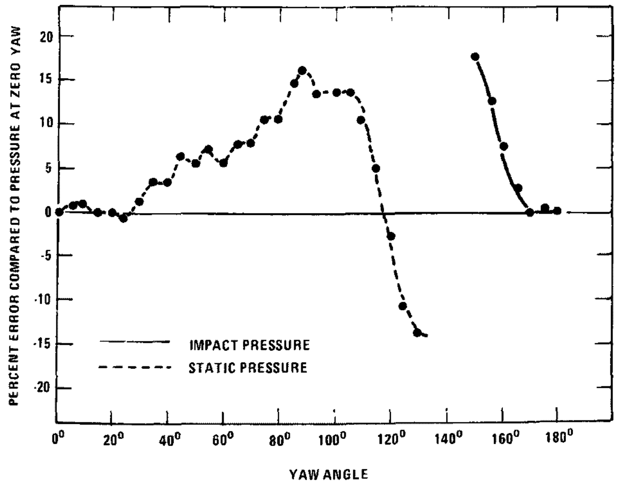


Figure 15. Effect of yaw on tube 5S.

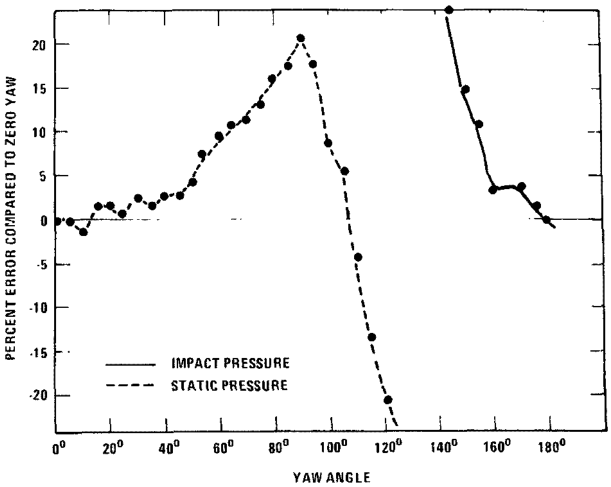


Figure 16. Effect of yaw on tube 10S.

TABLE 5. EFFECT OF YAW AND PITCH ON PRESSURE MEASUREMENT BY "S" PITOT TUBE LEGS

($mm\ H_2O$)

Yaw	0°			10°			20°			+90°	-90°	180°	ASME[a] Ref. pitot value	
Pitch	-20°	0°	+20°	-20°	0°	+20°	-20°	0°	+20°	0°	0°	0°	P_i	P_S
Tube														
1S	-3.25	-4.11	-7.52	-3.12	-4.29	-7.59	-3.18	-4.52	-7.92	-20.9	-22.7	-21.0	-3.48	-12.8
2S	-3.10	-2.82	-3.63	-3.23	-2.87	-3.23	-3.33	-3.00	-4.85	-24.6	-20.2	-17.6	-3.38	-12.6
3S	-3.02	-2.82	-4.09	-3.10	-2.82	-4.29	-3.12	-2.97	-4.39	-16.1	-23.1	-19.6	-3.45	-12.6
4S	-3.51	-6.53	-13.9	-3.78	-6.88	-13.6	-4.39	-7.95	-14.9	-23.9	-20.9	-17.4	-3.43	-12.3
5S	-2.74	-2.99	-6.25	-2.67	-3.25	-6.60	-2.74	-3.84	-6.99	-23.0	-21.8	-17.3	-2.97	-12.1
6S	-3.18	-3.05	-4.34	-3.18	-3.18	-4.27	-3.12	-3.15	-4.62	-19.7	-22.4	-19.5	-3.43	-12.3
7S	-3.02	-2.89	-3.61	-3.28	-3.00	-3.78	-3.35	-3.02	-4.17	-20.9	-23.1	-17.4	-3.45	-12.4
8S	-3.28	-3.84	-7.29	-3.48	-4.52	-7.65	-3.58	-4.65	-8.03	-20.5	-22.2	-20.8	-3.47	-12.3
9S	-3.20	-3.35	-6.29	-3.23	-3.71	-6.68	-3.40	-4.19	-7.59	-24.0	-21.7	-17.5	-3.40	-12.3
10S	-3.94	-3.78	-5.11	-3.86	-3.73	-5.13	-4.01	-3.05	-5.38	-22.3	-24.2	-19.3	-4.01	-12.1
11S	-3.18	-4.14	-7.69	-3.56	-4.72	-8.33	-4.04	-5.79	-9.37	-24.0	-18.0	-21.0	-3.30	-12.0
12S	-3.05	-3.35	-6.35	-3.23	-3.81	-6.81	-3.40	-4.34	-7.67	-23.9	-21.7	-17.1	-3.51	-12.1
13S	-3.71	-6.45	-12.2	-4.19	-7.11	-13.6	-5.23	-8.48	-15.2	-24.5	-18.5	-17.5	-3.51	-12.3

[a] ASME - American Society of Mechanical Engineering

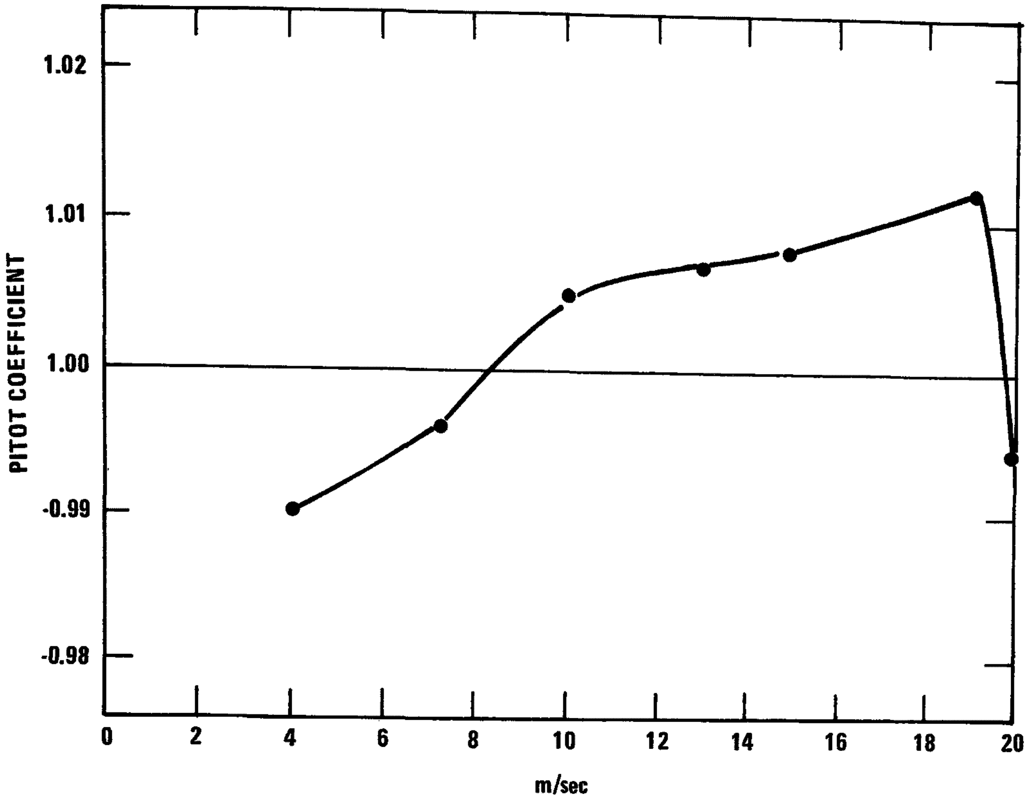


Figure 17. Variation of pitot coefficient with velocity for tube 1L.

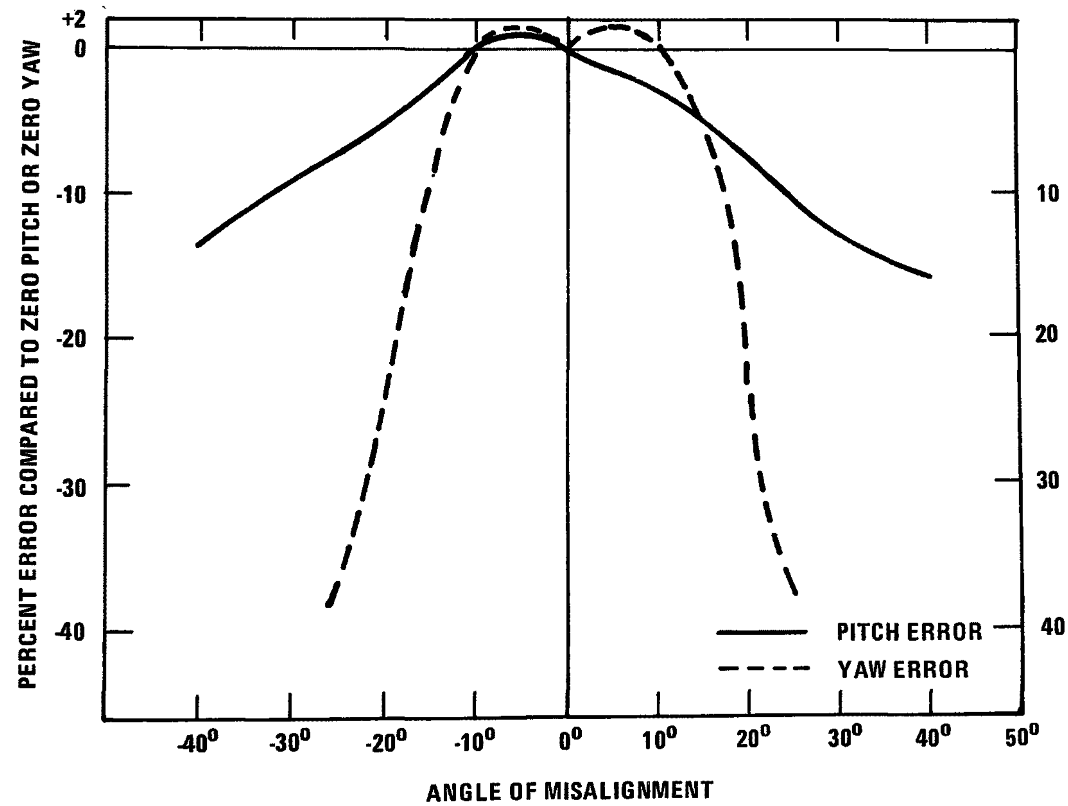


Figure 18. Yaw and pitch error curve for static pressure for tube 8L (8 m/sec).

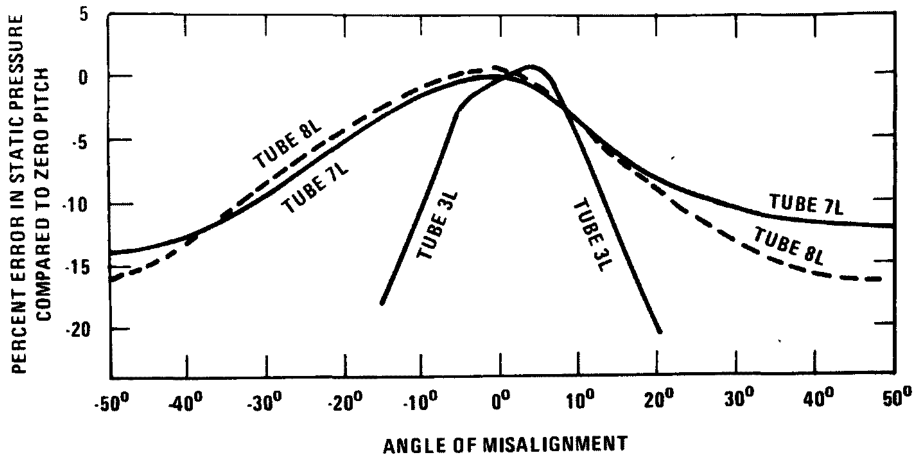


Figure 19. Error curve for static pressure for tubes 3L, 7L, and 8L.

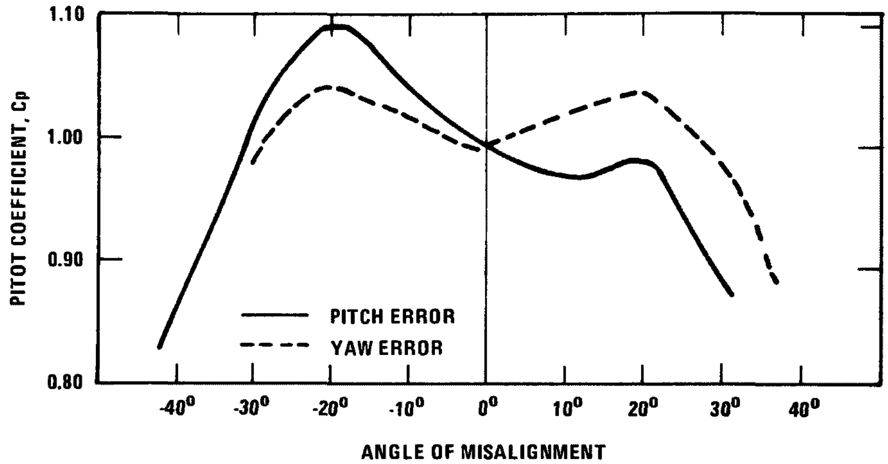


Figure 20. Error in pitot coefficient for tube 3L as function of yaw and pitch at 8 m/sec.

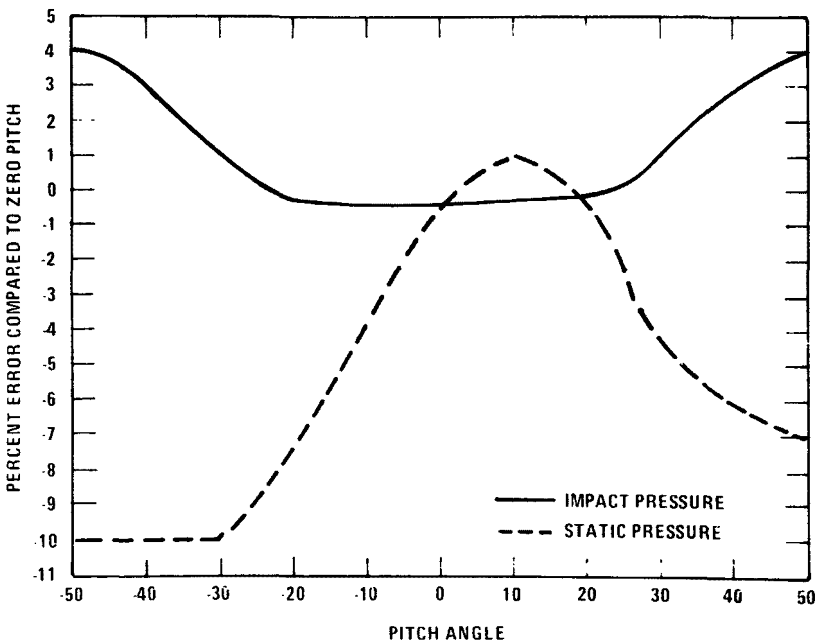


Figure 21. Relative error in pressure for tube 1K as function of pitch at 8 m/sec.

TABLE 6. EFFECT OF YAW ON CYLINDER PITOT TUBE PRESSURE MEASUREMENT[a]

	Yaw Angle	Tube 1C	4C	5C
IMPACT PRESSURE				
	0	—— Reference Point ——		
	5	1	0	0
	10	7	0	2
	15	22	2	8
	20	47	14	28
WAKE PRESSURE				
	180	—— Reference Point ——		
	170	0	0	1
	160	0	0	1
	150	0	0	3
	140	0	0	3
	130	0	0	2
	120	0	0	0
	110	-1	-1	0
	100	-1	0	0
	90	-1	4	4
	85	-1	10	7
	80	1	14	13
	75	4	12	14
	70	10	8	12
	65	12	1	7
	60	4	-8	0
	50	-15	-25	-20

[a]% error in pressure measurement at 8 m/sec.

TABLE 7. EFFECT OF PITCH ON CYLINDER PITOT TUBE WAKE PRESSURE MEASUREMENT[a]

Pitch Angle	Tube								
	1C	2C	3C	4C	5C	6C	7C	8C	9C
-40	3	7	15	0	6	-1	4	4	3
-30	0	0	10	-2	-1	-3	0	0	-2
-20	-1	-1	6	-3	-3	-2	-1	-1	-1
-10	-2	-2	2	-3	-3	-2	-1	-1	-1
0	Reference Point								
10	5	4	8	3	3	4	2	2	2
20	5	12	19	4	9	5	4	4	3
30	8	13	21	7	10	7	7	7	7
40	8	16	25	10	14	9	9	13	10

[a]% error in pressure measurement at 8 m/sec. The results for impact-pressure were similar to those for wake-pressure except that all tubes were in error by more than 5% for pitch angles greater than ± 25°.

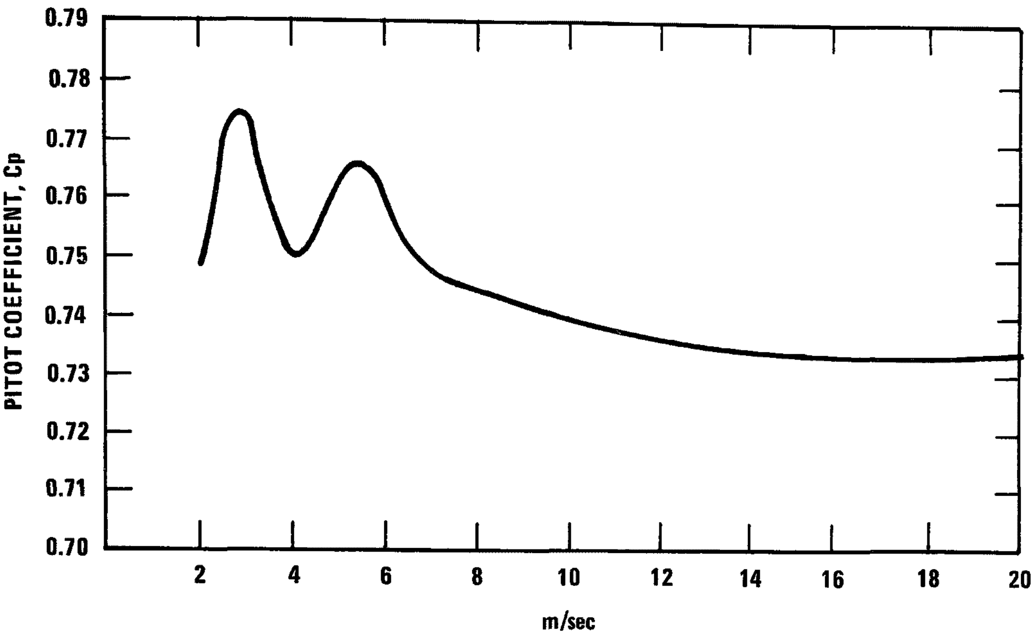


Figure 22. Calibration curve for tube 1K as function of velocity.

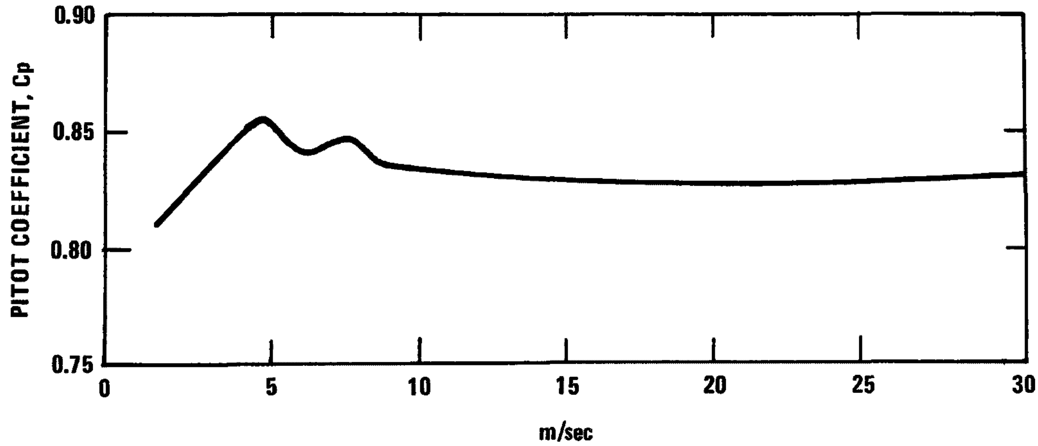


Figure 23. Calibration curve for "S" pitot 3-04 after Williams and De Jarnette (9).

TABLE 8. RELATIVE EFFECT OF PITCH WHEN DIRECTION OF GAS FLOW IS DETERMINED WITH KIEL/CYLINDER PITOT TUBE[a]

Pitch Angle	Distance Between Centers of Static and Impact Orifice		
	19 mm	38 mm	57 mm
25	3	6	2
20	2	3	1
15	2	2	1
10	1	2	0.5
5	0.5	1	0.5
	Reference Point		
-5	1	2	0.5
-10	1	3	0.5
-15	3	5	2
-20	6	7	5
-25	8	10	10

[a]% error in the velocity measured as function of pitch.

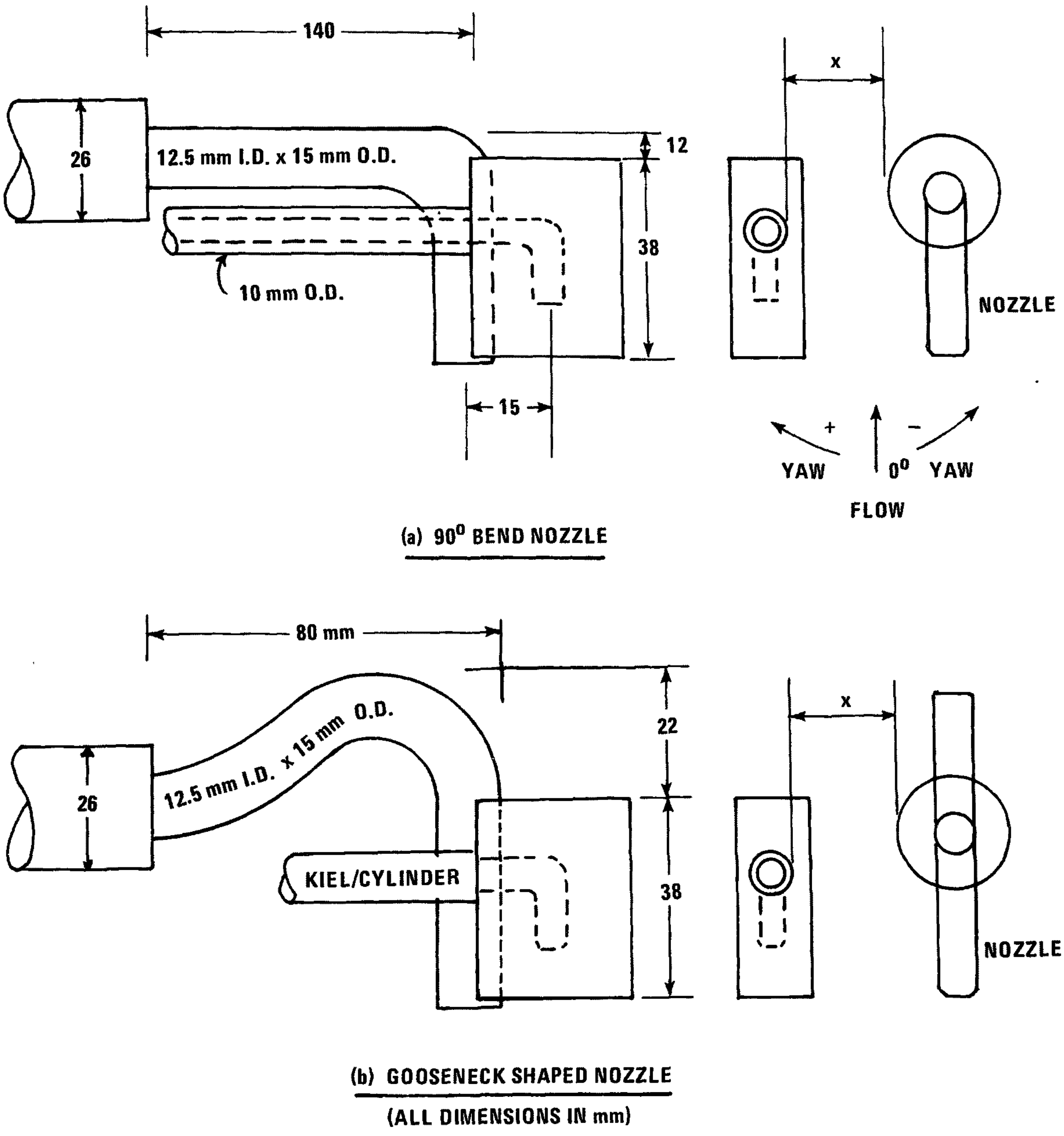


Figure 24. Nozzle/pitot orientations.

TABLE 9. EFFECT OF YAW ON PITOT COEFFICIENT FOR WAKE PRESSURE MEASUREMENT BY KIEL/CYLINDER PITOT TUBE[a]

Nozzle ID (mm)	X (mm)	Yaw Angle (nozzle upstream)						Yaw Angle (nozzle downstream)				
		+50	+40	+30	+20	+10	0	-10	-20	-30	-40	-50
6.4	8	1	2	-1	-2	-1	Reference Point	7	6	4	2	1
12.5	5	2	-4	-4	-3	-2		8	8	8	3	0
6.4	22	4	0	-3	-1	-1		7	9	4	3	1
12.5	18	-1	-3	-3	-3	-2		-2	-2	-3	-3	-2
12.5	22	-2	-2	-3	-3	-2		8	9	6	4	1

[a]The tests were conducted with the sampling probe attached.

TABLE 10. COMBINED EFFECT OF YAW AND PITCH ON COEFFICIENT OF KIEL/CYLINDER PITOT TUBE ATTACHED TO A PARTICULATE SAMPLING ASSEMBLY[a]

Pitch Angle	Yaw Angle										
	+50	+40	+30	+20	+10	0	-10	-20	-30	-40	-50
45	6	6	7	2	11	15	11	12	12	11	10
40	4	3	4	1	8	9	8	8	9	7	7
30	2	0	1	-1	3	4	2	2	3	2	2
20	0	-2	-2	-2	-1	1	-1	-1	0	-1	-1
10	-1	-3	-3	-2	-2	0	-1	-1	-2	-2	0
0	-1	-3	-3	-3	-2	—	-2	-2	-3	-3	-2
-10	-1	-2	-2	-4	-1	1	0	0	-1	-2	-1
-20	-1	0	0	-5	-1	2	3	3	2	1	1
-30	0	3	3	-3	0	4	5	6	6	3	3
-40	4	6	6	-1	3	5	8	10	9	6	6
-45	6	8	7	1	5	6	9	12	11	9	11

[a]% error in pitot coefficient with respect to zero yaw and pitch.

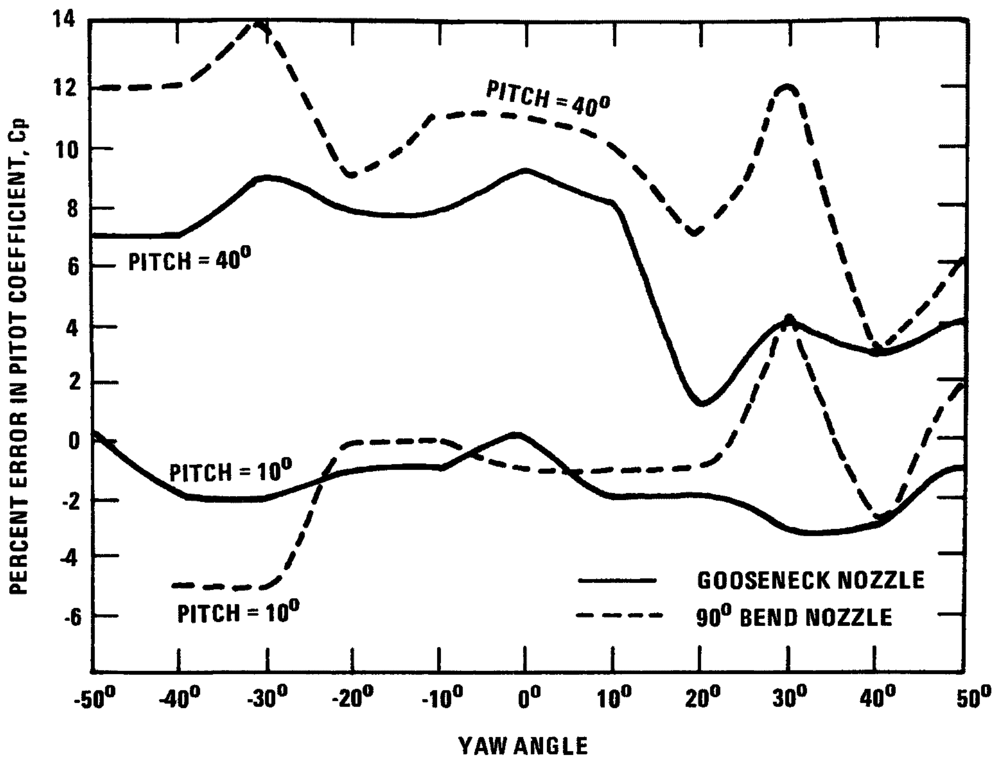


Figure 25. Combined effect of yaw and pitch on Kiel/cylinder pitot tube attached to sampling probe (8 m/sec) (Reference point Cp at zero yaw and pitch).

TABLE 11. SENSITIVITY OF "S" AND KIEL/CYLINDER PITOT TUBE COEFFICIENTS TO NOZZLE/THIMBLE INTERACTION[a]

Z^b (mm)	C_p for "S" Pitot		C_p for Kiel/Cylinder Pitot	
	Impact	Wake	Impact	Wake
+25	—	—	.99	1.33
0	.89	1.28	.98	1.34
-25	.89	1.25	.98	1.34
-50	.96	1.39	.98	1.34
-100	1.0	1.52	.98	1.28

[a]Measured relative to the Reference ASME Pitot Tube, C_p = 0.99

[b]Z = Distance between the pitot impact orifice and the leading edge of the nozzle. The thimble was equipped with a 12.5 mm ID x 15 mm OD, 90° bend nozzle, the spacing between the nozzle edge and the pitot sheath was 18 mm, and the nozzle centerline was 200 mm ahead of the leading edge of the thimble body. A negative "Z" value means the pitot tube orifice was between the nozzle centerline and the leading edge of the thimble body.

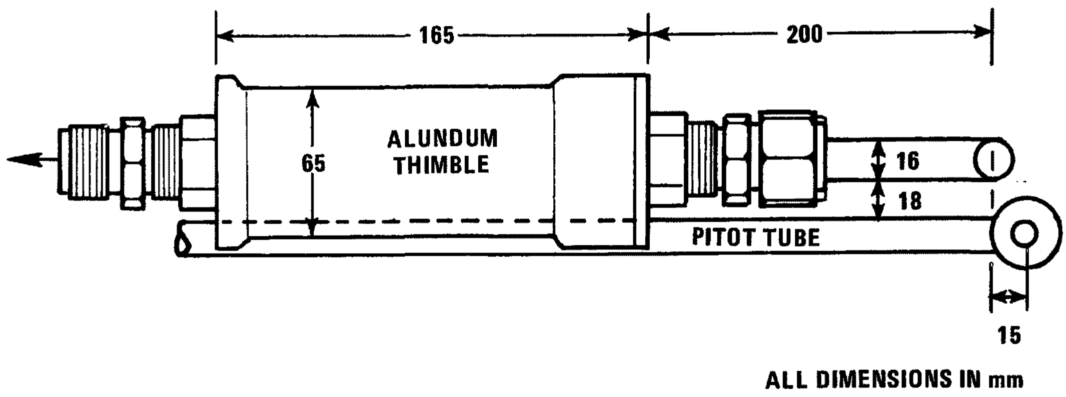


Figure 26. Orientation of Kiel/cylinder pitot tube with alundum thimble.

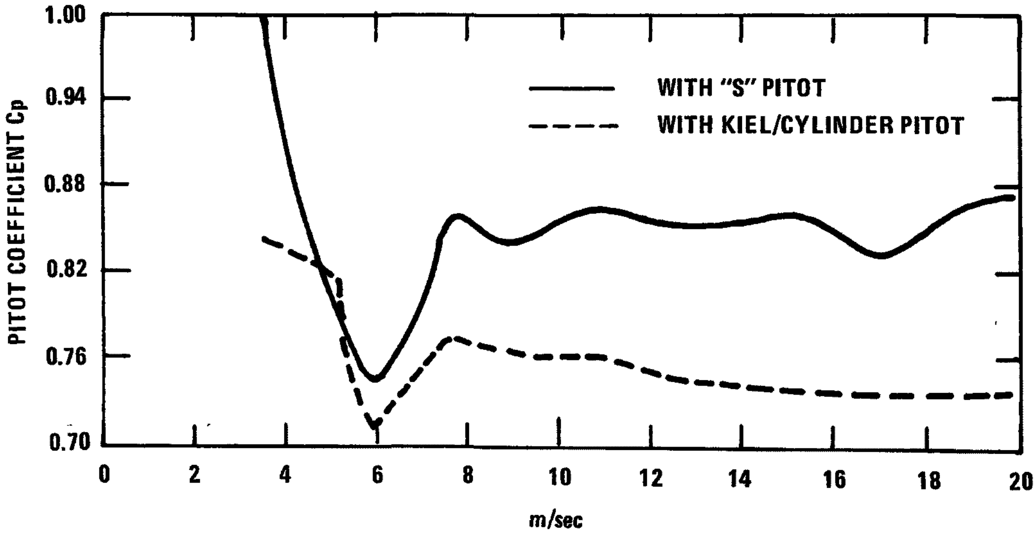


Figure 27. Variation of pitot coefficient with velocity for alundum thimble sampling assembly.

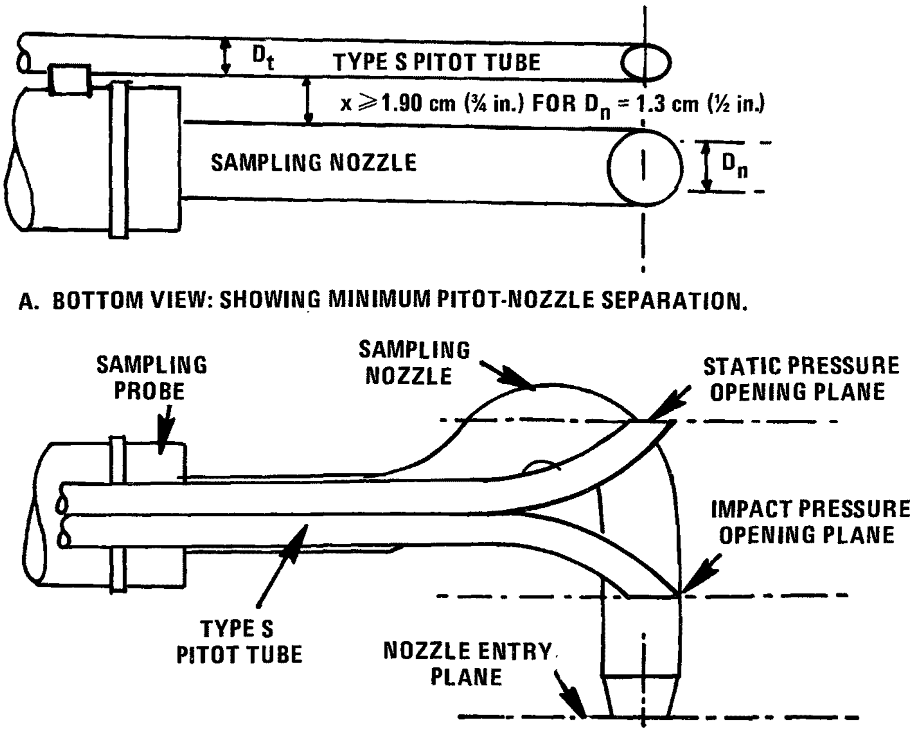


Figure 28. Standard EPA sampling assembly for particulate.

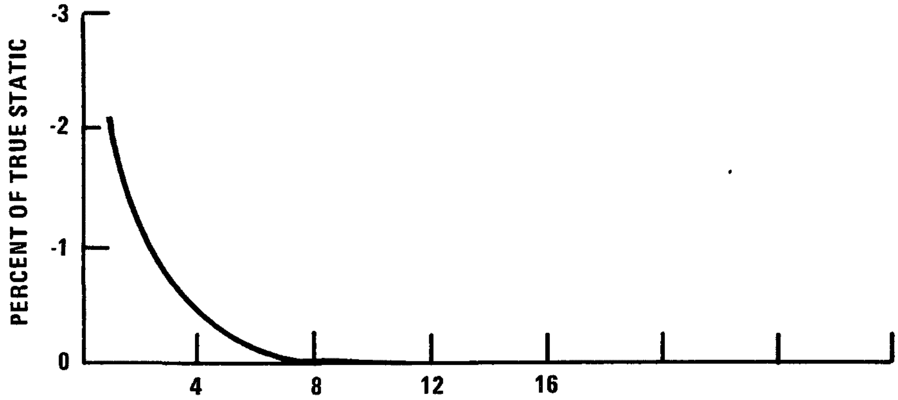


Figure 1A-a. Absolute error in static pressure as a function of orifice distance from tip of "L" pitot.

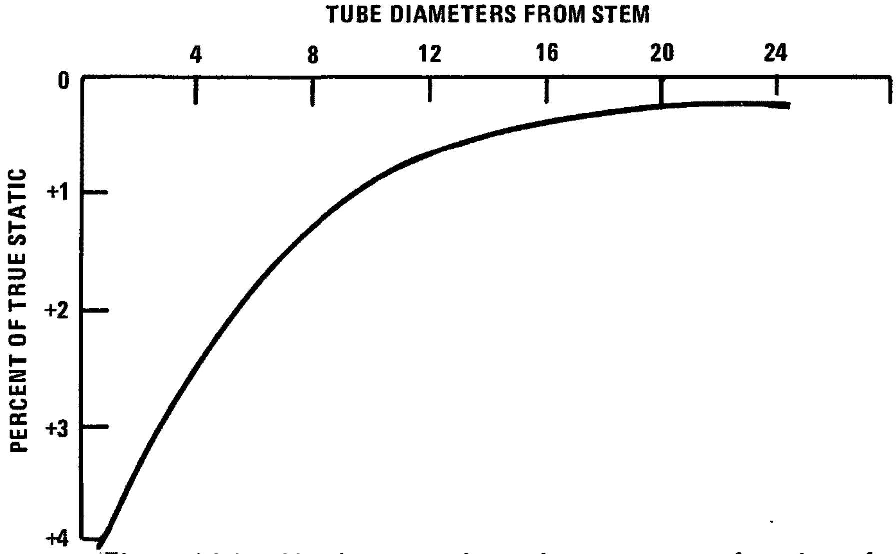


Figure 1A-b. Absolute error in static pressure as a function of orifice distance from stem of "L" pitot.

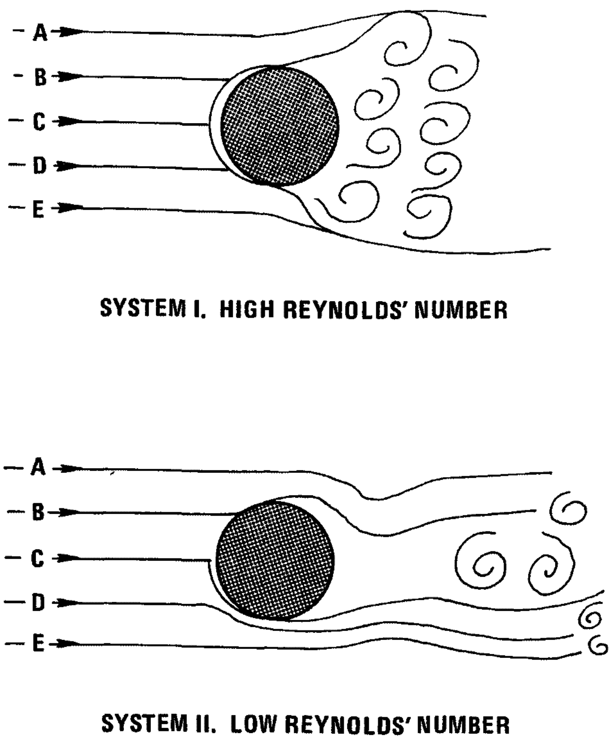


Figure C-1. Flow patterns downstream of a cylinder at high and at low Reynolds' number.

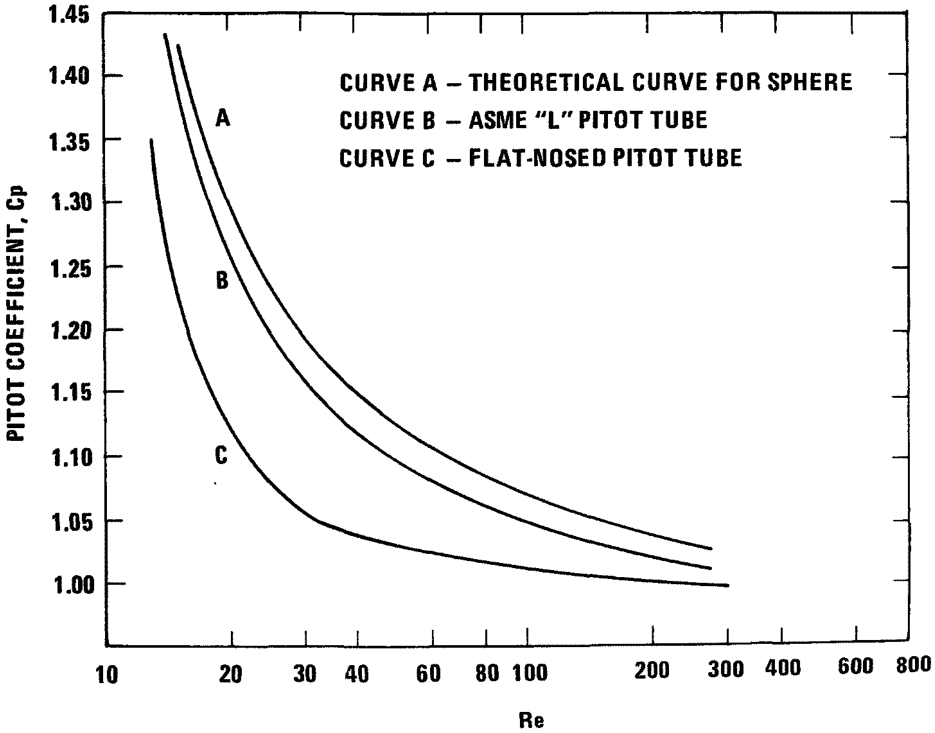


Figure C-2. Effect of Reynolds' number of pitot coefficient after MacMillan.

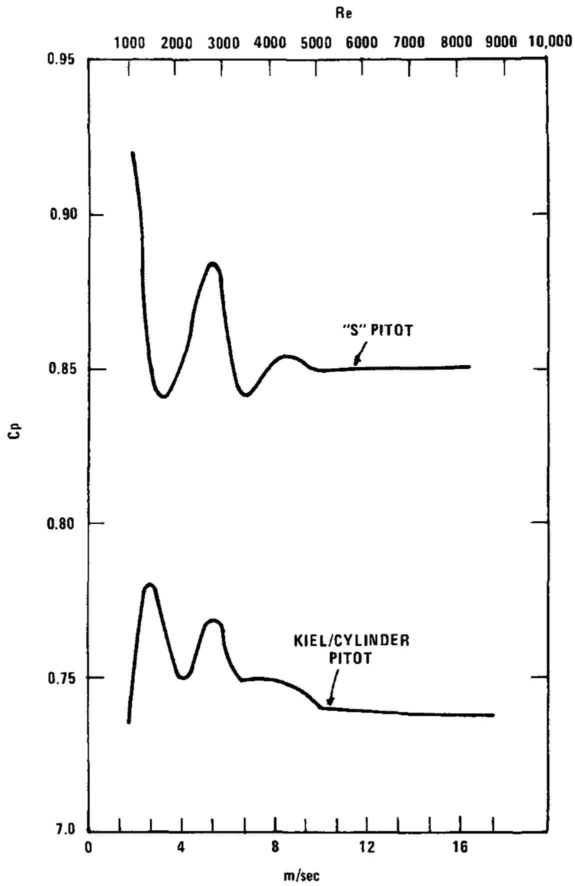


Figure C-3. Correlation of pitot coefficient and Reynolds' number at 35oC for "S" and Kiel/cylinder pitot tubes.

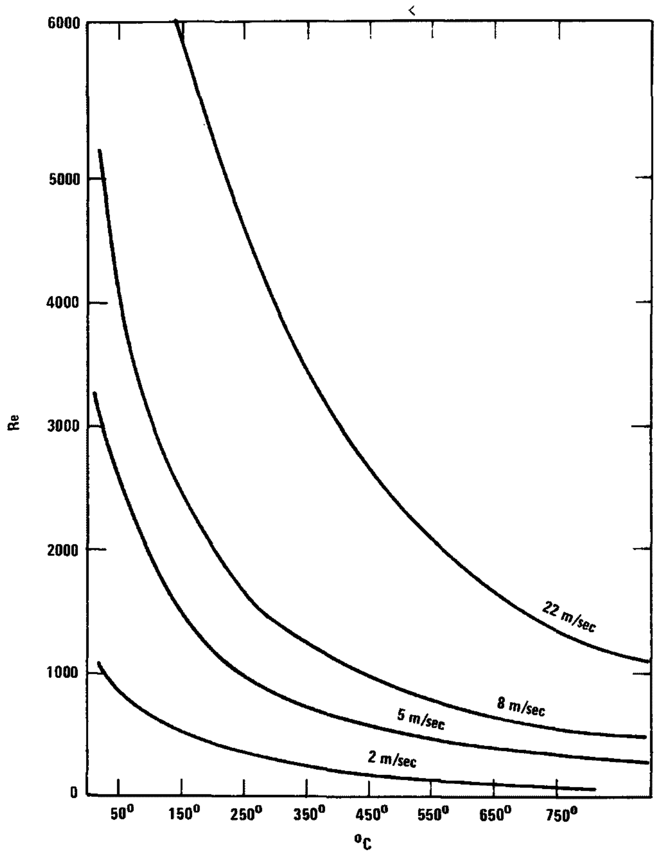


Figure C-4. Reynolds' number as a function of velocity for a 0.95 cm O.D. pitot tube.

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

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16. ABSTRACT

Five pitot tube designs were tested under various gas flow conditions for accuracy in measuring static and total pressure. The static- and impact-pressure measuring tubes least affected by angular flow were combine and then evaluated in the presence of standard particulate sampling nozzles. Tests were performed on "S", "L", Kiel and cylinder pitot tubes and a shielded static-pressure pitot tube. The percent error for each pitot tube was determined as a function of yaw, pitch, orifice size, orifice location, pitot tube size, and velocity. A pitot tube was developed that is accurate within 5% when yawed and pitched ± 30° even while attached to a standard EPA Method 5 sampling assembly. This pitot tube was field tested at a sewage sludge incinerator, a clay crushing plant and a power plant. Also included in the report are: a summary of the existing literature on design of "L" pitot tubes; a summary of the present state-of-the-art in sampling stacks with cyclonic flow and the errors involved in such sampling; a recommendation for straightening cyclonic flow by insertion of a venturi throat; and the effect of Reynolds Number on pitot tube accuracy.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Velocity measurement "S", "L", ASME, Kiel/cylinder pitot tubes Cyclonic Flow Reynolds Number	Yaw Error Pitch-Error	68A 43F

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