2.16 Pitot Tubes and Area Averaging Units


Types
A. Standard, single-ported
B. Multiple-opening, averaging
C. Area averaging for ducts

Applications
Liquids, gases, and steam

Operating Pressure
Permanently installed carbon or stainless-steel units can operate at up to 1400 PSIG (97 bars) at 100°F (38°C) or 800 PSIG (55 bars) at approximately 700°F (371°C); pressure rating of retractable units is function of the ratings of the isolating valve

Operating Temperature
For permanent installations, up to 750°F (399°C) in steel and up to 850°F (454°C) in stainless-steel construction

Flow Ranges
Can be used in pipes or ducts in sizes 2 in. (50 mm) or larger; no upper limit

Materials of Construction
Brass, steel, stainless steel

Minimum Reynolds Number
In the range of 20,000 to 50,000

Rangeability
Usually limited to 3:1

Straight-Run Requirements
Twenty-five to 30 pipe diameters upstream and 5 downstream are required if the pitot sensor is located downstream of a valve or of two elbows in different planes; if straightening vanes are provided, this requirement is reduced to 10 pipe diameters upstream and 5 downstream

Inaccuracy
For standard industrial units: 0.5 to 5% of full scale. Industrial pitot venturies must be individually calibrated to obtain 1% of range performance. Full-traversing pitot venturies under laboratory conditions meeting the National Bureau of Standards can limit the error to 0.5% of actual flow. Inaccuracies of individually calibrated multiple-opening averaging pitot tubes, when Reynolds numbers exceed 50,000, are 2% of range. The errors of area-averaging duct units are claimed to be between 0.5 and 2% of span. The errors listed above do not include that of the d/p cell, which is additional.

Costs
The cost of the pitot tube itself in case of a 1-in. dia. averaging tube in stainless-steel materials is $800 if fixed and $1500 if retractable for hot-tap installation. Hastelloy* units for smokestack applications can cost $2000 or more. A local pitot indicator cost $500; a d/p transmitter suited for pitot applications costs about $1,500. Calibration costs are additional and can amount to $1000/tube.

Partial List of Suppliers
ABB Automation Instrumentation (www.abb.com/us/instrumentation) (A)
Air Monitor Corp. (www.airmonitor.com) (C)
Alnor Instrument Co. (www.alnor.com) (A)
Blue White Industries (www.bluwhite.com) (A)
Brandt Instruments (www.brandt.com) (C)
Dietrich Standard (www.annubar.com) (Annubar—B)
Dwyer Instruments Inc. (www.dwyer-inst.com) (B)

© 2003 by Béla Lipták
For the measurement of the velocities of fluids, in 1732, Henri de Pitot invented the pitot tube. Pitot tubes detect the flowing velocity at a single point (standard), at several points that lead into an averaging probe (multiported), or at many points across the cross section of a pipe or duct (area-averaging). Their advantages are low cost, low permanent pressure loss, and the capability of inserting the probe-type sensors into the process pipes while the system is under pressure (wet- or hot-tapping). The disadvantages of pitot tube-type sensors are low accuracy, low rangeability, and the limitation of being suitable only for clean liquid, gas, or vapor service unless purged.

**THEORY OF OPERATION**

The impact pressure on a body, which is immersed in a moving fluid is the sum of the static pressure and the dynamic pressure. Thus,

\[ P_t = P + P_v \]  \hspace{1cm} (2.16(1))

where

- \( P_t \) = total pressure, which can be sensed by a fixed probe when the fluid at the sensing point is in an isentropic state (constant entropy)
- \( P \) = static pressure of the fluid whether in motion or at rest
- \( P_v \) = dynamic pressure caused by the kinetic energy of the fluid as a continuum

With respect to the energy relation at the isentropic stagnation point of an ideal probe,

\[ \int_P^p \frac{dp}{\rho} = \int_0^{v_p} \frac{v_p dv}{g_c} \]  \hspace{1cm} (2.16(2))

where

- \( v_p \) = approach velocity at the probe location
- \( \rho \) = fluid density
- \( g_c \) = a constant

For a liquid of constant density, integration yields, at a point,

\[ (P_t - P) = P_v = \frac{P_v^2}{2g_c} \]  \hspace{1cm} (2.16(3))

For a compressible perfect gas for which \( \frac{P}{P_t} \) remains constant during an isentropic change, a similar relation emerges.

\[ (P_t - P) = P_v = \frac{P}{\gamma} \left( \frac{V_p^2}{2g_c} \right) \]  \hspace{1cm} (2.16(4))

where \( \gamma \) = ratio of specific heats.

Assuming isentropic stagnation at the sensing point of the probe,

\[ \int_P^p \frac{dp}{\rho} = \int_0^{v_p} \frac{V_p^2 dv}{g_c} \]  \hspace{1cm} (2.16(5))

where, using English units,

- \( V_p \) = velocity of approach, ft/s
- \( P \) = pressure, lbf/ft\(^2\)
- \( \rho \) = fluid density, lbm/ft\(^3\)
- \( g_c = 32.2 \ \text{lbm} \text{ft}^{-1} \text{s}^{-2} \)

If density is constant, integration yields

\[ (P_t - P) = P_v = \frac{P (V_p^2)}{2g_c} \]  \hspace{1cm} (2.16(6))

For a compressible perfect gas, the ratio \( \frac{P}{P_t} \) remains constant during an isentropic change, and a similar relation is obtained.

\[ (P_t - P) = P_v = \left( \frac{\gamma - 1}{\gamma} \right) \frac{P (V_p^2)}{g_c} \]  \hspace{1cm} (2.16(7))

where \( \gamma \) is the ratio of specific heats.

To compute the fluid velocity at a particular point, it is necessary to measure the values of both the static pressure and the total pressure.

*Fig. 2.16a*

The velocity at a point (in the turbulent flow range) is related to the square root of the pressure difference between total and static pressures.
2.16 Pitot Tubes and Area Averaging Units

279

\[ P_t = -C \frac{(P - P)}{\rho} \]  

whence

\[ V_p = C \frac{(P - P)^{0.5}}{\rho} \]  

where \( C \) = a dimensional constant.

**PRESSURE DIFFERENTIAL PRODUCED**

One of the problems with pitot tubes is that they do not generate strong output signals. The d/p cells available are discussed in Chapter 5, under “Pressure Measurement.” The minimum span of a “smart” d/p cell is 0 to 2 in. of H\(_2\)O (0 to 0.5 kPa). These smart d/p cell units are accurate up to 0.1% of actual span. For narrower differentials, down to 0 to 0.1 in. H\(_2\)O (0 to 25 Pa), the membrane-type d/p cells can be used.

In addition to using d/p cells, one can also install elastic element or manometer-type readout devices, variable-area flowmeters (Figure 2.16b), or thermal flowmeters (Figure 2.16c) as pitot tube detectors. The thermal detector gives the highest rangeability, but it can be used only if the pitot tube is purged.

**STATIC PRESSURE MEASUREMENT**

In process fluids flowing through pipes or ducts, the static pressure is commonly measured in one of three ways: (1) through taps in the wall, (2) by static probes inserted into the fluid stream, or (3) by small apertures located on an aerodynamic body immersed in the flowing fluid.

The data of Shaw\(^1\) (presented by Benedict\(^2\)) show that errors in the measurement of static pressure are minimal for velocities up to 200 ft/s (60 m/s) if the wall tap dimensions conform to those in Figure 2.16d, where the tap diameter \( d \) is 0.0635 in., the sensing tube ID \( = 2d \), and the tap length-to-diameter ratio \( l/d \) is 1.5 < \( l/d < 6 \).

Static pressure errors also depend on fluid viscosity, fluid velocity, and whether the fluid is compressible. Shaw\(^1\) states that, for incompressible fluids flowing in a circular conduit with a pipe Reynolds number of \( 2 \times 10^5 \), an error of about 1% of the mean dynamic pressure may occur using a wall tap with a diameter 1/10th that of the pipe. Rayle\(^3\) mentions that a tap diameter of 0.03 in. (0.75 mm) with a conical countersink 0.015 in. (0.34 mm) deep will ensure nearly true static pressure sensing.

Static pressure may also be sensed through a tube inserted into the moving fluid. One configuration is shown in Figure 2.16e.

Other static probe designs are also described in the literature.\(^2\) The aerodynamic probe is a bluff body inserted into the flowing fluid with appropriately located holes on its surface through which pressure signals are obtained. The probe is oriented so that the sensed pressure is a measure of the static pressure. Two configurations taken from Benedict,\(^2\) the cylinder and the wedge, are shown in Figure 2.16f. The probes are rotated until the pressure sensed from each hole is the same or, alternatively, the two taps may be manifolded to obtain an averaged pressure.
The total pressure develops at the point where the flow is isentropically stagnated, which is assumed to occur at the tip of a pitot tube or at a specific point on a bluff body immersed in the stream. Figure 2.16g illustrates a typical pitot tube, also showing the taps for sensing static pressure. Another variation is shown in Figure 2.16h.

**SINGLE-PORTED PITOT TUBE**

Pitot tubes are sensitive to flow direction and must be carefully aligned to face into the flow. This can be difficult if the flow direction is caused to vary by changes in turbulence. The pitot tube is made less sensitive to flow direction if the impact aperture has an internal bevel of about 15° extending about 1.5 diameters into the tube. The characteristics of various designs and orientations are discussed in Benedict. Figure 2.16i illustrates the typical performance of a pitot tube.

Pitot venturi and double-venturi elements have been developed to amplify the pressure signals generated by the in-stream velocity sensors, as shown in Figures 2.16j and 2.16k. These elements are intended to remain in a fixed position, so their measurements must be converted to flow rate through calibration, which accounts for the properties of
the fluid and the velocity profile (e.g., Reynolds number). To obtain a stable velocity profile, it is recommended that a smooth, straight section of pipe, of a length equaling at least 10 to 15 pipe diameters, be provided both upstream and downstream of the probe.

To determine the average velocity in a pipe, it is necessary to traverse it with a pitot tube. For circular pipes, such an average is obtained from measurements of \( P - P \) on each side of the cross section at the following locations, expressed in percentage of the diameter measured from the center:

\[
\frac{2n - 1}{N} \times 100\%, \quad n = 1, 2, 3K \frac{N}{2}
\]

where \( N \) is the number of measurements per traverse. Two measurements normal to each other are recommended.

To improve the measurements made near the walls of pipes that are more than 6 in. (150 mm) in diameter, a reduction nozzle is inserted into the pipeline (Figure 2.16i).
Flow Measurement

Calibration of Pitot Tubes

In high-precision laboratory tests, the pitot tube is traversed across the cross-section of the pipe, thereby establishing the velocity profile that exists in the pipe. In industrial applications, the pitot tube is fixed and measures the flow velocity only at one point on the velocity profile (Figure 2.16m). If the velocity \( U \) measured by this fixed pitot tube is not the average velocity \( V \), a substantial error will result. This error cannot be easily eliminated because, even if the pitot tube insertion is carefully set to measure the average velocity \( V \) under one set of flow conditions, it will still be incorrect as soon as the flow velocity changes. At Reynolds numbers under 1000 (in the fully laminar region), the ratio between the average velocity and the center velocity is 0.5 (\( V/U_c = 0.5 \) in Figure 2.16m). In fully developed turbulent flow (\( Re = 50,000 \) or more), this same ratio is about 0.81 (\( V/U_c = 0.8 \)).

Unfortunately, the velocity profile is affected not only by the Reynolds number but also by the pipe surface roughness and by upstream valves, elbows, and other fittings. To reform the velocity profile, it is recommended to provide a straight pipe length of about 25 pipe diameters between the upstream disturbances and the pitot element.

If the data for calculating the Reynolds number is available, and if the pitot tube is installed in a pipe with smooth inner surface, it should be possible to design a microprocessor-based smart pitot tube that measures only the center velocity \( U_c \) and, based on that reading, accurately calculates the flow under all flow conditions.

The National Bureau of Standards calibrates pitot tubes by mounting them on a carriage, which is drawn through stagnant air at a known velocity. Smoke is introduced into the room to verify that the air is stagnant—that there is no turbulence. Such tests have shown that pitot tubes with coefficients very close to unity can be designed. Devices such as pitot-venturies or double venturies can provide flow rate measurements with less than 1% error, but only after extensive in situ calibration for each installation.

MULTIPLE-OPENING PITOT TUBES

One approach in attempting to overcome the inherent limitation of the pitot tube—that of being a point velocity sensor—was to measure the velocities at several points and average these readings. It was argued that, by averaging the velocities measured at four fixed points, for example (see Figure 2.16n), changes in the velocity profile will be detected, and therefore the reading of a multiple-opening pitot tube will be more accurate than that of single-point sensors.

The manufacturers of averaging pitot tubes usually claim that the flow coefficient \( K \) will stay within 2% between the Reynolds numbers of 50,000 and 1,000,000. This is probably so, but it might not be attributable to averaging action but rather to the fact that, in this highly turbulent region, the velocity profile is flat and changes very little.

Critics of this device argue that it offers little improvement over the single-opening pitot tube, because it is ineffective at Reynolds numbers below 50,000. This means that it is not applicable for the measurement of a large portion of industrial liquid flows. The other argument made by critics is that the averaging pitot tube openings are too large and,
consequently, these devices are not true averaging chambers; rather, the sensed pressure is dominated by the pressure at the nearest port. For these reasons, further testing by independent laboratories is still needed.

The reason for making the ports of the averaging pitot tubes so large is to prevent plugging. Some manufacturers of area-averaging pitot tubes do overcome this limitation by purging, because the small port openings are kept clean by the purge gas, and these units can act as true averaging chambers. Naturally, they can be used only on processes in which the introduction of a purge media is acceptable.

One advantage of the averaging pitot tubes that both its manufacturers and its critics agree on is their ability to be installed into operating, pressurized pipelines. This hot-tapping capability, and the ability to remove the sensor without requiring a shutdown, are important advantages of all probe-type instruments (Figure 2.16o).

In calculating the pressure differential produced by an averaging pitot tube, one might use the equations listed in Table 2.16p. For the metric equivalents of the units used in this table, refer to the Appendix. The flow coefficient (K) of the pitot tube varies with its design. The K values of the averaging pitot tube shown in Figure 2.16n are listed in Table 2.16q. The distance “A” used in Table 2.16q is also defined in Figure 2.16n.

### AREA-AVERAGING PITOT STATIONS

Area-averaging pitot stations have been designed for the measurement of large flows of low-pressure gases. Measurements include the flow rate of combustion air to boilers, air flow to dryers, and air movement in HVAC systems. These units are available with circular or rectangular cross sections (Figures 2.16r and 2.16s) and can be mounted in the suction or discharge of fans or in any other large pipes or ducts. These stations are designed so that one total pressure detection port and one static pressure sensing port are located in each unit area of the cross section of the duct, and they each are

---

**TABLE 2.16p**

<table>
<thead>
<tr>
<th>Equation Description</th>
<th>Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid, gas, steam (mass rate of flow)</td>
<td>( h_w = \frac{1}{K} \left( \frac{lb_{/hr}}{358.94KD^2} \right)^2 )</td>
</tr>
<tr>
<td>Liquid (volume rate of flow)</td>
<td>( h_w = (G_f/\rho_f) \left( \frac{GPM}{5.666KD^2} \right)^2 )</td>
</tr>
<tr>
<td>Gas (standard volumetric flow)</td>
<td>( h_w = \left( \frac{T_f}{\rho_f} \right) \left( \frac{SCFH}{7.711KD^2} \right)^2 )</td>
</tr>
<tr>
<td>Gas (actual volume rate of flow)</td>
<td>( h_w = \left( \frac{ACFH}{358.94KD^2} \right)^2 )</td>
</tr>
</tbody>
</table>

* Courtesy of Dietrich Standard.
Flow Measurement

connected to their own manifold. The manifolds act as averaging chambers, and they are also purged to protect the sensing ports from plugging.

The straight-run requirement of these units is reduced by the addition of a hexagon-cell-type flow straightener and a flow nozzle in front of the area-averaging flow sensor. This nozzle also serves to amplify the differential pressure produced by the unit (Figure 2.16s). According to the manufacturer, this design (Figure 2.16s) reduces the straight-run requirement of most installations to a range of 0 and 10 diameters. The longest straight run (10 diameters) is recommended when the flow meter is installed downstream of a butterfly valve or a damper.

Because these area-averaging pitot stations generate very small pressure differentials, special d/p cells are required to detect these minute signals. One such detector is the membrane-type design (Fig. 2.16t), which can have a span as small as 0 to 0.01 in. H₂O (to 2.5 Pa). When such extremely small pressure differentials are detected, the pressure drop in the tubing between the d/p cell and the pitot station must

<table>
<thead>
<tr>
<th>Paper Size</th>
<th>Flow Coefficient-K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size/Sch</td>
<td>D-in</td>
</tr>
<tr>
<td>2&quot; sch 40</td>
<td>2.067</td>
</tr>
<tr>
<td>2\frac{1}{4}&quot; sch 40</td>
<td>2.469</td>
</tr>
<tr>
<td>3&quot; sch 40</td>
<td>3.068</td>
</tr>
<tr>
<td>3\frac{1}{4}&quot; sch 40</td>
<td>3.548</td>
</tr>
<tr>
<td>4&quot; sch 40</td>
<td>4.026</td>
</tr>
<tr>
<td>5&quot; sch 40</td>
<td>5.047</td>
</tr>
<tr>
<td>6&quot; sch 40</td>
<td>6.065</td>
</tr>
<tr>
<td>8&quot; sch 40</td>
<td>7.981</td>
</tr>
<tr>
<td>10&quot; sch 40</td>
<td>10.020</td>
</tr>
<tr>
<td>12&quot; sch std.</td>
<td>12.000</td>
</tr>
<tr>
<td>14&quot; sch std.</td>
<td>13.250</td>
</tr>
<tr>
<td>16&quot; sch std.</td>
<td>15.250</td>
</tr>
<tr>
<td>18&quot; sch std.</td>
<td>17.250</td>
</tr>
<tr>
<td>20&quot; sch std.</td>
<td>19.250</td>
</tr>
<tr>
<td>24&quot; sch std.</td>
<td>23.250</td>
</tr>
<tr>
<td>30&quot; sch std.</td>
<td>29.250</td>
</tr>
<tr>
<td>36&quot; sch std.</td>
<td>35.250</td>
</tr>
<tr>
<td>42&quot; sch std.</td>
<td>41.250</td>
</tr>
<tr>
<td>48&quot;</td>
<td>48.00</td>
</tr>
<tr>
<td>60&quot;</td>
<td>60.00</td>
</tr>
<tr>
<td>72&quot;</td>
<td>72.00</td>
</tr>
</tbody>
</table>

*Courtesy of Dietrich Standard.

**TABLE 2.16q**

The Flow Coefficient K for the Averaging Pitot Tube Shown in Figure 2.16n Having the “A” Dimension Also Defined in That Figure*

*FIG. 2.16r*

Installation in rectangular duct of area-averaging pitot tube ensembles for metering the flow rate of gases. (Courtesy of Air Monitor Corp.)

© 2003 by Béla Lipták
be minimized. This is achieved by making the connecting tubes short and large in diameter. The pressure differential generated by the flow element shown in Figure 2.16s can be calculated by using the equations in Table 2.16u. For the equivalent SI units for use in these equations, refer to the Appendix.

**SPECIAL PITOT TUBES FOR PULSATING FLOW**

The mean velocity measurements of unsteady flows, if made by conventional pitot tubes, are usually inaccurate. In such measurements, one can expect errors in the range of 5 to 30% of mean total pressure. This measurement can be improved by using specially designed probes when the application involves unsteady or pulsating flows.

Figure 2.16v shows a design provided with a low-capacity capillary probe filled with silicon oil. The oil serves to transmit the process pressure to the d/p transducer. This type of probe was developed and is used by Deutsche Forschungs- und Versuchsanstalt für Luft und Raumfahrt in Germany.

Figure 2.16w shows another example of a probe designed to measure unsteady flow. This probe was developed in the Aeronautical Research and Test Institute in Czechoslovakia. The main design challenge in this design is to equalize the resistances in the input and output openings of the probe. Also, to protect against resonance during measurement, the natural frequency of the probe must be carefully tuned.

<table>
<thead>
<tr>
<th>Equations for Differential Pressure Calculation</th>
<th>Terms Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>( DP = \left( \frac{ACFM}{Area} \right)^2 \times \frac{DENS}{(1096.845)^2} )</td>
<td>Area = Cross-sectional area of duct section in ft²</td>
</tr>
<tr>
<td>( DP = \left( \frac{SCFM}{4000.7 \times Area} \right)^2 )</td>
<td>ACFM = Actual cubic feet per minute</td>
</tr>
<tr>
<td>( DP = (V)^2 \times \frac{DENS}{(1096.845)^2} )</td>
<td>( DP ) = Differential pressure in inches w.c.</td>
</tr>
<tr>
<td>( DP = \left( \frac{M}{60 \times Area} \right)^2 \times \frac{1}{DENS \times (1096.845)^2} )</td>
<td>( M ) = Mass flow in pounds per hour</td>
</tr>
<tr>
<td></td>
<td>SCFM = Standard cubic feet per minute</td>
</tr>
<tr>
<td></td>
<td>( V ) = Velocity in feet per minute</td>
</tr>
<tr>
<td></td>
<td>PABS = Absolute pressure in PSI</td>
</tr>
<tr>
<td></td>
<td>PATM = Atmospheric pressure in PSI</td>
</tr>
<tr>
<td></td>
<td>Ps = Static pressure in inches w.c.</td>
</tr>
<tr>
<td></td>
<td>( T ) = Temperature in degrees F</td>
</tr>
<tr>
<td></td>
<td>DENS = Density at actual conditions lbs/ft³</td>
</tr>
<tr>
<td></td>
<td>DENSTD = Density at standard conditions lbs/ft³</td>
</tr>
</tbody>
</table>

*Courtesy of Brandt Instruments.*
On highly pulsating flow measurements a minute flow of silicon oil through a capillary can serve as a pressure-averaging purge.

FIG. 2.16w
Pitot tube designed for pulsating flow averaging using tuned natural frequency.

References

6. Neruda, J. and Soch, P., Measurement System with a Pitot Tube, Czechoslovak patent no. 218417.

Bibliography

Hiser, R., Increased functions and reduced costs of differential pressure flowmeters, Meas. Control, September 1990.
Malherbe, G. and Silberberg, S., Device for measuring the flow of pulverized control, central electricity generating board, Translation CE 4938 from Automatism, 13(3) 114–122, 1968.