Evolution of the Pitot Tube Sensor

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In the field of fluid velocity measurement, the Pitot Tube has enjoyed a good reputation in university centers for a long time.

However, with the types of flow encountered in industry, the standard Pitot Tube has been supplanted by other, increasingly sophisticated instruments.

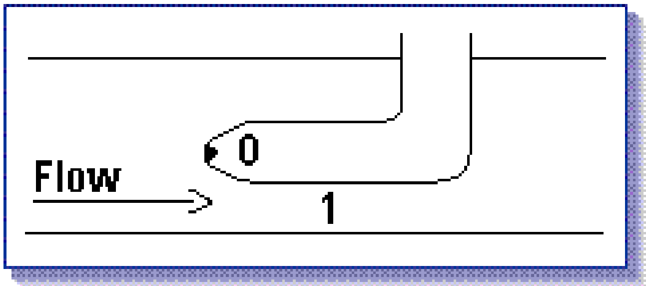
The purpose of this article is to analyze the evolution of these diverse averaging Pitot Tubes, and compare the advantages of the different types.

STANDARD PITOT TUBE: PRINCIPLE

The Pitot Tube is a direct application of the Bernoulli theorem where total energy remains a constant in a flow.

$$P + \varrho g H + 1/2 \ \varrho V^2 = \text{CONSTANT}$$

The Pitot Tube measures the differential pressure in a flow between point 1 where $V_1 = V_{flow}$ and point 0 where $V_0 = O$.



Since $H_0 = H_1$, the equation becomes:

$$P_1 + 1/2 \quad V^2_1 = P_0 + P_1$$

$$V_1 = \sqrt{\frac{\triangle P.\,2}{\varrho}} = \text{Vflow}; \ \triangle P = P_0 - P_1$$

The basic equation at flowing conditions in consistent units is thus in Customary Units:

$$Q_m = A\sqrt{2 \ x \varrho \ \ x \triangle P} \quad ; Q_V = Q_m/\varrho$$

The working equations may require modifications outlined by the different manufacturers. These modifications may include, but are not limited to:

- Specific gravity factor
- Manometer factor
- Location factor
- Pipe area change due to thermal expansion
- Pipe area change due to internal pressure
- Reynolds number factor

AVERAGING PITOT TUBE: DESCRIPTION

The term “Multiport Averaging Pitot Primary Flowmeter” covers a family of head-type devices with greatly varying design detail and one thing in common, i.e. they all sense a differential pressure due to the fluid velocity in the closed conduit which can be related to the volumetric or mass-flow rate.

The high pressure signal is the average of the impact pressures generated at the upstream multiple ports by partially or completely stagnating the fluid flow and is always a pressure higher than line static pressure. The averaging of the pressure at the sensor multiple ports can be either internal or external to the conduit.

The low pressure signal is the pressure from a single port or the average of multiple ports sensing the pressure downstream of the

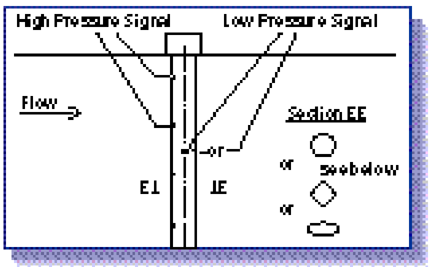


Figure 1.

sensor. This pressure can be equal to or lower than the static line pressure depending on the arrangement of the sensing port(s). The averaging of the pressure at the sensor multiple ports can be either internal or external to the conduit.

INSTALLATION EFFECTS FOR MULTIPORT: AVERAGING PITOT FLOWMETERS

The deviation of the actual velocity distribution in the conduit from a fully developed flow profile may affect the performance of the flowmeter. The flow profile deviation can be caused by the in-line equipment, piping configurations and installations, and disturbances upstream and downstream of the flowmeter. Improper installation of the flowmeter and its components can impair the performance of the flowmeter.

The manufacturer’s performance specifications should include a statement of the reference condition under which the flow coefficient and uncertainties were determined. The flowmeter performance can be affected by velocity distribution (e.g. profile, swirl, secondary flows), pulsation in the pipe flow, and mounting conditions (e.g. alignment and orientation).

UPSTREAM AND DOWNSTREAM PIPE LENGTH REQUIREMENTS

The minimum upstream and downstream straight lengths of pipe required to meet the performance specification of the flowmeter should be stated by the manufacturer. The minimum lengths required downstream of different types of valves and pipe fittings may vary for each flowmeter installation and piping configuration.

In the event the flowmeter installation condition does not match one of the manufacturers listed installation conditions, the flowmeter manufacturer should be consulted before installing the flowmeter or the flowmeter can be calibrated in-situ.

CONDUIT INTERNAL SURFACE CONDITION

Surface roughness of the flow conduit can affect the velocity distribution at the metering location, thereby affecting the performance of the flowmeter. If the conduit surface is different from the surface of a commercially available new pipe, the flowmeter manufacturer should be consulted.

FLOW CONDITIONER

Insufficient lengths of conduit upstream and downstream of the flowmeter can affect its performance.

> Surface roughness of the flow conduit can affect the velocity distribution at the metering location, thereby affecting the performance of the flowmeter.

When space for the flowmeter installation is limited, the upstream and downstream straight pipe lengths may need to be shorter than the minimum allowable lengths specified in the installation manual. Consult the manufacturer to determine if the use of flow conditioners will allow shorter upstream and downstream straight lengths.

REMEDIAL STEPS FORABNORMAL INSTALLATIONS

Conditions that cannot be corrected with the use of a flow conditioner, or corrections for abnormal installations, may be resolved by consulting the manufacturer or performing an in-situ calibration. In-situ calibration establishes the flow coefficient and uncertainty under actual operating conditions. The calibration should be done according to acceptable standards identified by method. These standards are e.g.:

- Weighing Method for Liquids - ANSI/ASME MFC-9M
- ISO 4185 Volumetric Method for Liquids - ASME MFC-10M (in preparation)

Body Shape			C_v	Reynolds Number
Circular Cylinder	→		1.2	10^4 to 1.5×10^5
Elliptical Cylinder	→		0.6	4×10^4
		2:1	0.46	10^5
	→		0.32	2.5×10^4 to 10^5
	→	4:1	0.29	2.5×10^4
		8:1	0.20	2×10^5
	→		2.0	3.5×10^4
Square Cylinder	→		1.6	$10^4 \times 10^5$
Triangular Cylinders	→	120°	2.0	10^4
	→	120°	1.72	10^4
	→	90°	2.15	10^4
	→	90°	1.60	10^4
	→	60°	2.20	10^4
	→	60°	1.39	10^4
	→	30°	1.8	10^5
	→	30°	1.0	10^5
	→		2.3	4×10^4
Semitubular	→		1.12	4×10^4

Table 1: Typical drag coefficients for various cylinders in two dimensional flow.
Data from W.F- Lindsey, NACA Tech.Rep.619.

- ISO DIS 8316 Critical Flow Nozzles for Gas ANSI/ASME MFC-7M 1987

POSITION ON PIPE

The primary station can be installed in any position on vertical or horizontal lines. However, for the best result on horizontal liquid lines where the risk of air/gas entrapment in the meter tubing is prevalent, install the element with the head under the horizontal center line. For horizontal air or gas lines, the head should be above the center line to prevent condensation.

EVOLUTION OF THE SHAPE

The distinguishing factor amongst intrusive models is the probe shape The shape of the probe dictates the fluid flow separation point(s) - that point at which the laminar flow of the fluid sub-boundary layers around the probe body separate/detach from the body.

This point of separation is critical to the accuracy of low pressure port measurements in the three prominent annular pitot tube models are discussed.

Fluid flows have long been studied by physicists and engineers. Concurrently, the devices developed to measure flow have largely adhered to the findings of these researchers.

> A new design has been developed based on the aerodynamics and streamlining theories.

Obviously, in order to measure flow with a minimum of error and with an acceptable degree of repeatability, the true nature and rate of flow must be perturbed as little as possible by the measuring device.

When a given fluid traveling in a turbulent fashion comes in contact with an obstacle in its flow path the nature of the flow is altered. From the point at which the fluid comes in contact with the obstacle body, the fluid's sub-boundary layers (those fluid layers in immediate contact with the obstacle body) are rendered laminar.

The fluid will continue its smooth passage along the obstacle's surface for a distance which varies according to the shape of the obstacle. At some point along; or shortly past, the obstacle, the fluid's sub-boundary layers (those fluid layers in immediate contact with the obstacle body) will separate from the obstacle's surface — the laminar nature of the sub-boundary layers will be disrupted.

This separation marks the beginning of the region in which the rate and nature of the flow is most significantly perturbed. Measurements taken within this region are subject to significant errors. Variable intensity vortices and a vacuum region are inevitably created along the flow path following the point(s) of separation.

Pressure losses also have to be analyzed. In Table 1, typical drag coefficients are shown for several cylinders.

In general, the values given are for the range of Reynolds numbers in which the coefficient changes little with the Reynolds number. In each case, the drag coefficient C_v is defined by:

$$\text{Drag} = \frac{C_v A \ \rho V^2}{2}$$

in which A is the projected area of the body on a plane normal to the flow.

Now let us examine the designs of the three sensors known best within the industry, as they relate to flow perturbances, measuring accuracies and reliability.

The first generation of pilot tubes introduced was a cylindrical annular model, where high and low pressure sensing ports were located on the upstream and downstream surfaces of the sensor body respectively.

Referring to Figure 2 and to our mention of laminar flow, it is evident that the low pressure sensing port of this model is located in an area subject to two sources of measuring error variable intensity vortices and vacuum.

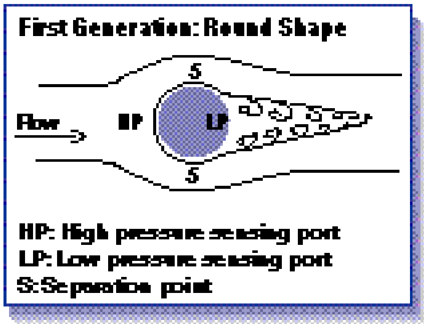


Figure 2

In addition to the variations registered in the low pressure signal due to the vortices, the cylindrical model enjoys a turndown ratio of only 4 to 1. in turn, this low turndown ratio creates variations in the vacuum which further has an impact upon the variations of the low pressure signal.

Finally, the variable intensity vortices cause the cylindrical probe to vibrate and produce sound waves which are transmitted to the secondary instrumentation (transmitter, gauge, flow computer, etc.) and contribute to a reduced repeatability of measuring performance. Accuracy is between 1.5% to 3%. Pressure losses are rather high: drag coefficients equal 1.2 (see Table 1).

In an effort to reduce low pressure port inaccuracies, a second generation of sensor tubes was developed which was square in shape. The square probe is oriented such that its axis of gyration is parallel to the flow velocity vector. The purported advantage to this design is that the points of fluid flow sub-boundary layer separation are fixed/known.

Referring to Figure 3, we observe that the same perturbing effects are realized — vortices and a vacuum are in evidence. The diamond shape of the probe referred to as a "bluff" probe body by engineers obstructs the flow in a manner different to that in Figure 2.

High intensity vortices occur in the perturbed region downstream from the fluid separation points, and a more pronounced inaccuracy of the low pressure reading results.

As with the cylindrical model, the separation of the fluid flow sub-boundary layers from the probe body occurs upstream to the low pressure sensing port.

The resulting disruption of the normal turbulent flow within the pipe results in a turndown ratio of 10 to 1, with purported accuracies of ±1%. Repeatability of the diamond-shaped probe (±0,1%) is higher than that of the cylindrical probe since vortices of the former are less variable in nature. Pressure losses are very high: drag coefficient equals 1.6 (see Table 1).

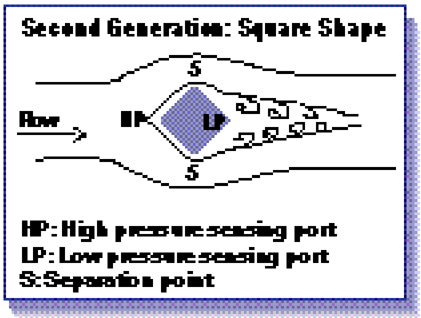


Figure 3.

A new design has recently been developed based on the aerodynamics and streamlining theories. In answer to the problems addressed above, the low pressure sensor ports were located on the elliptical sensor body prior to that point at which the fluid flow sub-boundary layer detaches from the probe.

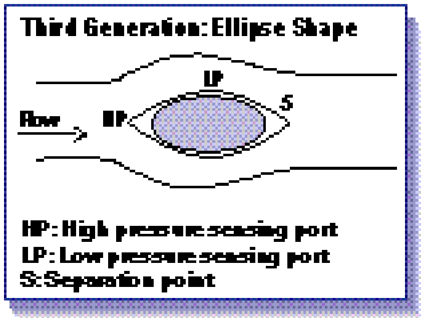


Figure 4.

Referring to Figure 4, the difference in probe shape clearly offers several advantages. Normal laminar flow continues across (and past) the low pressure sensing ports located along either side of the elliptical sensing body. Thus the low pressure measurement registered is a more accurate portrayal of the true rate of flow at this point.

Indeed, the separation region (SR) occurs downstream from the low pressure port to produce flow perturbations at points removed from the point of measurement Due to the elliptical shape of the probe, the sub-boundary layers separate from the body without producing fluid vortices, turbulence or vacuums. Hence the probe vibrations suffered by the cylindrical model are avoided in the elliptical probe.

With the elliptical model, accuracies of ±3/4% are ensured over a flow turndown ratio of 17:1, while repeatability is ±0, 1%. Pressure losses are the lowest: typical drag coefficient equals 0.32 (see Table 1).

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