Transducers in Fluid Flow Applications

Technical Note

INTRODUCTION

People have been building fluid systems for many millennia and the knowledge of how to measure pressure in the fluids is centuries old. So what's so special about the line of transducers introduced by Honeywell? In a nutshell, the solid state transducer allows much better sensing and, therefore, much better control of fluid systems for a given amount of money spent on system control.

To give the electrical engineer a better understanding of the strange worlds of mechanical, chemical, aeronautical, civil, and acoustical engineers, we will describe the three basic classes of transducer applications. All transducer usages will fit into one of the following categories:

1. Pressure Vessel
2. Open Flow
3. Closed Flow

Each is thoroughly described and the key equations of each class are derived.

For a mental model think of "open flow" as represented by the flow of a fluid in which the main energy involved is simply kinetic. Water in an aqueduct or a long pipe where the potential energy at the dam up in the mountains or the compressive energy of the pump, has long since been converted to the kinetic energy of the flowing stream.

For "closed flow," think of a compressor as used for example in refrigeration systems. Here the fluid density is changing and thus significantly contributing to the energy of the system, still primarily kinetic.

In a "pressure vessel" a stationary fluid is assumed.

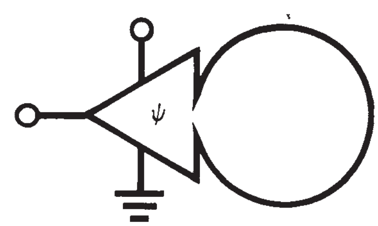
Now on to the system modeling.

"PRESSURE VESSEL" APPLICATION

The simplest application of an absolute pressure transducer is the direct measurement of absolute pressure of a fluid at rest within a pressure vessel.

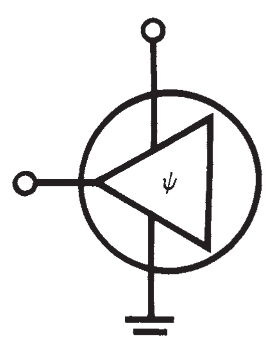
The concept of a pressure vessel is very general here ... it merely represents that container of fluid which keeps the fluid free of dynamics. Thus, using this broad view, on a calm day the world is a pressure vessel. Likewise, a vacuum chamber is a pressure vessel. As indicated in Figure 1, the sensor can be plumbed into the pressure vessel, thus adding its own package volume and that of the plumbing to the volume of the pressure vessel. Where the pressure vessel is small, this additional volume must be considered if the measurement or control function involved seeks some relationship between pressure and volume.* It is important to recognize that the change in volume of the transducer package with pressure change is entirely negligible.

FIGURE 1



As indicated in Figure 2, the sensor can be totally enclosed within the pressure vessel, working fluid chemistry allowing, so that little volume change in the system is experienced. When the volume of the vessel is large compared to that of the sensor package, as is usually the case, the two alternative hook-ups are equivalent.

FIGURE 2



Finally, when the walls of the pressure vessel disappear, we have a barometer ... a very good application of Honeywell absolute sensors.

*Care must be taken to avoid any temperature gradients between the pressure vessel and the tranducer.

Pressure — Temperature Measurements
Another important family of “pressure vessel” applications involves the measurement of temperature used in conjunction with an absolute pressure reading. The integrated temperature sensing diode reads the temperature of the silicon diaphragm in the transducer package. This temperature signal may be used for the additional temperature compensation of the pressure signal.

The accuracy of the transducer depends primarily upon the temperature coefficients of the pressure signal. This is typically one to two orders of magnitude looser than the precision, which depends upon hysteresis and deadband. Therefore, for such devices, if one were to calibrate the pressure signal temperature error in terms of the temperature signal, then a correction table could be established to increase its accuracy to the same order as its precision.

Other Fluid Functions
By suitably combining the temperature with the pressure signal, other fluid variables within the pressure vessel can be formulated. Two important fluid variables are density and heat content.

Density of a known gaseous fluid can be calculated without knowledge of the fluidic thermodynamic process going on simply by measuring simultaneously the pressure and temperature at the same point as described in equation 1.

Equation 1:

$$\rho = C_2 \frac{P}{T} \quad ;$$

where
ρ = Density
P = pressure
T = temperature
C_2 = inverse gas contsant

Knowing the pressure, temperature and the density of the fluid at one or more points simultaneously, much can be learned about the nature of the processes causing change in the fluid. In a bounded pressure vessel, one variable often of concern is the heat transfer or energy exchange within some portion of a cycle or during some specific period. The change in heat content at a specific point in the system can be traced most easily in the bounded pressure vessel by tracking the fractional change in pressure as shown in equation 2.

Equation 2:

$$dh = C_3 \frac{P}{\rho} \left(\frac{dp}{P}\right) \quad ;$$

Where dh = change in heat content

$\left(\frac{dp}{P}\right)$ = fractional change in pressure with time

C_3 = inverse Joule’s constant

If one were willing to track the fractional change of temperature and density as well as that of pressure, then complete knowledge of the state of the enclosed fluid as well as a complete characterization of the changing process results. Expressing equation 1 in terms of fractional changes yields equation 3.

Equation 3:

$$\left(\frac{dp}{P}\right) - \left(\frac{dT}{T}\right) = \left(\frac{d\rho}{\rho}\right) \quad ;$$

where

$\frac{dT}{T}$, $\frac{d\rho}{\rho}$ = functional change of temperature and density with time

Define a process characterization constant C_4 as shown in equation 4 and substitute in equation 3.

Equation 4:

$$C_4 = \frac{\left(\frac{dp}{P}\right)}{\left(\frac{d\rho}{\rho}\right)} = 1 + \frac{\left(\frac{dT}{T}\right)}{\left(\frac{d\rho}{\rho}\right)}$$

Figure 3 is a table of this characterization constant under a number of important practical conditions.

So, by measuring absolute pressure changes and absolute temperature changes in an enclosed fluid system, one is able to characterize the process which caused the change of fluid properties. The process characterization constant (C_4) relates original oil changes in system energy to changes in fluid state defined by pressure, temperature, and density.

FIGURE 3

State and Process Characterization

C_4	FLUID STATE	FLUID THERMODYNAMIC PROCESS	
0	$\left(\frac{dp}{P}\right) = 0$	P = constant	ISOBARIC
1	$\left(\frac{dT}{T}\right) = 0$	T = constant	ISOTHERMIC
$1 < n < k$	$\left(\frac{dp}{P}\right) = n\left(\frac{d\rho}{\rho}\right)$	$\frac{P}{\rho n} = \text{constant}$	POLYTROPIC (Adiabatic and Irreversible)
k	$\left(\frac{dp}{p}\right) = k\left(\frac{d\rho}{\rho}\right)$	$\frac{P}{\rho k} = \text{constant}$	ISENTROPIC (Adiabatic and Reversible)
∞	$\left(\frac{d\rho}{\rho}\right) = 0$	ρ = constant	INCOMPRESSIBLE (If bounded fluid gaseous, then process is ISENTHALPIC)

Note: In all cases dP dT, d*p* represent changes with time of the absolute values of P, T, and *p*.

Phase Change

The process characterization constant poorly defines thermodynamic processes where changes of phase are involved. Where a phase change from gaseous to liquid fluid is involved, a characteristic energy transfer called latent heat (H_{LATENT}) occurs in accordance with expression given by Clapeyron, shown as equation 5.

Equation 5:

$$H_{LATENT} = \frac{T}{C_2} \cdot \frac{\left(\frac{dp}{P}\right)}{\left(\frac{dT}{T}\right)} \;;$$

where

C_2 = inverse gas constant

For various fluids entering phase change, a new process characterization constant (C_5) given by Clausius/Clapeyron, shown in equation 6.

Equation 6:

$$C_5 = LOG_e\, P + \frac{C_2}{T} \cdot H_{LATENT}$$

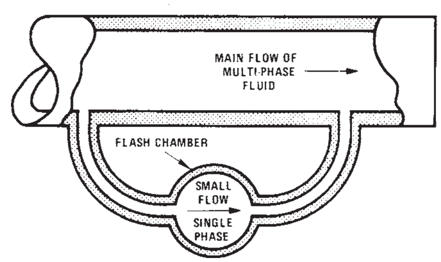
or

$$C_5 = LOG_e\, P + \frac{\left(\frac{dp}{P}\right)}{\left(\frac{dT}{T}\right)}$$

Thus, we have developed the equations of state for fluids undergoing thermodynamic processes with and without phase changes so as to characterize these processes via measurement of pressure and temperature within a pressure vessel using the absolute transducer.

Generally, measurements of pressure and temperature in a multiphase system are difficult. Often for the purpose of measurement, a small parallel tap is made into the main flow channel so as to divert a negligible portion of the fluid flowing; then a sudden expansion is performed in the tap, and a small tap is led back into the main flow channel. This type of device is called a flash chamber and is shown in Figure 4.

FIGURE 4



The flash chamber accomplishes the conversion of multiphase system (liquid and gas) to a single phase system (gas).

Such a chamber is simply a pressure vessel susceptible to analysis by the aforementioned modeling techniques.

OPEN FLOW APPLICATIONS

Just as pressure vessel processes were characterized by thermodynamic changes in fluid media rather than kinetic or spatial changes, open flow conditions and processes are best characterized as those in which we are primarily concerned with the kinetic properties of a fluid system and their changes, rather than the state and changes of state of a controlled volume of fluid. Whereas in the pressure vessel measurements involve absolute pressure, the kinetic state of an open flow system most often requires gage and differential pressure transducers.

The form of Bernoulli's flow equations most applicable to open flow conditions is given in equation 7.

Equation 7:

$$\left.\frac{P}{\rho}\right)_{STAGNATION} = \left.\frac{P}{\rho}\right)_{STATIC} + \frac{V^2}{2g} + y;$$

$$\left.\frac{P}{\rho}\right)_{STAGNATION} = \text{Stagnation pressure head}$$

$$\left.\frac{P}{\rho}\right)_{STATIC} = \text{Static pressure head}$$

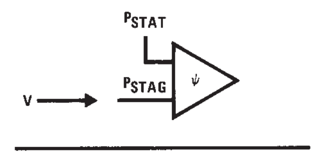
$$\left.\frac{V^2}{2g}\right) = \text{Kinetic flow head}$$

y = Potential flow head

This particular form of Bernoulli's equation is valid where fluid density remains reasonably constant. As seen in the definition of terms (equation 7), the concept of a head is key to open flow applications. Easiest to conceive is the potential head, wherein a particle of fluid at a different height than at some other location has some potential to flow to that other location. That potential is proportional to the height difference. It is small wonder, therefore, that dimensions of a head are those of a column of fluid; inches of mercury, feet of water, millimeters of mercury or torr. If that particle of fluid were to fall, so as to change location or flow, without changing pressure within that particle, then that potential flow head would convert to a kinetic flow head. Another useful concept in equation 7 is that of stagnation. If you were waiting with a catcher's mitt at a fixed location and a particle of fluid at a given pressure flowed into the mitt, in order to stop that particle with your mitt you would have to bring it to rest. In doing so, assuming the fluid particle remained at the same density and temperature, the particle's pressure head would increase by the absorbed kinetic head. If you were then to pull the mitt down to ground level, the stagnation head would in addition increase by the potential head. Therefore, the stagnation head of a given fluid particle is an expression of that particle's pressure were it suddenly brought to rest and dragged to the bottom. Bernoulli's equation indicates that however that particle may meander under open flow conditions; the sum of its static pressure head, its kinetic flow head, and its potential flow head remains constant. In most open flow situations the variable of major interest is flow velocity. In situations where it is convenient to measure both stagnation pressure and static pressure at essentially the same point (y is constant) a differential pressure transducer can be used in a method similar to that of a pilot-tube as shown in *Figure 5*. Equation 7 can then be rearranged as shown in equation 8.

FIGURE 5

Flow Rate Pressure Square Law Relationship



Equation 8:

$$V_y = \sqrt{2g\left[\left.\frac{P}{\rho}\right)_{STAGNATION} - \left.\frac{P}{\rho}\right)_{STATIC}\right]}$$

Applications where this type of measurement is common are air speed indication for airplanes and weather balloons, water speed for boats and aqueducts and irrigation ditches, ventilation control, sewage processing, industrial mixing, and others. More generally, where y varies in open flow conditions, changes in flow conditions due to geometric changes in the flow boundaries are monitored by measurements of fluid level changes and fluid pressure changes. Equation 9 gives the applicable form of Bernoulli's equation.

Equation 9:

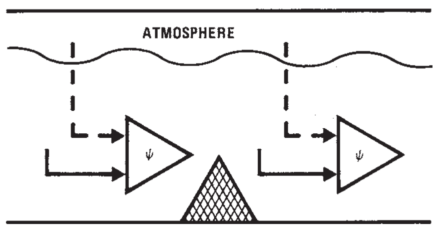
$$\frac{dv}{g} + \frac{dp}{\rho} + dy = 0,$$

where dv, dp, dy are changes with distance

Figure 6 shows this general case of open flow boundary condition monitoring. Notice that both the fluid level and each of the gage transducers used are vented to atmosphere for reference. In this particular case, the use of a differential transducer is not practical due to the physical separation of the points of interest.

Two transducers must be used. Examples of applications include weir and dam flow and level control, oceanographic measurements, and for the special cases of near zero velocities, general level control.

FIGURE 6
Flowmeter Output with Exaggerated Pressure Transducer Common- Mode Inaccuracy



The schemes of both *Figures 5 and 6* are ideal for accuracy improvement via auto-referencing

Once again there are some cautions that must be respected in the application of transducers in open flow conditions. Perhaps the most often overlooked and frustrating caution involves temperature gradient. As was explained in the pressure vessel section, although good transducers are temperature compensated, temperature gradients within the transducer are deadly enemies producing errors that defy all compensation techniques. If the temperature signal from the transducer is used in determining the density of the working fluid, then the transducer wants to be thermally well-coupled. However, if the atmospheric environmental temperature is significantly different from that of the working fluid, a severe gradient of temperature can occur within the transducer unless the transducer is totally immersed in the working fluid (a condition usually impractical). Fortunately, in most open flow applications, the temperature reading is not needed to determine density and the dynamics of the flow do not prohibit fairly long tube lengths from the transducer to the point of measurement. The result is that it is practical to provide a situation wherein the working fluid within the transducer is at the same temperature as the surrounding environment.

The IC pressure transducers are ideally suited for coupling to VCOs for FM transmission (see Signal Conditioning section) the method favored by all modern trends in instrumentation. Among the many advantages are extremely low noise susceptibility even when bundled with many other signal carrying cables, ease of conversion to digital signals to facilitate interface with modern control logic or input to general purpose digital computers, and ease of combination with other analog FM signals to form a composite system variable.

ACOUSTICS
One special form of open flow application is the case where the pressure wave velocity is high compared to the fluid flow velocity. Such applications are called acoustic. The acoustic energy of a sound wave is directly proportional to the sound pressure as shown in equation 10.

Equation 10:

$$dh = C_3 \frac{dp}{\rho}$$

For acoustics, the open flow approximation of an “incompressible, isothermic medium” must be replaced by the model of a “stationary, isentropic medium.” That is, the propagating pressure wave shakes each fluid particle about its stationary location proportional to the sound pressure constituting a dynamic change in density (dp). As shown in equation 11, the proportionality constant between the change in the fluid density and the sound pressure is the inverse squared speed of sound in that medium.

Equation 11:

$$d\rho = C_7 \; dp; \quad C_7 = \frac{1}{a^2} \;;$$

where “a” is the speed of sound.

Sound pressure measurements should be made with differential transducers in which the reference point monitors the quiescent pressure level.

High frequency response can be severely limited by bounded chambers. In fact, just the tube and lid can limit response normally in the tens of kilo Hertz to the low kilo Hertz region. However, the silicon pressure diaphragm response alone with the tube and lid removed or when liquid coupled is such that calibrated sound pressure measurements can be achieved at frequencies well above 50 kilo Hertz. Thus, pressure transducers are capable of calibrated pressure measurements in open flow conditions ranging in dynamics from static to ultrasonic frequency.

CLOSED FLOW APPLICATIONS
Pressure vessel applications require the investigation of time dependent variables at one point. Open flow applications require the investigation of time independent variables at many points. In closed flow applications, we need to investigate both kinds of variables. That is, the processes at work within the fluid

system involve state change energies of like order of magnitude as kinetic energies. Perhaps the most obvious examples of systems reliant on such processes are engines of all kinds, as well as refrigerators and air conditioners, compressors, gas pipelines, fire extinguishers, gun cartridges and explosives.
In closed flow, the equation used to model the flow between two locations must be altered to include the change of state.

Equation 12:

$$h_{STAGNATION} - h = C_3\left[\left(\frac{P}{\rho}\right)_{STAGNATION} - \frac{P}{\rho}\right] = C_3\left(y + \frac{V^2}{2g}\right)$$

In equation 12, $h_{STAGNATION}$ represents the total equivalent heat energy of the system and is constant; h is the heat content of a fluid particle at a particular location such that (h_{STAG} - h) represents the kinetic and potential flow energy. In open flow, the density of the fluid is assumed to be known and constant. Consider a working fluid that is gaseous and whose density variation may be described by equation 1 of the pressure vessel applications section. Equation 13 shows the substitution of equation 1 in equation 12.

Equation 13:

$$h_{STAGNATION} - h = \left(\frac{C_3}{C_2}\right) T\left[\frac{P_{STAGNATION}}{P} - 1\right] = C_3\left(y + \frac{V^2}{2g}\right)$$

In the same manner in which equation 8 was derived from equation 7 in the section on open flow applications, equation 14 is derived from equation 13 to show flow velocity.

Equation 14:

$$V_y = \sqrt{2g\left[\frac{T}{C_2}\left(\frac{P_{STAGNATION}}{P} - 1\right)\right]}$$

Thus, where the system allows a Pitot tube measurement of the two absolute pressures and temperatures at one point, the closed flow can be modeled by equation 14 and two transducers. Common applications include high velocity air flow as in compressors, and engine manifold gas flow.

To measure closed flow in small flow channels, it is usual to insert an obstruction in the passage between two points at which fluid properties can be sensed.

Again, rather than the incompressible and isothermic conditions applicable to liquids in open flow, heat transfer and in fact heat loss due to flow conditions is experienced. Equation 15 presents Bernoulli's equation for this situation with the energy loss due to obstruction indicated in terms of change in heat content. For extremely long, thin, rough-walled, closed-flow vessels, the fractional loss can actually approach unity.

Equation 15:

$$\left[\frac{Y_2 + \frac{V_2^2}{2g}}{Y_1 + \frac{V_1^2}{2g}}\right] = 1 - \left(\frac{h_1 - h_2}{h_{STAGNATION} - h_1}\right);$$

where

$$\left(\frac{h_1 - h_2}{h_{STAGNATION} - h_1}\right) = \text{Loss of energy}$$

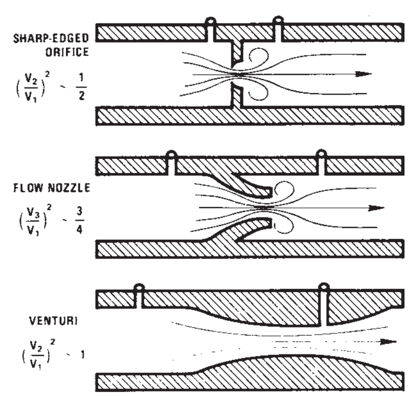
Structures are used that tend to minimize the distance between sensing points as well as minimize the fractional loss of energy. Commonly used structures range from orifices where losses are up to half of the total energy and sensing points are very closely spaced, to Venturi's where losses are negligible but sensing points are widely spaced. Equation 16, derived from equation 15 shows a typical calibration equation for a specific obstruction over a specific range of flow.

Equation 16:

$$\left.\frac{V_2}{V_1}\right)_y = \sqrt{1 - \left\{\frac{h_1 - h_2}{h_{STAGNATION} - h_1}\right\}}$$

Figure 7 shows some typical flow measurement obstructions.

FIGURE 7



It must be remembered that these are rule of thumb examples and fluids undergoing drastic thermodynamic changes will not approximate these processes for these flow conditions. For example, the nearly lossless Venturi of streamlined flow conditions forms a roaring energy loser when turbulent hot gases are pushed through so as to become the converging-diverging nozzle of rocketry fame.

OPEN VS CLOSED FLOW

Conventionally, differential pressure transducers rather than absolute transducers are used for flow measurement. Three arguments are popular for maintaining this convention, one of them very good and the other two rather weak.

In low flow rate applications the dynamic head is most often small compared to the static head. The incompressible isothermic model, expressed in the equations of the open flow applications section, is often appropriate under such low flow conditions. The resulting simple expression of Bernoulli's equation that leads to the use of differential pressure transducer is given by equation 17.

Equation 17:

$$d\,(V^2) = C_8 \left(\frac{dp}{\rho}\right); \quad \rho \neq \rho\,(p,\,t)$$

In addition to being the analytically obvious best choice when equation 17 is an appropriate model of flow conditions, a single differential transducer can be made to perform with much greater accuracy than a pair of gage or absolute transducers of comparable quality because the differential transducer need only range both the dynamic and static heads. Since the static head is not called for in equation 17, the added ranging requirement merely adds common mode error to the measurement. Under these conditions the differential pressure transducer convention for flow measurement is justified and the differential transducers are highly recommended, particularly with auto-referencing.

Equation 18:

$$d\,(V^2) = C_9\, d\left(\frac{p}{\rho}\right); \quad \rho = \rho\,(p,\,t)$$

Traditionally, even in cases where more complex Bernoulli models (equation 18) should be used, the simple incompressible model is substituted. One argument claims that one can always make up for errors in the modeling equation by specifying greater accuracy in the differential pressure transducer. Proponents of this argument consider the alternate use of two absolute pressure transducers along with two temperature transducers (to achieve a more accurate modeling equation) too sophisticated. The tradition of simple single variable models using few highly accurate transducers to achieve moderate system accuracy is so well founded in the measurement and control industries that until recently only manufacturers of low volume, high accuracy, high cost transducers existed.

In most closed flow applications the variables of interest are functions of absolute pressure, differential pressure, and temperature, with respect to time and location. If the system modeler desires a certain tolerance on this complex function he may either gather single variable data at multiple locations or multivariable data at few locations.

In either case, auto-referencing techniques can greatly improve system accuracy.

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