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Sensor Design the Key Advantage in Thermal Mass Flow Meter Performance

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Immersible thermal sensors are finding growing acceptance in the gas flow measurement field. By using two Platinum Resistance Temperature Detectors (PRTDs) immersed in a stream of flowing gas, modern thermal flow meters can directly measure mass flow, without the need for temperature or pressure compensation. Thermal meters offer very high turndown, accuracy and repeatability at an economical price. However, all thermal sensors are not created equal. Recent optimization of sensor design has led to a marked increase in the performance of thermal mass flowmeters in the field.

To understand just what role sensor design plays in thermal flow meter performance, it is necessary to understand the basics of how immersible thermal sensors work.

An immersible sensor typically consists of a heated element (called the velocity sensor) and a passive element (called the temperature sensor). Both are precision PRTDs. In operation, the velocity sensor is heated to a temperature Tv. As the gas velocity (the flow) increases, heat (Q) is removed via forced convection and the velocity sensor begins to cool. The gas temperature (Tg) is simultaneously being measured by the temperature sensor (see Figure 1). The sensor electronics compares the measured temperature value of the velocity sensor (the resistance of the PRTD changes linearly with temperature) to that of the temperature sensor and is designed to maintain the velocity sensor at a constant temperature differential above that of the gas. In other words, the difference, Tv-Tg , is maintained at a constant "set-point" value. This is accomplished by adding more power to the heated PRTD that heats up the velocity sensor until Tv has been increased to its set-point value. The wattage (power) added to accomplish this is proportional to the heat, Q, removed, and this is directly proportional to the mass velocity.

Here, it is critical to note that since the heat, Q, is carried away by the molecules of the gas flowing over the velocity sensor, the wattage is proportional to the mass velocity, pU, and not the actual, or volumetric, velocity, U, itself. It is this simple, but crucial fact that makes an immersible thermal flow meter a mass flow meter, instead of a traditional volumetric flow meter. The electrical output is selected by the user to be any one of three forms of mass flow rate: m, the total mass flow rate through a pipe or flow channel; pU, the mass velocity, also called mass flux; or Us, the point velocity related to standard temperature and pressure conditions.

From this basic description, we can see that the velocity sensor is the key element, and its design parameters will determine the accuracy and functionality of an immersible thermal meter. A closer look inside a standard velocity sensor illustrates how the design of the sensor affects its performance. A typical velocity sensor consists of a core (typically a ceramic mandrel) around which is wound a platinum wire. This entire assembly is inserted into a thermowell (typically a stainless steel tube) and fixed (typically with glue, cement or epoxy) in place.

The basic equations for the velocity sensor derive from the first law of thermodynamics as applied to a heated cylinder in cross flow. Figure 2 shows such a sensor. Applied to Figure 2, the first law states that the energy into the control volume equals the energy out plus the energy stored. Assuming steady-state operation and no heat transfer via radiation, we get:

$$w = q_c + q_L$$

Where:
w = electrical power in watts supplied to the sensor

q_L = heat conducted to the probe stem (end loss)

q_c = heat transfer due to natural and forced convection

L = sensor length

d = sensor diameter

Tv = temperature of the velocity windings

Te = average surface temperature over length L

Tg = temperature of gas

pU = mass velocity or mass flux (mass per unit area per unit time)

p = gas mass density

U = velocity in the flow stream impinging the sensor (point velocity)

Us = velocity related to standard temperature and pressure

As stated previously, electrical power is added to maintain a constant differential temperature (Tv-Tg). The temperature of the velocity windings (Tv) changes with the mass flux (and thus with point velocity U) as gas molecules convect heat away. Thus, the electrical power added is directly related to the point velocity, U.

Figure 2 suggests three critical design issues with thermal sensors that must be minimized. The first of these is stem conduction, or end loss (q_L). The presence of stem conduction (heat lost out the base of the sensor) means that the temperature of the mass flow sensor varies with the axial coordinate y (the length dimension of the velocity sensor) in Figure 2. The temperature, Tv, actually sensed by the mass flow sensor is the average temperature over sensing length L, or: $T_v=(1/L)\int_0^L \mathbf{Tv}(y)dy$ over the length 0 to L. Short, stubby sensors have more end conduction. Long sensors have less.

A second issue with stem conduction is sometimes known as cross talk. The heat lost via stem conduction is transmitted from the velocity sensor, through the sensor gland and then not only into the probe shaft, but also into the temperature sensor. This gives a false gas temperature measurement (Tg) and, since maintaining a constant temperature differential (Tv-Tg) is at the heart of the measurement process, leads to inaccuracies. This effect is even more pronounced if sensor spacing is close together and if the temperature and velocity sensors are short and stubby as in traditional ½-inch diameter probes.

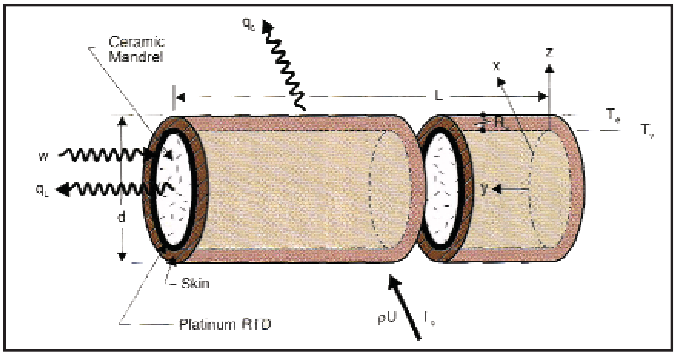

Figure 2. First Law of Thermodynamics Applied to a Sheathed Industrial Thermal Mass Flow Sensor

High performance immersible thermal sensors that minimize both end loss and cross talk typically have ¾-inch diameter probes and very long sensors having overall lengths of 10 to 20 diameters. The key is that stem conduction must be either minimized or accounted for.

The third issue with immersible thermal sensors, and indeed the most critical design consideration, is known as skin resistance. Figure 2 shows a mass flow sensor with a tubular metal sheath. In this case, the surface temperature, Te, is slightly less than the temperature, Tv, of the platinum winding because a temperature drop is

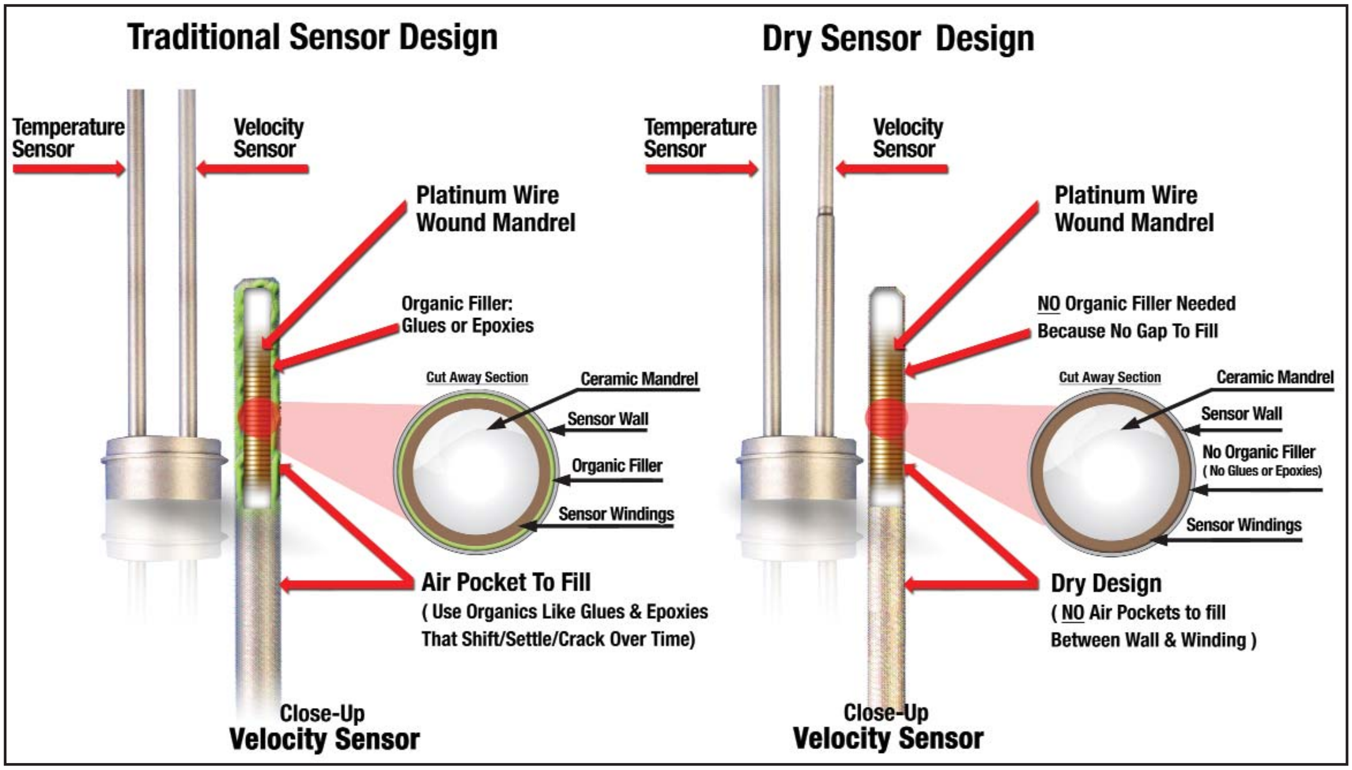

Figure 3. Design Differences in Traditional vs. Dry Sensors

required to pass the heat, q_c, through the intervening "skin" - the glue, cement or epoxy plus the metal tube itself. This is expressed as $T=Tv-q_cRs$, where Rs is the thermal resistance of the skin in units of K/W (degrees Kelvin per watt). It turns out that Rs is a very important factor in the calibration of immersible thermal mass flow meters. Rs should be a constant for a given sensor and is the sum of the thermal resistances of the components constituting the skin.

Note the word should. Many, if not most current manufacturers of immersible thermal sensors use thermal greases, heat sink compounds, organic expoxies, ceramic cements or other "glues" to fix the velocity PRTD core in place. While these traditional sensors are cheap and easy to manufacture, sensors that use such "glues" do NOT exhibit a constant skin resistance over time. Practice in real-life installations has proven that such glues exhibit cracks and compositional changes over time. This is caused by the high stresses induced by their curing processes and by the alternating thermal expansions and contractions experienced in field applications with high or cyclical gas temperatures. The unfortunate result is large changes in Rs with consequent loss of accuracy.

A much better alternative is to use a so-called "dry" sensor. In such sensors no "glues" are used. Instead the wire-wound velocity core is swage-fitted into the sheath. This is illustrated by Figure 3. Note that the traditional sensor uses a "glue" to fill the air pockets, with the disadvantages discussed above.

The unfortunate result of velocity sensors designed with glues is large unknown changes in the critical thermal resistance parameter, Rs, that can occur at a present or future time utterly unknown to the user. This changes the flow calibration, resulting in what is commonly called "flow drift". This means recalibration. Immersible thermal mass flow meters using glues in the velocity sensor generally require an annual factory recalibration since drift is on the order of 1 percent of reading per year at a minimum. Calibration in the factory is required because the meter needs a sophisticated flow loop to insure accurate calibration.

Meters with dry sensors installed in every conceivable flow condition have proven to have no such drift. Flow meters using this technology only need to periodically validate their flow capabilities instead of an annual recalibration, another added advantage of dry sensors over traditional sensors. End users save time and money over the lifetime of their flow instrument.

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