Part 1: Thermal

Core Technology White Paper Series

A Tale of Two Thermals: Capillary & Immersible

Authors:
Mark McMahon, Scientific Product Manager
Scott Rouse, Industrial Product Manager

Publication Date: August 7, 2008

About:
The Core Technology White Paper Series is a four part series detailing the flow technologies that allow Sierra to offer a flow solution for nearly any gas, liquid and steam application. Part 1 focuses on Sierra's two types of thermal mass flow technologies for gas mass flow measurement and control—Capillary Thermal & Immersible Thermal. Part 2 will focus on our Multivariable Mass Vortex for gas, liquid and steam, Part 3 focuses on Transit-Time Ultrasonic for liquids, and Part 4 will detail our Primary Standard Gas Flow Calibration technologies.

Introduction: A Tale of Two Thermals

For **gas mass flow measurement and control**, Sierra offers the broadest selection of thermal mass flow measurement products on the market. This is because our thermal mass flow products incorporate two types of advanced thermal technologies, each complementary to the other and each with unique advantages. These two thermal sensing technologies directly measure gas mass flow based on principals of heat transfer and are commonly called **Capillary Thermal Sensor Technology** and **Immersible Thermal Sensor Technology.** Taken together they cover the entire spectrum of gas mass flow measurement and control applications found in industry. Sierra is the only company in the industry to provide both thermal technologies to our customers.

The following tells “A Tale of Two Thermals” and is meant to educate our customers about Sierra’s thermal mass flow technology. Our thermal products are divided into two identifiable families—The Scientific Products Family which uses proprietary capillary thermal sensor technology and the Industrial Products Family which uses our advanced immersible thermal (sometimes called thermal dispersion) sensor technology. We discuss the virtues of each technology below.

Although both technologies have “thermal” in their name, their principles of operation are quite different. They both directly measure gas **mass flow rate**, not volumetric flow rate, because both have a heated surface that transfers heat energy to the **molecules** that bear the **mass** of the flowing gas stream. In the case of capillary tube thermal mass flowmeters, the heated surface is a capillary tube that transfers heat energy to the **bulk**, or to **all**, of the gas flowing through the tube.

In contrast, in the case of immersible thermal mass flowmeters, the heated surface is a cylinder immersed in the flow stream that transfers heat to the viscous **boundary layer** surrounding the cylinder. Therefore, the theoretical models expressing the first law of thermodynamics for each type of thermal mass flowmeter are not the same. To best serve the purpose of this paper, we have chosen to present easy-to-understand descriptions of the principles of operation instead of the complex solutions to the theoretical models.

We will start our technical discussion with Capillary Thermal Technology and follow with the discussion of Immersible Thermal.

CAPILLARY THERMAL
(Gas Mass Flow up to 1000 slpm)

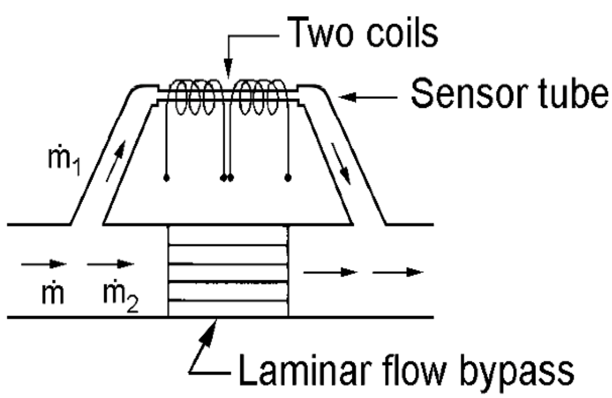
Our Scientific Product Family offers you a powerful choice in gas mass flow products. If you only need to measure the mass flow rate of gas, choose from our line of Mass Flow Meters (MFM). If you would like to regulate as well as measure gas mass flows, select from among our Mass Flow Controllers (MFC) with integrated valve and control electronics. Our Scientific Products can be used with any clean dry gas you choose, including mixtures, toxics and corrosives. The Scientific Product Family utilizes our patented Laminar Flow Element Technology, Advanced Fluid Dynamics Technology and Capillary Thermal Sensor Technology to create some of the highest performance, inherently linear mass flow instruments in the world. Our Scientific Products are widely used for precise measurement and/or control over an enormous flow range: from ultra low flows (4 sccm full-scale) up to 1000 slpm full-scale (up to 5600 slpm available upon request).

Principal of Operation: Capillary Thermal Technology

The Capillary Thermal principal of operation is based on heat transfer and the first law of thermodynamics. During operation, process gas enters the instrument's flow body and it divides into two flow paths. The vast majority of the gas flow passes through the Laminar Flow Element (LFE) bypass. A very small portion of the total flow is diverted through a small "Capillary" sensor tube with an ID between .007 to .028 inches.

The LFE Bypass

Sierra's LFE bypass is designed so that the process gas maintains a smooth, uniform flow profile called laminar flow (in other words, the gas has a Reynolds number below 2000). As a result, the small fraction of the total flow measured in the sensor tube **($\dot{m}_1$)** remains in direct proportion to the gas flowing through the LFE bypass **($\dot{m}_2$).** If we can measure the flow in the sensor tube, we can calculate the total mass flow rate $\dot{m}$ as shown in Figure 1 below:



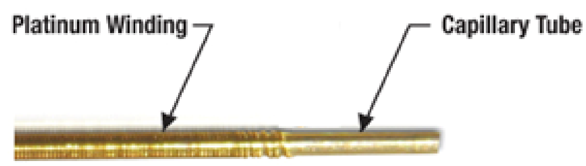
$$\dot{m} = \dot{m}_1 + \dot{m}_2$$
$$\dot{m} = \dot{m}_1 (1 + \dot{m}_2 / \dot{m}_1) = k_1 \dot{m}_1$$

Fig. 1 Capillary Thermal Principle of Proportionality

Both the $\dot{m}$ and $\dot{m}_1$ in Figure 1 are in mass flow rate units of gm/sec or kg/sec. In practice, we don't actually calculate this constant k_1, we simply flow calibrate each instrument over its full $\dot{m}$ range.

The Capillary Sensor Tube

To determine the mass flow rate through the Sierra sensor tube, two platinum resistance temperature detector (RTD) coils are wrapped around the outside. Because they are on the outside of the tube, this sensing technology is non-invasive—the flow only encounters 316 stainless steel wetted parts. This is a great advantage of Capillary Thermal Technology. The two identical RTD coils are heated equally by connecting them to an electronic circuit. This provides an easy method to measure any change in temperature by measuring the change in voltage of the circuit created by the RTD coils. As the gas flows through this very small, evenly heated tube, the molecules of the gas carry some heat from the upstream section to the downstream section. This creates a temperature differential between the two sections which yields the output signal.



Small Section of Capillary Thermal Sensor (Scale: Approx. 10:1)

Within the sensor, the first law of thermodynamics states that the total HEAT IN must equal the HEAT OUT. To explore the physics of this heat transfer, we must consider two separate thermal interactions:

- The temperature distribution of the tube.
- The temperature distribution of the gas inside the tube.

Here is an exaggerated representation of the tube and gas temperature distributions shown together for very small gas flows:

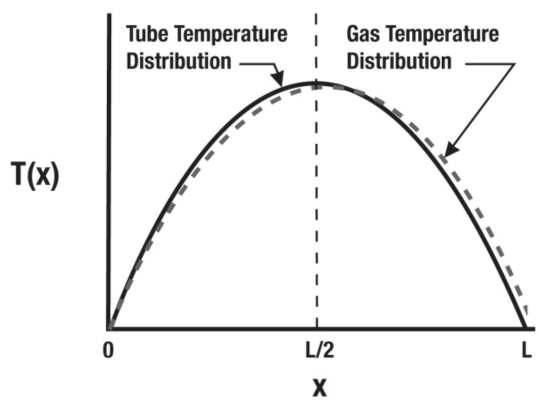


Fig. 2 Combined Temperature Distributions of Tube and Gas

The two temperature distributions are symmetrical, but have a slight offset as we move down the length of the tube.

Next, we show an exaggerated representation of the tube temperature distribution for zero flow and for a typical flow.

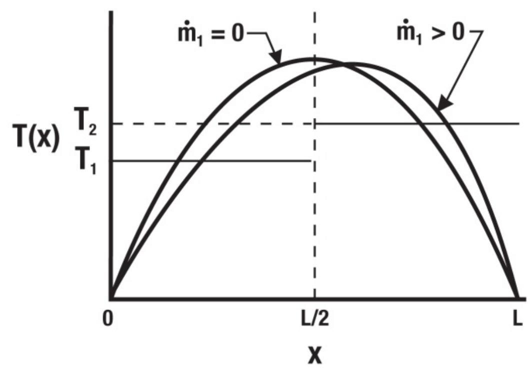


Fig. 3 Capillary Tube Temperature Distribution at Two Mass Flow Rates

The description of the temperature distributions for the tube and for the gas can only be described by two distinct differential equations, each in two dependent variables: the tube temperature and the gas temperature. Solving these two equations is a complex endeavor beyond the scope of this article. In 1988, Sierra Instruments found the solution to these differential equations and used it to optimize the design of subsequent generations of capillary tube mass flow meters and controllers.

If we make the sensor tube very small and we restrict the mass flow rate through the tube (**$\dot{m}_1$**) by careful selection of our LFE bypass, then we limit the solution of these equations to a narrow range over which **$\dot{m}_1$** is directly proportional to **$T_2 – T_1$,** the difference in the average temperatures of the downstream coil **(T_2)** and the upstream coil **(T_1).**

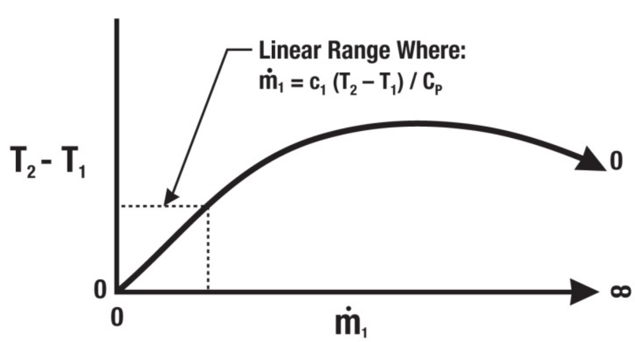


Fig. 4 Capillary Tube Sensor Linear Range for a Given Gas

In the linear range shown above in Figure 4, we have for any given gas:

(1) $\dot{m}_1 C_P = c_1 (T_2 – T_1)$

Where:

C_P = The coefficient of specific heat for the given gas.

c_1 = A constant for a given MFC applicable to all gases (in the linear range only).

From Figure 1, we have derived $\dot{m} = k_1 \dot{m}_1$. Substituting this into Equation (1) above, we get:

(2) $\dot{m} C_P = c (T_2 – T_1)$

Where:

$c = k_1 c_1$ = A constant for a given MFC but applicable to all gases.

If we choose a “reference” gas “r” (i.e. nitrogen), we write Equation (2) as:

(3) $\dot{m}_r C_{Pr} = c (T_2 – T_1)$

For an “actual” gas “a” of a particular application, we write Equation (2) as:

(4) $\dot{m}_a C_{Pa} = c (T_2 – T_1)$

For the same output signal $T_2 – T_1$ for both the reference gas and the actual gas, we arrive at the following by dividing Equation (4) by Equation (3):

(5) $\dot{m}_a C_{Pa} / \dot{m}_r C_{Pr} = 1$

This can be re-written as:

(6) $\dot{m}_a / \dot{m}_r = C_{Pr} / C_{Pa} = k_m$

Where:

k_m = k-factor (dimensionless) used for the measurement of mass flow rate in units of gm/sec or kg/sec.

It is common in our industry to describe mass flow rates of gases not in mass units, but in standardized volumetric flow rate units. To determine the k-factor for standardized volumetric flow rate units, remember that mass flow $\dot{m}$ can also be described by:

(7) $\dot{m} = \rho_s Q_s$

Where:

ρ_s = The mass density of the gas under “standardized” conditions (i.e., at temperature T_s and pressure P_s).

Q_s = The volumetric flow rate of the gas under “standardized” conditions expressed in units of sccm or slpm.

If we substitute into equation (6) for $\dot{m}_a$ **and** $\dot{m}_r$, we have:

(8) $\rho_{sa} Q_{sa} / \rho_{sr} Q_{sr} = C_{Pr} / C_{Pa}$

This we rearrange to arrive at the k-factor for mass flow rate expressed as a standardized volumetric flow rate:

(9) $Q_{sa} / Q_{sr} = \rho_{sr} C_{Pr} / \rho_{sa} C_{Pa} = k_v$

Where:

k_v = The well-known k-factor (dimensionless) for the measurement of mass flow rate in units of sccm or slpm.

The constant $\mathbf{k_v}$ is commonly referred to as the K-factor for gas "a" relative to reference gas "r" and is the quantity that appears in published K-factor tables. This K-factor is clearly dependent on the physical properties of the gas that affect heat transfer (the standard gas density and specific heat). This means that once we have flow-calibrated the response of a sensor tube with a reference gas (i.e., air or nitrogen), we can predict its behavior for any other gas. Fortuitously, since the standard mass density of a gas $\boldsymbol{\rho_s}$ is a constant, and its coefficient of specific heat $\mathbf{C_P}$ varies negligibly with temperature, the K-factor is essentially constant over specified operating ranges.

Sierra has demonstrated this exact behavior in our Premium Digital 100 Series family of Instruments. Because each instrument utilizes our patented, inherently linear, modular LFE design, the performance is so linear that even our base calibration may be done with only two points: Zero and Span. Outside effects from temperature, pressure, pipe size and installation can be ignored. This linearity enables our patented Dial-A-Gas® feature--every instrument may be used on multiple different gases or mixtures with comparable accuracy. We simply enter the appropriate K-factor into digital memory.

Capillary Thermal Technology and Sierra's careful engineering have created the Scientific Family of instruments that:

- Are used on any gas including toxics, corrosives and mixtures
- Are used for a wide range of applications including research, manufacturing, analysis, pharmaceutical, combustion management and quality control.
- Will control flow at very high accuracy when coupled with our direct-acting electro-magnetic valve
- Remain accurate despite changes in process temperature, pressure, tube diameter and installation specifics
- Demonstrate incredible flexibility, sensitivity and performance

---

IMMERSIBLE THERMAL
(Gas Mass Flow above 35 scfm (1000 slpm)

Sierra's second thermal mass flow technology is Immersible Thermal. The following section details this technology.

Our industrial thermal products are ideal for higher gas flows above 35 scfm (1000 slpm) and utilize “immersible thermal” sensing technology. They are widely used for precise mass flow measurement in light-industry, heavy-industry, hazardous environments, and ultra high purity (UHP) applications.

Rugged and reliable, our line of industrial thermal mass flow meters are work horses in industry and are commonly used to measure air and natural gas, as well as all other industrial gases and mixtures. Full scale flow rates can go up to thousands of scfm (pipe size dependent). We offer a high temperature (HT) industrial thermal version for high temperature gases above 300 C (700 F). For high pressure gas (above 250 psi and up to 5000 psi), we recommend our Multiparameter Vortex products as a great solution.

Principal of Operation: Immersible Thermal Technology

In contrast to capillary thermal mass flow meters, where flow is measured with an LFE bypass and a capillary tube mass flow sensor, the immersible thermal sensor is completely immersed into the flow stream (hence the name immersible). As a result, immersible thermal mass flow meters measure much higher gas mass flow rates in harsher environments than capillary thermal mass flow meters. This is true because there is very little pressure drop across an immersible sensor, and the flow does not have to pass through the LFE as it does with a capillary thermal mass flow sensor. There is no small capillary tube through which a portion of the flow passes, Instead the sensor is fully immersed in the flow.

Sierra’s patented immersible thermal sensor technology consists of two precision platinum resistance temperature detectors (PRTD's) protected by a platinum-iridium sheath. In operation, the gas temperature sensor measures the temperature of the gas, while the velocity sensor is electronically maintained at a temperature typically 40 C degrees hotter than the gas temperature. Once the gas begins to flow, the velocity sensor is cooled as the molecules of gas take heat away from the heated velocity sensor (think of blowing on your wetted finger…it will feel cooler as your breath passes over it). The amount of heat removed from the velocity sensor is added back by the electronic heater circuit so a constant temperature differential ΔT between the temperature sensor and the velocity sensor is maintained.

Just as in capillary thermal sensor technology, the total heat transfer is governed by the first law of thermodynamics (the total heat INTO the sensor must equal total heat OUT of the sensor). **Equation 1** represents the heat taken away from the velocity sensor by the gas flow in a pipe or duct via convective heat transfer. By applying the first law and assuming steady-state operation and no heat transfer via radiation, we get:

(1) $$w = q_c + q_L$$

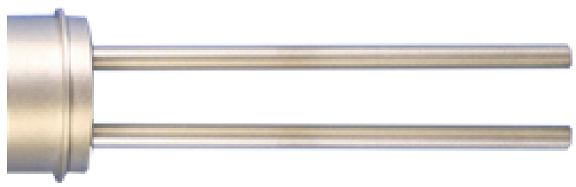
Where:

w = Electrical power in watts supplied to the heated velocity sensor.

q_c = Heat transfer due to natural and forced convection.

q_L = Heat conducted to the probe stem called end loss or stem conduction.

A good sensor design uses long sensor stingers that minimize the end loss and stem conduction that make up the non-flow related heat lost out of the end of the sensor (q_L). As a result, long sensor stingers (as opposed to short and stubby sensors) makes end loss (q_L) a very small number and leads to a more accurate measurement. This means the heat INTO the velocity sensor (which we can measure electronically) is virtually equal to the heat OUT of the sensor that is convected away by the flow stream. It should be clear that **q_c = heat transfer due to natural and forced convection** is the quantity we wish to measure.



Immersible Thermal Sensor (Scale: Approx. Full Size)

By applying an energy balance to the cylindrical velocity sensor in cross flow, we derive **Equation 2** as follows:

(2) $q_c = hA_v(T - T_g)$

Where:

h = The film coefficient for convective heat transfer.

$A_v = \pi dL$ = The external surface area of velocity sensor.

T = Temperature of the heated velocity sensor.

T_g = Temperature of the flowing gas.

In order to calculate **q_c**, we must solve **Equation 2**, but since the flow around cylinders in cross flow is confounded by boundary-layer separation and a turbulent wake, it has defied analytical solution. Therefore, the film coefficient, **h**, in **Equation 1** is found using empirical correlations. Correlations for **h** are expressed as a function of various non-dimensional parameters. **Equation 3** describes this relationship.

(3) $Nu = Function(Re, Pr, Gr, M, Kn)$

Where:

Nu = hd/k, the Nusselt number (the heat-transfer parameter).

Re = ρVd/μ, the Reynolds number (the ratio of dynamic to viscous forces).

Pr = $\mu C_p/k$, the Prandtl number (the gas properties parameter).

Gr = The Grashof number (natural convection parameter).

M = The Mach number (the gas compressibility parameter).

Kn = The Knudsen number (the ratio of the gas mean free path to d).

In the above equations, **k** is the thermal conductivity of the gas; **μ** is its viscosity; **ρ** is its density; and $\mathbf{C_p}$ is its coefficient of specific heat at constant pressure. **d** is the outside diameter of the velocity sensor.

By assuming that: (1) natural convection is embodied in **Re** and **Pr**; (2) the velocity is less than 1/3 the speed of sound of the gas; and (3) the flow is not in high vacuum, we can ignore the effects of natural convection **Gr**, gas compressibility **M** and the gas mean free path **Kn**, leaving us with the heat transfer parameter (**Nu)** as a function of the ratio of viscous to dynamic forces **(Re)** and the gas properties parameter **(Pr).** With this we have enough to empirically solve our equation, as follows:

(1) We electrically measure the electrical power in watts supplied to the heated velocity sensor and relate this to the heat transfer due to natural and forced convection via **Equation 1**: $\mathbf{w = q_c + q_L}$ (recall that $\mathbf{q_L}$ has been made very small by good sensor design).

(2) We have established a relationship between the temperature differential ΔT between the temperature sensor and the velocity sensor and the heat lost via natural and forced convection with **Equation 2**: $\mathbf{q_c = hA_v(T - T_g)}$**.** We still cannot completely solve **Equation 2** since we do not know the film coefficient **h**.

(3) However, we have established that the heat transfer parameter (the Nusselt Number **Nu**) is a function of various dimensionless numbers and, using some engineering assumptions, this is simplified into **Equation 4**:

(4) $\mathbf{Nu = A + B\ Pr^{0.33}\ Re^{n}}$

A, **B** and **n** are calibration constants, while the Prandtl number **Pr** is defined by the properties of the gas being calibrated, and the Reynolds number **Re** is defined by the gas mass velocity **ρV**, the geometry of the pipe and the viscosity **μ** of the flowing gas.

By calibrating with the actual gas, under operating conditions and in a flow body or equivalent pipe, Equations 1-4 allow us to derive a calibration curve relating the power input to the sensor **w** to the mass velocity in the pipe **ρV**. As long as the film coefficient **h** does not change with time (due to sensor degradation), we have a perfectly stable sensor.

The best immersible thermal sensor design contains no cements or organics. While this is much more expensive to manufacture, it is the most stable thermal sensor. In many immersible thermal sensor designs, the PRTD's we talk about above are glued or epoxied into the sheath. This may lead to cracking or shrinkage in this layer, and thus to a change in the thermal heat transfer properties of the sensor, causing drift or outright failure. In Sierra's patented design, the PRTD windings use no epoxies or cements.

Conclusion: A Tale of Two Thermals

Sierra's capillary and immersible thermal sensor technologies are direct reading mass flow devices. Each molecule of the gas transfers a little bit of heat downstream through the capillary tube or away from the immersible velocity sensor sting.

In capillary thermal sensor technology (by measuring the change in resistance due to heat transfer) and in immersible thermal sensor technology (by measuring how much heat must be added to replace the heat removed), Sierra thermal flowmeters actually "count" the number of molecules, or mass, passing the sensor per unit time. Because Sierra's thermal flowmeters measure gas mass flow rate at the molecular level, they are extremely accurate and repeatable, do not need to compensate for temperature and pressure effects, have tremendous turndown ratios, and are excellent at low flows.