Magnetrol®

Thermatel®

Thermal Dispersion Mass Flow

Measurement Handbook

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Introduction

Accurate mass flow measurement of gas is difficult to obtain. The main reason is that gas is a compressible fluid. This means that the volume of a fixed mass of gas depends upon the pressure and temperature it is subject to.

Consider a balloon containing one actual cubic foot of gas at room temperature (70° F) and atmospheric pressure. An increase in the room temperature causes the balloon to expand. An increase in the pressure surrounding the balloon results in a decrease in volume. Although the volume of the balloon changes with variations in pressure and temperature, the mass of the gas inside the balloon has remained the same. This illustrates how pressure and temperature affect the actual volume.

There are many well established methods of measuring the actual volumetric flow rate. However, the measured flow rate will vary with changes in temperature and pressure. For virtually all industrial process operations, the user wants to measure the *mass flow rate* instead of the actual flow rate. Chemical reactions work on the basis of mass relationships of ingredients. Combustion is based upon the mass flow rate of the air and the fuel. Gas consumption in a facility is based upon mass flow rate. To accurately measure mass flow, the actual flow rate must be adjusted to correct for any change in temperature and pressure.

Thermal mass flow technology is a method of gas flow measurement that *does not require* correction for changes in process temperature or pressure. Thermal mass flow technology also has a benefit of measurement at low velocities and greater turndown capabilities than those obtainable with other flow measurement devices.

$$\text{Turndown} = \frac{\text{Normal Maximum Flow}}{\text{Minimum Measurable Flow}}$$

What is Mass Flow Measurement?

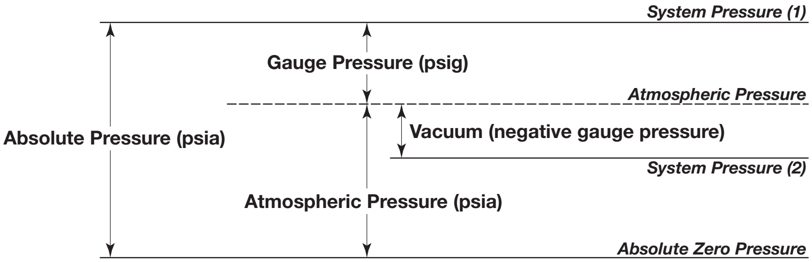
Mass Flow is the measurement of the flow rate without consideration of the process conditions. Mass flow is equivalent to the actual flow rate multiplied by the density. $M = Q \times \rho$ where Q is the actual flow and ρ is the density. As the pressure and temperature change, the volume and density change, however the mass remains the same.

To obtain standardization of gas flow measurement, Standard conditions of Temperature and Pressure (STP conditions) are utilized. Gas flow measured at STP conditions is corrected from the actual process conditions to standard conditions; this will be discussed in more detail later.

The simplest way of measuring mass flow of gas is in units of cubic feet per minute or cubic meters per hour, corrected to STP conditions. This is referred to as SCFM (standard cubic feet per minute) or the metric equivalent of Nm^3/h (normal cubic meters per hour). The density of a gas at standard conditions is known, thus providing a relationship between SCFM and pounds per hour or between Nm^3/h and kg/h.

The conversion between the volume at actual conditions and the volume at standard conditions is based on the ideal gas law — actual volume increases in direct proportion to an increase in absolute temperature, and decreases in direct portion to an increase in absolute pressure. Consider the balloon example — as the temperature increases, the volume expands; as the pressure increases, the volume shrinks.

Absolute pressure of zero psia (pounds per square inch at absolute conditions) is a perfect vacuum. One atmosphere of pressure is defined as 14.69 psia or zero psig. The conversion between psia and psig is easy: PSIA = PSIG + 14.69. If you have a pressure gauge calibrated for psig, it will read zero at sea level and only measure gauge pressure above atmospheric pressure. The following chart will help clarify this.



Absolute zero is defined as the temperature where molecular motion stops. It is defined as 0 K (Kelvin) which is -273.16° C or 0° R (Rankine) which is -459.67° F. To convert between actual temperature and absolute temperature, simply add 460 to the temperature in degrees Fahrenheit or 273 to the temperature in Celsius.

Once we establish a set of conditions as a standard temperature and pressure (STP conditions), we can convert between the flow rate at actual conditions and the flow rate at standard conditions.

$$\text{SCFM} = \text{ACFM} \left(\frac{T_{(s)}}{T_{(a)}} \right) \left(\frac{P_{(a)}}{P_{(s)}} \right)$$

The subscript (a) refers to actual conditions; the subscript (s) refers to standard conditions.

Unfortunately, not all STP conditions are universal. Many users consider one atmosphere and 70° F as STP. Some industries use one atmosphere and 60° F as standard; others use one atmosphere and 32° F as standard. The metric equivalent is Normal conditions which are based on a pressure of one bar (14.5 psia) and 0° C.

The important issue is that Standard Conditions are not Standard and a mass flow meter needs to be able to permit the user to select the desired STP condition. An error of approximately 8% will occur if there is a difference in STP conditions between 70° F and 32° F.

Once a set of standard conditions is identified, the density of that gas at these conditions is known. Therefore, it is a simple matter to convert from SCFM to mass in pounds per hour:

$$\frac{\text{pounds}}{\text{hour}} = \text{SCFM} \times \rho \, \frac{\text{pounds}}{\text{cubic foot}} \times \frac{60 \text{ minutes}}{\text{hour}}$$

In this formula, the density in pounds per cubic foot is the density at the specified STP conditions. A list of common gases and their density is in the appendix.

Types of Flow Transmitters

There are many types of flow transmitters — some are used for both liquid and gas flow measurement, while others are specifically used for one fluid. The following table identifies many of the different types of flow transmitters and their use in liquid, steam, or gas service, and if they measure actual flow or mass flow.

Technology	Liquids	Steam	Gas	Actual Flow	Mass Flow
Differential Pressure	X	X	X	X	
Vortex	X	X	X	X	
Turbine	X	X	X	X	
Magnetic	X			X	
Positive Displacement	X		X	X	
Variable Area	X		X	X	X
Coriolis	X		X		X
Ultrasonic	X		X	X	X
Thermal			X		X

As shown, there are many technologies to measure the flow rate of gas. Most of these methods measure the flow rate at the actual operating pressure and temperature and require pressure and temperature correction to obtain the mass flow.

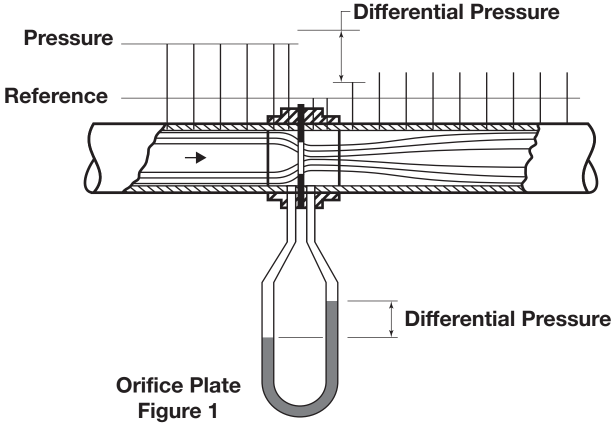
The following discusses some of the common types of flow measurement:

Differential Pressure

Measuring the pressure difference across a flow element is the most common method of flow measurement. There are several types of flow elements.

Orifice

The most common flow element is the orifice plate as shown in Figure 1.



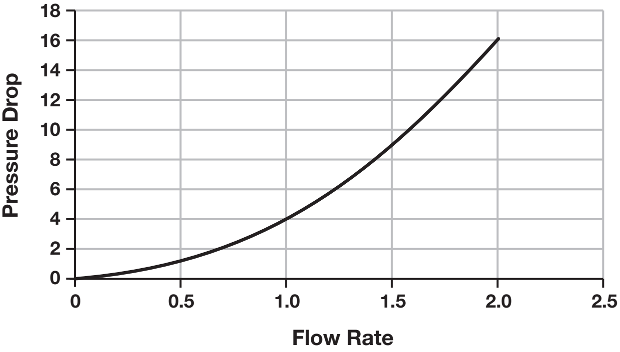
Orifice Plate
Figure 1

This method of flow measurement utilizes a proven technical concept called “Bernoulli’s Equation.” This relation states that the pressure drop across a flow restriction is based upon the square of the flow:

$$\text{Flow} = \text{constant} \times \left(\frac{\Delta P}{\rho}\right)^{1/2}$$

The flow rate is based upon flow at actual conditions.

The pressure drop across the flow element is proportional to the square of the flow. If the pressure drop (ΔP) is equal to “a”, and the flow rate doubles, the pressure drop increases to 4a. If the flow rate triples, then the pressure drop increases to 9a. Therefore the signal strength increases as the flow rate increases. At zero flow there is no signal, and the signal strength slowly increases as the flow increases as shown in the chart below. This results in poor low flow sensitivity.



Basic limitations of this type of flow measurement are:

1. Limited turndown. A 3:1 turndown causes a 9:1 reduction in pressure drop. A 4:1 turndown causes a 16:1 reduction in pressure drop. There becomes a limit on the turndown ratio of any differential pressure measurement instrument due to the DP transmitter. Some newer DP transmitters permit turndown ratio as high as 8:1. However, this is based on the maximum possible flow rate that the flow element can handle and does not necessarily reflect the user’s actual requirements.
2. Limited low flow measurement. There is a minimum flow rate, which generates a pressure drop that can be measured with any differential pressure measurement instrument. This is illustrated in the above graph.

3. Creates pressure drop. Because the flow measurement is based upon measuring a differential pressure, the flow measurement requires that additional pressure drop be added to the process, which increases operating cost. The pressure drop created by the primary element is frequently overlooked when considering operating cost.
4. Measures actual flow rate. Any differential pressure flow device measures *the actual flow rate* in ACFM. To determine the mass flow rate, correction from actual conditions to standard (mass) conditions is required. To determine mass flow from actual flow, it is necessary to measure:

    — Differential pressure

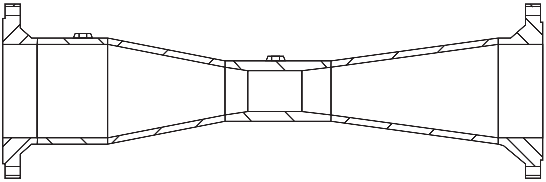
    — Absolute pressure

    — Absolute temperature

These measurements are then sent to a flow computer that calculates the mass flow rate in SCFM, using the equations previously discussed.

Venturi

A venturi flow element is very similar to the operation of the orifice plate, except that, due to the construction of the venturi, there is a recovery of energy reducing the overall pressure drop. A typical venturi flow element is shown in Figure 2.



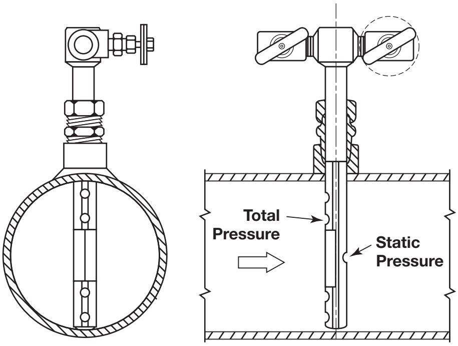
Venturi Flow Element
Figure 2

While reduction in energy consumption is desirable, a venturi flow element is considerably more expensive than an orifice plate; and, still suffers similar limitations, with respect to low flow sensitivity and sensitivity to changes in process pressure and temperature.

Averaging Pitot Tube

The averaging pitot tube can be an effective differential pressure measurement device. It is an insertion device that measures the average velocity across the pipe as shown the illustration below. While this type of instrument is effective for liquid and steam flow, it has limitations with air flow measurement, particularly low flow sensitivity and turndown.

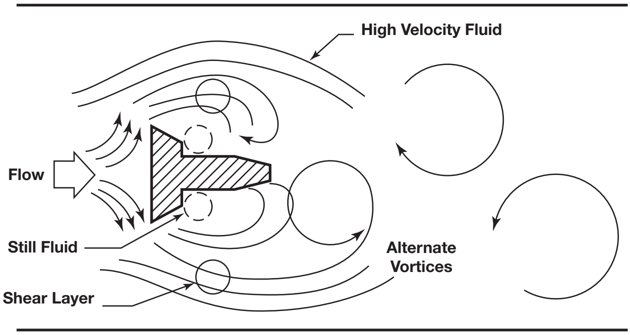
The flow measurement is based on determining the velocity pressure, which is the difference between the total pressure (measured on the upstream side) and the static pressure (measured on the downstream side). The velocity pressure provides an indication of the actual velocity at the operating temperature and pressure. The averaging pitot tube samples at various points across the pipe or duct in order to reduce the effect of flow profile. Refer to Figure 3.



Averaging Pitot Tube
Figure 3

Vortex Shedding

This technology is well accepted for flow measurement at high flow rates. The principle of operation is based upon the shedding or the creation of vortices from a blunt element. The instrument counts the number of vortices created; and, through a known relationship, converts this to the actual flow rate through the element. Refer to Figure 4.



Vortex Shedding
Figure 4

There is an empirical relationship between the number of vortices and the flow rate. There are limitations when using this technology for measurement of gas flow rates:

1. Vortex flow meters measure the actual flow rate, moving past the flow element. To convert to mass flow, it is necessary to measure pressure, temperature, and use a flow computer to calculate mass flow.
2. Minimum flow rate. There is a minimum flow velocity that generates vortices. At flow rates below this minimum flow rate, the instrument will not generate vortices. For many gas flow applications, the flow rate may not be high enough to create vortices. This reduces the ability to detect low flow rates and reduce overall turndown of the instrument. This is a physical limitation that exists for all vortex flow meters.

While vortex flow transmitters are occasionally used for high velocity gas flow, their most common applications are for liquid or steam flow.

Turbine Flow Meters

Frequently used for air and gas flow measurement, turbine flow meters are available as both an in-line body and an insertion probe.

The vanes of the turbine flow meter spin as the fluid moves — the greater the flow rate, the faster the vanes will turn. Various methods are used to count the pulse rate (number of turns) of the vanes.

Turbine meters can be accurate for measuring the actual gas flow rate; but, like other devices, they require pressure and temperature correction to obtain mass flow measurement. Turbine meters also have a minimum velocity that they can detect, and may require some type of lubrication of the bearings.

Many applications for turbine flow meters are for smaller, in-line flow bodies where pressure and temperature are fairly constant.

Ultrasonic Flow

Ultrasonic technology is used to measure the velocity of the fluid in a closed pipe. The sensors can be either insertion type or a non-invasive type, which clamp onto the side of the pipe. Multi path designs provide full coverage of the flow in the pipe.

Originally closed pipe ultrasonic technology was used for liquid flow measurement. Advances in the technology now permit it to be used for gas flow measurement, where the actual velocity in the pipe is measured. Some units will also determine gas density, in addition to velocity, and calculate the mass flow. These units tend to be extremely expensive.

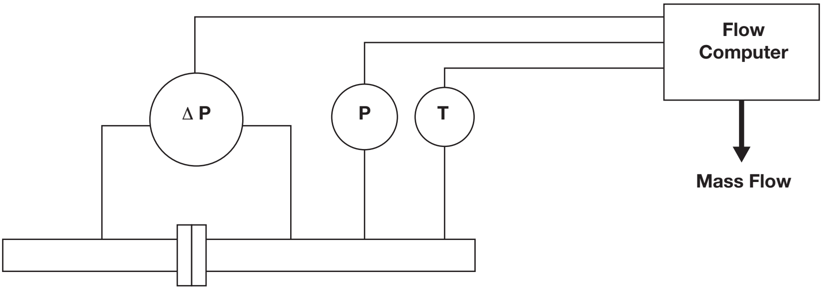
Coriolis

Coriolis is a direct form of mass flow measurement, which does not rely upon the physical properties of the fluid. When first developed, Coriolis flow meters did not have the sensitivity for gas flow measurement; however, the technology has improved and Coriolis is now used to measure gas flows.

The advantage of Coriolis is that it is a true, high accuracy, mass flow measurement, independent of the properties of the fluid. Disadvantages are that it is available only as an in-line device in sizes typically up to four inches. Coriolis flowmeters are expensive to purchase and install. May not be suitable for low flow, low pressure applications. Pressure drop across a Coriolis flowmeter is also a consideration.

Pressure/Temperature Correction

As previously discussed, many flow meters measure the actual flow rate rather than the mass flow rate. In order to obtain a mass flow measurement, it is necessary to correct for the actual pressure and temperature. Figure 5 illustrates what is necessary to obtain a mass flow measurement from a differential pressure flow measurement device (the most common form of flow measurement). The differential pressure across a flow element must be measured to obtain the actual flow rate; then, the actual flow rate must be corrected for pressure and temperature. This requires three separate instruments to measure differential pressure, pressure, and temperature. These signals are sent to a flow computer to determine the mass flow rate. Thermal mass flow technology replaces all of this with one instrument that directly measures the mass flow rate of the gas.



Actual to Mass Flow Conversion
Figure 5

Multi-Variable Transmitters

A multi-variable transmitter combines the function of the three transmitters (ΔP, P, and T) and the flow computer into one transmitter. The multi-variable transmitter measures the pressure and temperature of the gas, the pressure drop and then calculates the mass flow.

While only one 4–20 mA signal is generally available, measurement of the other variables is available via HART communication. The functionality of three transmitters in one device reduces the installation cost of differential pressure mass flow measurement.

Multi-variable transmitters are frequently used with averaging pitot tubes. Turndown ratios up to 8:1 are obtainable. This turndown ratio is based on the maximum allowable flow rate that the averaging pitot tube can detect. The actual turndown rate for the user's specific application will be less, depending upon the maximum flow the user wants to detect. Limitations in low flow measurement capabilities still exist.

Multi-variable transmitters are also integrated into some vortex flow transmitters. These instruments measure the actual flow rate using a vortex; then, also measure the pressure and temperature and provide a correction to mass flow. These instruments tend to be rather expensive.

Thermal Mass Flow

Thermal Mass Flow offers many advantages over other, more traditional, methods of measuring gas flow.

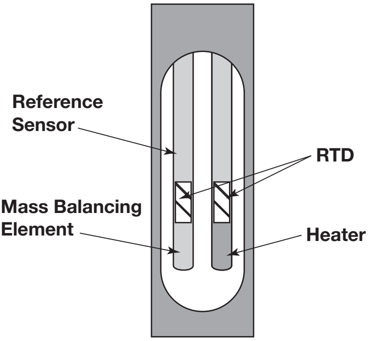
1. Mass flow measurement. Thermal mass flow transmitters provide a measurement of the mass flow rate of the gas based upon heat transfer. The gas flows past a heated surface creating a cooling effect. Heat transfer is caused by the mass (or molecular) flow of the gas providing a mass flow measurement. Correction of the gas flow rate for pressure and temperature is not required.
2. Excellent low flow sensitivity. Thermal technology can measure velocities down to 25 standard feet per minute —much lower than any other flow device. The heat transfer rate is greatest at low flow rates and decreases as the flow rate increases. This makes this technology especially sensitive for low velocity measurement.
3. Excellent turndown. Magnetrol's Thermal Mass Flow Transmitter offers the ability to measure the low velocities as well as high flow rates. This can provide a turndown rate of 100:1 or more depending upon the application requirements.
4. Low pressure drop. The insertion probe has little blockage of the pipe, thereby, creating very low pressure drops.
5. Ease in installation. Using an insertion probe, the instrument can easily be installed in a pipe or duct.
6. Factory Calibrated. Each instrument is calibrated by Magnetrol for the application specific requirements and configured to the user's specifications. The instrument can be installed and placed directly into service without any need for field set up, calibration, or adjustment.
7. Lowest installed cost. When considering options to measure mass flow, the TA1/TA2 has the lowest installed cost while providing excellent performance. No additional instrumentation is required to obtain a mass flow measurement.
8. Linear output signal. The TA1 and TA2 provide an output signal which is linear with the mass flow rate. Compare this against differential pressure flow measurement which provides a non-linear – square root curve of flow vs. signal which then must be linearized by the user.

Magnetrol offers two different thermal dispersion mass flow transmitters with different functionality to meet the user's application requirements:


Model TA1


Model TA2

The sensor used with Magnetrol's Thermal Mass Flow Transmitters is illustrated in Figure 6.



TA1/TA2 Sensor
Figure 6

The sensors on the TA1/TA2 are protected to prevent possible damage from "bottoming out" when inserted into a pipe. This is an important consideration if the probe is installed into the pipe with a compression fitting. There are two sensors — a heated sensor (shown on the right) and a reference sensor which measures the temperature of the gas. Precision matched Platinum RTDs are used for the temperature measurement. A mass balancing element is used to ensure that both sensors will respond the same to changes in temperature.

Different Types of Thermal Mass Flow Meters

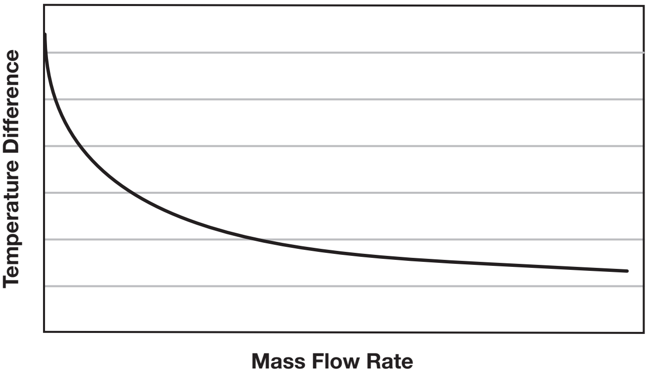
There are two different technologies utilized for thermal mass flow measurement. Both methods obtain the same results, and the user should not care which method is used. Magnetrol has experience with both types.

Constant Power

This technology uses a constant power to the heater. The instrument measures the temperature difference between the heated sensor and the reference sensor, which measures the process temperature. The temperature difference decreases as the flow rate increases. This is the method utilized in the TA1.

At low flow rates the temperature difference between the sensors is greatest. As the flow rate increases, the temperature difference decreases. A curve of temperature difference versus mass flow rate is shown in the chart below.

The change in temperature difference with mass flow rate is very large at the low flow rates – this provides excellent low flow sensitivity as previously mentioned. As the flow rate increases, the temperature difference decreases yet the curve still shows good sensitivity at very high flow rates providing high turndown capabilities.

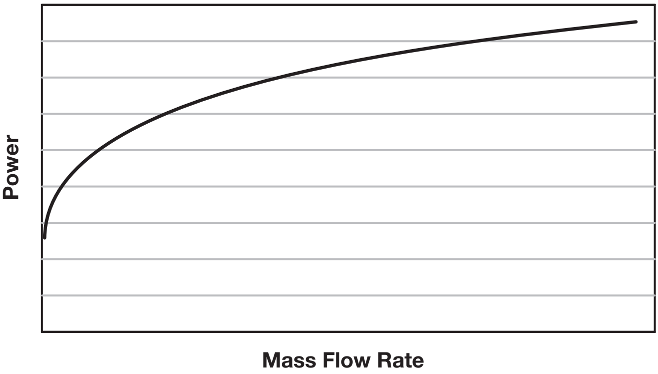


Constant Temperature Difference

This technology maintains a constant temperature difference between the heated sensor and the reference sensor. The instrument controls the amount of power to the heater to maintain this temperature difference. As the flow rate increases, more power is required to maintain this constant temperature difference. Refer to the chart at right. This is the technology used in the TA2.

As shown in the illustration, at low mass flow rates, there is little heat transfer, and thus the amount of power required to maintain the desired temperature difference is low. As the mass flow rate increases, the amount of power required to maintain a constant temperature difference increases.

As with the constant power operation, changes in heat transfer are greatest at low velocities thus providing excellent low flow sensitivity. As the mass flow rate increases, the power increases as shown. This permits flow measurement at very high flow rates providing high turndown capabilities.



With both the TA1 and TA2, there is an inherently non linear signal between mass flow rate and signal (either temperature difference or power). The instrument linearizes the signal to produce a linear 4-20 mA output signal over the dynamic range of the instrument.

The user can easily modify the 4 and 20 mA points if desired in the field. Other field configuration may include changing the pipe or duct size, units of measurement, damping, and other specific application factors.

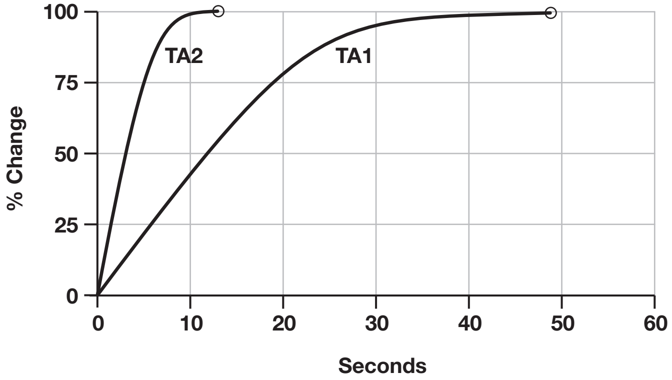
Response Time.

Magnetrol's first Thermal Dispersion Mass Flow Transmitter – the TA1 uses a constant power operation. The technology has performed very well, however it suffers from slow response to changes in flow rate. With the development of the TA2, we desired to have a faster response time which is available with a Constant Temperature Difference operation.

Both the TA1 and TA2 use the same sensor. There is an inherent time response for the thermal mass of the sensor to heat up or cool down due to changes in flow rate. The difference in response time between the two technologies is explainable.

Constant Power operation is a passive operation. The temperature difference is dependent upon how long it takes for the heated sensor to heat up or cool down with flow changes. The response time depends upon the amount of the step change, if there is an increase or decrease in flow rate, and the type of gas.

The constant temperature difference operation used in the TA2 has a faster response time to changes in flow. The TA2 controls the power to the heater to always maintaining a constant temperature difference between the reference RTD and the RTD measuring the temperature of the heater. The response time of the TA2 compared with the response time of the TA1 is shown in the chart below.



The TA2 uses control algorithms in the instrument to provide a response time that is significantly faster than the TA1. The result is an instrument that provides improved real time gas flow measurement.

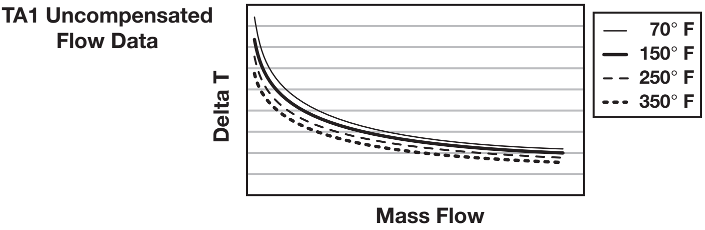
Temperature Compensation

Thermal Mass Flow Transmitters measure heat transfer and infer the mass flow based upon calibration information. Calibration will be discussed in more detail later.

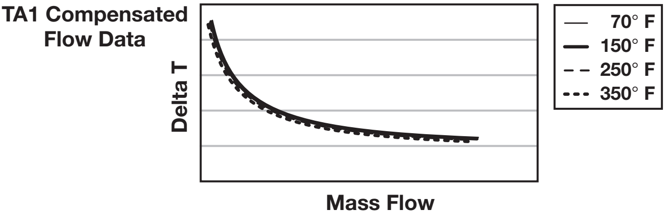
However, the gas properties that affect convective heat transfer are affected by changing temperature.

Magnetrol has done extensive testing and analysis on the effect of changes in flow at different temperatures and has developed a proprietary method of providing temperature compensation over the entire operating range of the instrument. The chart at provides typical curves for the TA1 showing flow vs. temperature difference over a range of temperatures.

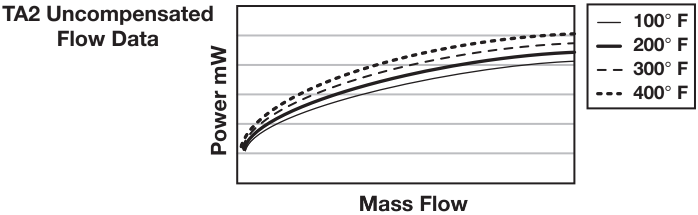
Magnetrol compensates temperature over the entire operating temperature range of the instrument. *The TA1/TA2 measures the temperature and then applies a correction in the flow measurement based upon the operating temperature.*

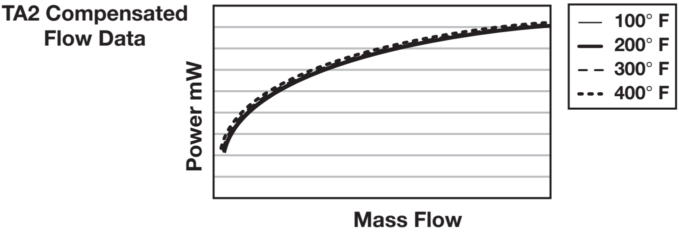


The chart below shows the same data after we apply our temperature compensation.



The same effect occurs with the TA2 using constant temperature difference. The charts below show data from the TA2 with and without temperature compensation.





These illustrations demonstrate the effectiveness Magnetrol's temperature compensation of the mass flow measurement based upon varying gas properties.

Some thermal mass flow manufacturers just temperature compensate the electronic circuit. What these manufacturers overlook is that the gas properties that affect convective heat transfer are temperature dependent. Thus changing temperature changes heat transfer. Magnetrol provides real time temperature compensation that measures the temperature of the gas and automatically corrects the mass flow measurement based on temperature variations.

Without real time temperature compensation, the accuracy of the flow measurement will degrade with temperature changes. In some competitive designs, the rated accuracy is only good within 50° F of the calibration temperature.

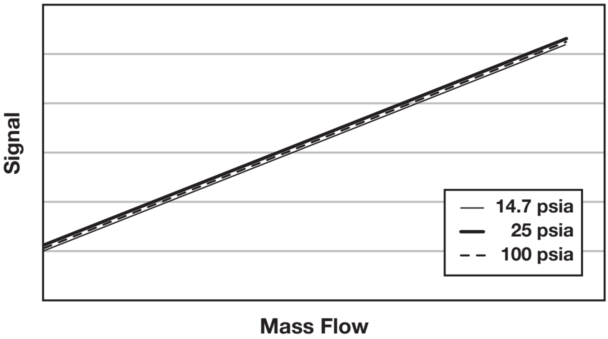
If the instrument does not provide a temperature measurement, the instrument can not provide real time temperature compensation. This is especially a consideration with other manufacturer's constant temperature difference operation; these designs have a reference RTD and a self heated RTD. The reference RTD is used in the electronic circuit and does not provide temperature measurement. Thus these instruments do not provide real time temperature compensation.

Another consideration in using a self heated RTD is that the resistance of the self-heated RTD changes with temperature. Without knowing the temperature, the instrument cannot compensate for the changing resistance of the heated RTD.

Magnetrol's advanced real time temperature compensation is an important feature which provides superior performance for the Model TA1 and TA2.

Pressure Effects

Heat transfer is affected by changing temperature. This is based upon both theory and Magnetrol's own experience. However, heat transfer is not affected by changing pressures. The chart below demonstrates that pressure does not affect thermal mass flow measurement.



An increase in pressure will increase the gas density – there is the same amount of heat transfer with a low velocity, high density gas as there is with a high velocity, low density gas.

Calibration

Each instrument is calibrated for the gas and the specified flow rate. Calibration involves flowing a known amount of gas over the sensor and measuring the signal. This is repeated for at least 10 different flow rates. A curve fit of the data versus flow rate is developed and then loaded into an EPROM in the instrument. The calibration is NIST traceable. A calibration certificate is included with the instrument and all calibration data is retained at Magnetrol for future reference.

When installed and placed into operation, the instrument measures a signal, and then converts that signal to the flow rate for the user's application. The instrument adjusts for differences in area and blockage effect between the calibration fixture and the field installation.

Each gas has different thermal properties that effect convective heat transfer. An instrument calibrated for air will not give accurate measurements if used for natural gas. Each instrument is calibrated for a specified gas over the maximum flow rate specified.

Each instrument has its own unique calibration. The sensor and the electronics are a matched pair—each has a serial number to enable matching the units in the field. This has been a difficulty with this technology. Previously, if the probe needs to be replaced, the probe and associated electronics must be calibrated together as a unit. There are tolerances in both the probe and the electronics which effect the calibration. With the development of the TA2, Magnetrol has developed a method by which the probe (or circuit boards) can be field replaced. A new calibration certificate will be provided with the replacement probe and the user will enter these new probe calibration factors into the instrument using either the key pad and display or via HART.

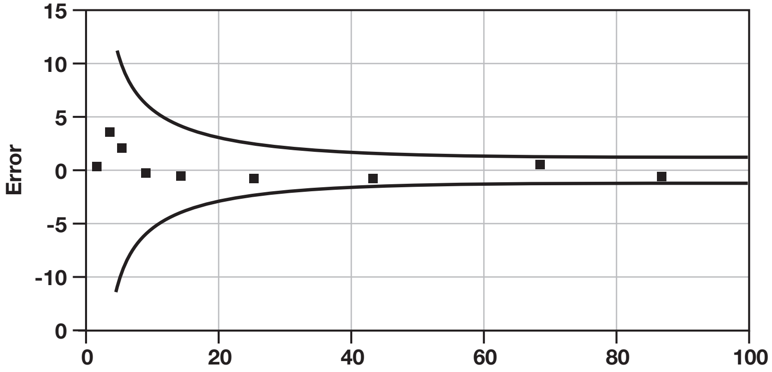
The cable length is totally independent of the calibration. This enables the customer to provide their own cable or to change the cable length in the field. Some competitors' units require that the instrument be calibrated with the specified cable length, and any change in cable will affect the accuracy.

Calibration vs. Configuration

Often users will want to calibrate an instrument in the field. Often what they really want to do is to configure the instrument in the field. Calibration requires a flow bench; configuration of the instrument for the specific application is very simple permitting the user to change pipe or duct size, range and span of the 4-20 mA signal, units of measurement, installation factors. The user has full capability to configure the TA1 or TA2 to fit the application.

Accuracy

The accuracy of the TA1/TA2 is well accepted in the industry. Our stated accuracy is ± 1% of reading plus 0.5% of full scale.



The accuracy component is made up of both a measurement of reading and a percentage of overall span. At 100% of full scale, the accuracy will be ±1.5 %. As the flow decreases, the accuracy is represented in the chart above. All calibration points must fall within these boundaries.

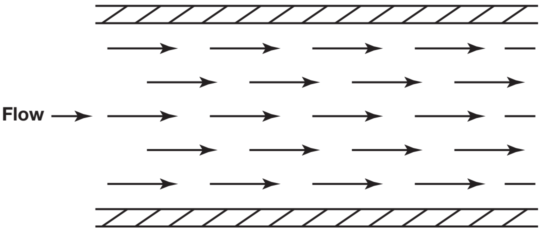
Flow Profile

While Magnetrol goes to great extent to provide an instrument with excellent accuracy, our accuracy is the calibration accuracy. When the probe is inserted into a pipe or duct, the sensor will measure the flow at that point. Therefore the measured flow is affected by the flow profile at the location of the sensor.

When a fluid flows in a pipe, it develops a flow profile. A flow profile will either be laminar or turbulent. These terms are sometimes misused.

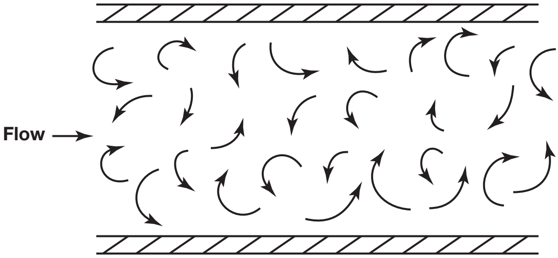
In laminar flow, each fluid particle travels in a straight line as it flows through the pipe. Refer to Figure 7.

The fluid moves in layers with each layer sliding over the other. The velocity of the fluid at the wall is zero and increases as the distance from the wall increases as shown in Figure 9.



Laminar Flow
Figure 7

With turbulent flow, the flow path consists of eddies and swirls within the fluid; there is intermixing as the fluid flows. Typical turbulent flow is shown in Figure 8.



Turbulent Flow
Figure 8

Turbulent flow and laminar flow have very specific definitions based upon its Reynolds number.

Reynolds Number is defined as:

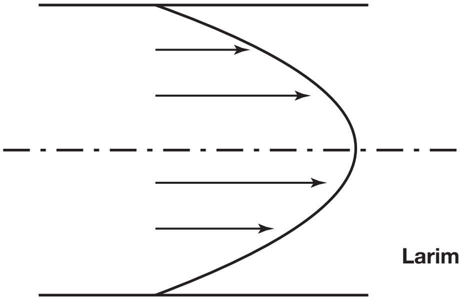
$$Re = \left[\frac{VD\rho}{\mu}\right]$$

Reynolds Number shows the relationship between:

V = Velocity
D = Diameter
ρ = Density
μ = Viscosity

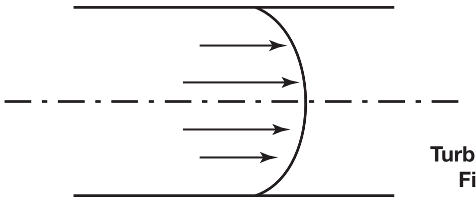
Reynolds numbers less than 2,000 are laminar flow, larger than 4,000 are turbulent flow, and between 2,000 and 4,000 are considered transition zone.

The flow profile in the pipe for laminar flow and turbulent flow are considerably different. With laminar flow the flow moves straight ahead without mixing. The velocity at the wall is zero and the velocity profile across the pipe will look something like Figure 9. Because there is no mixing, the velocity at the centerline is much greater than the average velocity.



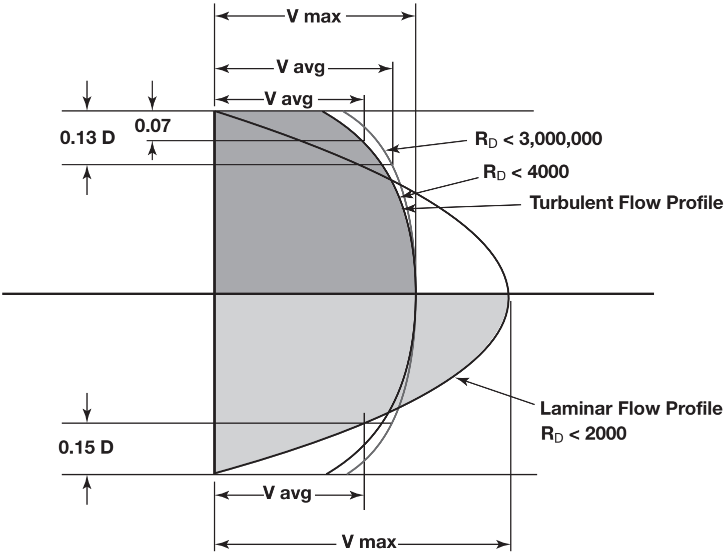
Larimar Flow Profile
Figure 9

A fully developed turbulent flow profile is shown in Figure 10.



Turbulent Flow
Figure 10

Virtually all gas flow applications will be in the turbulent flow area. Theoretically the velocity at the pipe wall is zero and the velocity at the centerline is approximately 20% higher than the average velocity. In turbulent flow, the flow profile will change slightly with Reynolds Number as shown in Figure 11.



Laminar vs. Turbulent Flow Profile
Figure 11

In turbulent flow, the location of the average velocity will range between 0.07 D (1⁄14 the diameter) to 0.13 D (1⁄8 the diameter), depending upon the Reynolds number. At this location, changes in velocity (Reynolds number) will change the flow profile.

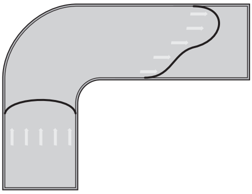
The center line velocity in turbulent flow is approximately 20% greater than the average velocity. The lower portion of Figure 11 shows a laminar flow profile — the centerline velocity is approximately twice the average velocity.

Another factor, which is not shown, but will also affect the velocity profile, is the roughness factor of the pipe. Rough pipe will have a different velocity factor than smooth pipe.

There are difficulties locating the sensor at the point of average velocity. This location may be difficult to accurately determine as the profile will change with changes in velocity. The velocity profile is very sensitive at this point; a slight variation in flow profile will cause a major change in the flow measurement.

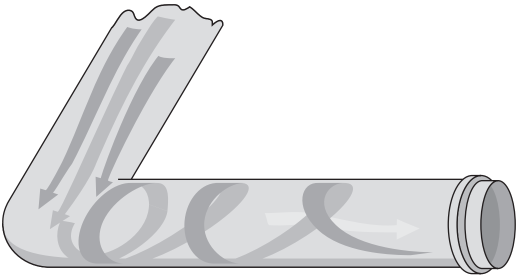
The best place to locate the sensor is at the centerline of the pipe. The pipe centerline is easy to determine, and changes in profile will have minimal effect on the flow profile. The disadvantage is that the centerline velocity of a fully developed turbulent flow profile is 20% theoretically higher than the average velocity.

These flow profiles are based on what is referred to as a fully developed turbulent flow profile. This flow profile will exist in a long straight section on pipe. As the gas flows around an elbow, the momentum causes the gas velocity on the outside of the elbow to increase and the velocity on the inside to decrease. This is shown in the Figure 12.



Turbulent Flow Profile
Figure 12

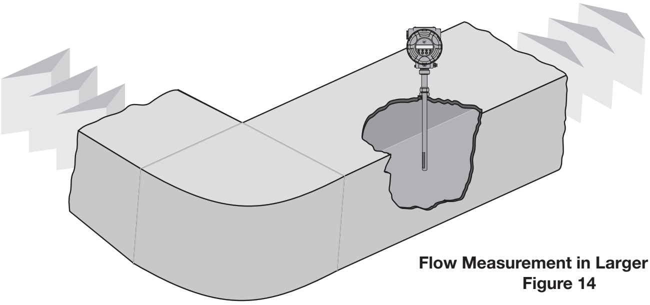
In addition to changing the flow profile, as the gas flows around an elbow, a rotational component, or swirl is introduced into the flow profile as shown in Figure 13.



Swirl Flow Profile
Figure 13

With sufficient straight run of pipe, swirl patterns will dissipate and a fully developed turbulent flow profile will redevelop. Historically, 10 diameters upstream and 5 diameters downstream was considered as adequate straight run. Recent testing by NIST has demonstrated that these dimensions may not be sufficient, especially if there are two elbows. Magnetrol's brochure 54-131 provides additional information on recommended probe locations.

For flow measurement in larger ducts, a single probe can be used to obtain a repeatable flow measurement suitable for combustion air flow applications. In some applications, the probe has been inserted directly following an elbow. Refer to Figure 14.



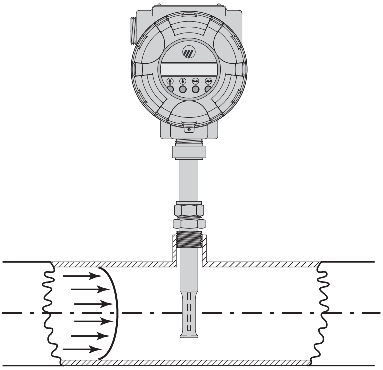
Flow Measurement in Larger Ducts
Figure 14

The effect of flow profile variations and swirl patterns may result in the probe being positioned at a location where the flow profile is different that the flow profile during calibration.

For most process flow measurement, there is insufficient room to obtain a perfect flow profile. The basic rule is to attempt to get as much straight run as possible and position the probe to get two to three times the upstream as downstream distance.

Installation Options

There are various options for installing the probe into the pipe or the duct. Perhaps the most common and simplest is the simple compression fitting shown in the Figure 15 below.



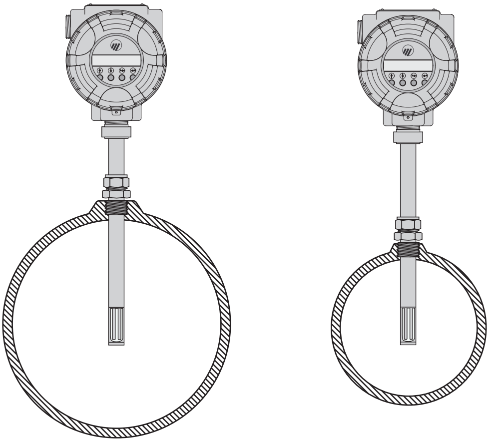
Typical Probe Installation
Figure 15

Insertion probes with compression fittings can fit into pipe sizes1½" and larger.

A standard bored-through compression fitting is commercially available through Magnetrol or Swagelok, Parker-Hannifin, and others. Either a ¾" NPT or 1" NPT for ¾" tubing is useable.

Compression fittings are available with either Teflon ferrules or stainless steel ferrules. The Teflon ferrules are useable for pressures up to 100 psig and have the advantage of being able to slide along the probe and readjust the position. Stainless steel ferrules are suitable for much higher pressures; however, once the ferrules are swaged onto the probe they cannot be removed. This has an advantage to ensure that the probe is reinserted into the same location.

Another benefit of using compression fittings with Teflon ferrules is the ability to interchange units in the field. Providing that the probe length is long enough, the same instrument can be used in multiple pipe sizes, or an additional unit kept as a spare. Refer to Figure 16.



Probe Installation in Different Pipe Sizes
Figure 16

Hot tap Retractable Probe Assembly is also available for the TA1/TA2 probe. Designs are available for different pressure ranges.

Other process connections include NPT threads, BSP threads, and ANSI and DIN flanges. We recommend locating the end of the probe one inch (25 mm) past the center line of the pipe. This places the sensor at the centerline.

Accuracy vs. Repeatability

While most users talk about accuracy, for process flow applications, repeatability of flow measurement is most important. Does the flow transmitter measure the same today, for the same set of conditions, as it did last week? From this respect, thermal mass flow measurement is excellent. Our repeatability of flow measurement is specified as 0.5% of reading.

While our absolute accuracy is important, and we have gone to great extent to be able to calibrate the instrument to the stated accuracy, we have no control over external factors.

Factors which can affect total system accuracy, include:

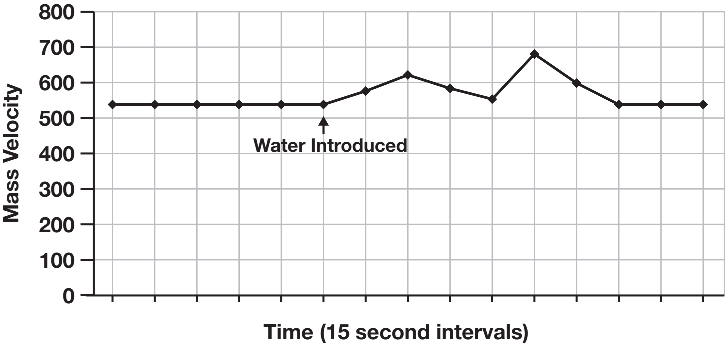
1. Blockage effect. The sensor and probe block a portion of the flow path, reducing the cross sectional flow area. Magnetrol takes this blockage into account with area compensation built into the software. This feature is not available on all competitors' units.
2. Error in entering flow area. If this information is entered inaccurately, the flow rate will be in error.
3. Standard conditions are not always standard. The TA1/TA2 permits the user to select the desired standard conditions. The TA1/TA2 will adjust the flow measurement based on different STP conditions. An error of approximately 8% will occur with differences in STP conditions between 70° F and 32° F.
4. Flow profile. As discussed above, flow profile can have a significant impact on flow measurement. The TA1/TA2 has the ability to correct the flow measurements for flow profile.

Magnetrol has taken into account many factors to provide the user with the ability to configure the instrument to their own requirements, thereby, providing the best possible overall performance.

Limitations of Technology

While thermal mass flow measurement offers many advantages, there are also some limitations:

1. Condensed moisture. Droplets of moisture coming in contact with the heated sensor will cause additional cooling of the sensor. Moisture in the vapor state is not a problem. Applications where condensed moisture is present must be avoided. The effect of moisture on the flow measurement is show in the chart below.



2. Changing gas compositions. The instrument is calibrated for the heat transfer created by a particular gas composition. If the gas composition changes, the heat transfer rate will change, which affects the overall accuracy of flow measurement. Minor changes in composition (such as variations in the humidity of air) will not have a noticeable effect.
3. Buildup. Buildup on the sensor will reduce the heat transfer rate, thus creating less cooling and indicating a lower flow than actual. For applications where buildup may be present, it is suggested that after startup, the condition of the sensor is periodically checked and a history of frequency of cleaning be developed and followed.

Applications

There are many applications for thermal dispersion mass flow measurement. Some of the more typical and successful applications are:

1. Compressed air/gas. Measurement and totalization of compressed air or gas flow is utilized for internal plant allocation and measurement of overall consumption.
2. Combustion air flow. Measurement of the mass flow rate of combustion air is desirable when determining fuel to air mixtures for proper combustion control. Thermal mass measurement is very appropriate due to combination of direct mass measurement, excellent low flow sensitivity, wide turndown, and low pressure drops.
3. Natural gas. In-plant measurement of natural gas flows to boiler, furnaces, dryers, and heaters is an ideal application for thermal mass flow measurement. While the composition of natural gas may vary slightly during the year, these changes will be minor; and, the advantages of thermal mass flow measurement will outweigh the limitations of other technologies.
4. Digester/Bio-Gas. Difficult application due to low flow rates and low pressures. Gas is a mixture of Carbon Dioxide and Methane. Gas is very wet. Thermal dispersion is a proven method to measure and totalize this flow.

There are many other applications for thermal dispersion mass flow measurements, however, it is difficult to list all them all. Main factors to consider are:

1. Is the gas composition relatively constant?
2. Is the flow range within the acceptable rates, considering the flow rate and the pipe size?
3. Is there any condensed moisture in the gas flow?
4. Is there particulate matter?

If any answers are questionable, check with Magnetrol to ensure that the application is suitable.

Difficult Applications

1. Flare lines. Thermal dispersion mass flow offers many benefits for flare lines — wide turndown, low flow detection, and low pressure drop. Thermal flow measurement has successfully been used in this application. However, consideration must be given to changes in gas composition.

   Different gases have different thermal properties that affect convective heat transfer. Changes in gas composition will change heat transfer rates, resulting in inaccuracies in flow measurement.

   If used in a flare line with relatively constant gas compositions, there is no difficulty. However, if used in an application with wide variations in gas composition, especially major changes in concentration of hydrogen, the user must be made aware of the considerable potential for inaccurate flow measurement. Hydrogen cools the sensor much greater than other gases; a small flow of hydrogen will appear like a much larger flow of other hydrocarbons.

   In many cases with changing gas composition, the instrument is calibrated for a typical gas analysis. Magnetrol can provide some estimates on how gas composition changes will effect the flow measurement. If there are changes in composition, the instrument will still provide trend indication.

2. Stacks. While thermal mass flow measurement has successfully been used for measurement of stack flow, generally multiple point array systems are utilized for large diameter stacks. Another option is to use four or more single point probes inserted from opposite sides of the stack. An external device is needed to average the flow rates.

Unique Features

There are several unique features of the TA1/TA2:

1. Temperature compensation, over the entire dynamic range of the instrument, by measuring the temperature and adjusting the flow measurement for changes in physical properties. For more information, review the section on Temperature Compensation.
2. Area blockage. When the probe is installed in a pipe, a certain amount of the cross sectional area is blocked. The smaller the pipe, the greater the blockage effect. The instrument measures the velocity past the sensors. Competitors' units simply multiply the velocity by the cross sectional area to obtain flow rate. By doing this, they are assuming that there is zero blockage of the pipe due to the insertion of the probe. This can cause a considerable error in the flow measurement. The TA1 and TA2 automatically adjust the blockage factor based upon the flow area.
3. Self-Diagnostics. The TA1/TA2 has greater self-diagnostics than found on competitors units. The electronics monitor the return signal from the sensor to ensure that the sensor is operating within range. The electronics also conduct self-diagnostics on the electronics to ensure that there is no drift or failure of the electronic circuit. The TA2 provides additional diagnostics permitting the user to individually check the status of the heater and RTDs.
4. Software. The TA1/TA2 software has the same feel as similar Magnetrol products. This intuitive programming makes it easy for the user to configure and operate the instrument.
5. Flow profile compensation. Advanced users can factor the flow measurement for flow profile.
6. Two 4–20 mA outputs—one for flow and one for temperature (TA1 only). The 4–20 mA signals can be set up for either active and passive operation.

7. Selectable STP conditions. The TA1 and TA2 permit the user to select STP conditions utilized at their facility. Without having this option, flow errors of approximately 8% can occur.

9. Digital communication capabilities. The TA1 provides RS-485 Modbus communication while other competitive units provide only proprietary protocol.

9. HART. The TA2 provides HART communication with a full operational DD which permits the user to virtually do anything over HART which can be accessed via the key pad and display.

10. The TA2 has an optional Probe Simulation Module. This device permits the user to replace the probe with a known standard to verify proper operation of the transmitter.

References:

David Spitzer, Industrial Flow Measurement, 1990. Instrument Society of America

Richard W. Miller, Flow Measurement Engineering Handbook, Second Edition, 1989, McGraw-Hill Book Company

Common Conversion Factors

Atmosphere	× 1.01325	= Bars
	× 33.8995	= Feet of water (32° F)
	× 29.92125	= Inches of Mercury (32° F)
	× 406.794	= Inches of Water (32° F)
	× 101.325	= Kilopascals
	× 760	= mm Mercury (0° C)
	× 1.01325 x 105	= Newtons/square meter
	× 1.01325 x 105	= Pascals
	× 14.696	= Pounds/square inch
	× 760	= Torr
Bar	× 0.986923	= Atmospheres
	× 100	= Kilopascals (Kpa)
	× 14.5038	= Pounds/square inch
Cubic Feet	× 0.028316	= Cubic meters
	× 28.31605	= Liters
Cubic meters	× 35.31467	= Cubic feet
	× 1000	= Liters
Feet	× 30.48	= Centimeters
	× 0.3048	= Meters
Inches	× 0.083333	= Feet
	× 25.4	= mm
	× 0.0254	= Meters
Kilograms	× 2.2046	= Pounds
Kilopascal (Kpa)	× 0.1450377	= Pounds/ sq inch
	× 4.01474	= Inches water
Meters	× 3.2808	= Feet
	× 1000	= mm
NM^3/H	× 0.5886	= SCFM
	× 1000	= l/h
Pounds/sq inch	× 0.068046	= Atmospheres
	× 0.0689476	= Bar
	× 27.6807	= Inches water (32° F)
	× 6.89476	= Kilopascals
Square feet	× 144	= Square inches
	× 0.09290304	= Square meters
Square meters	× 10.7639	= Square feet
	× 1550.0031	= Square inches
	× 1 × 106	= Square mm
SCFM	× 1.69990	= NM^3/H
	× 1,698.96	= Nl/h

Temperature:

T° C = (T° F -32)/1.8
T° F = 1.8 × T° C + 17.8
T° K = T° C + 273.15
T° R = T° F + 459.67

Gas Density at Standard Conditions

Gas	Chemical Formula	Molecular Weight	Density lb/ft^3 (1)	Density kg/m^3 (2)	Gravity SG
Air	-	28.96	0.0748	1.2740	1.000
Ammonia	NH_3	17.03	0.0440	0.7491	0.588
Argon	Ar	39.95	0.1032	1.7572	1.379
Bio Gas	65% Methane, 35% CO_2	25.83	0.0668	1.1363	0.892
Butane	C_4H_{10}	58.12	0.1502	2.5567	2.007
Butylene	C_4H_8	56.11	0.1450	2.4681	1.937
Carbon Dioxide	CO_2	44.01	0.1137	1.9359	1.520
Carbon Monoxide	CO	28.01	0.0724	1.2321	0.967
Chlorine	Cl_2	70.91	0.1833	3.1205	2.449
Ethane	C_2H_6	30.07	0.0777	1.3227	1.038
Ethylene	C_2H_4	28.05	0.0725	1.2340	0.969
Helium	He	4.00	0.0103	0.1761	0.138
Hexane	C_6H_{14}	86.18	0.2227	3.7908	2.976
Hydrogen	H_2	2.02	0.0052	0.0887	0.070
Methane	CH_4	16.04	0.0415	0.7057	0.554
Nitrogen	N_2	28.01	0.0724	1.2323	0.967
Oxygen	O_2	32.00	0.0827	1.4076	1.105
Pentane	C_5H_{12}	72.15	0.1865	3.1738	2.491
Propane	C_3H_8	44.10	0.1140	1.9397	1.523
Propylene	C_3H_6	42.08	0.1088	1.8510	1.453
Sulfur Dioxide	SO_2	64.06	0.1656	2.8191	2.213

1. Gas Density at 70° F and 14.7 psia
2. Gas Density at 0° C and 1 bar

Magnetrol®

Worldwide Level and Flow Solutions^{SM}

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Bulletin: 54-621.3 • Effective: September 2007