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 gas flow measurement devices.

## 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 of the gas. $M = Q \times \rho$ where $Q$ is the actual flow and $\rho$ 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.

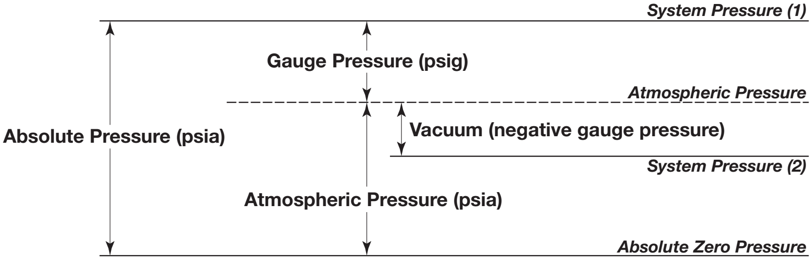


**Figure 1**

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 or 1 bar and 20°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 | |
| 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 2.

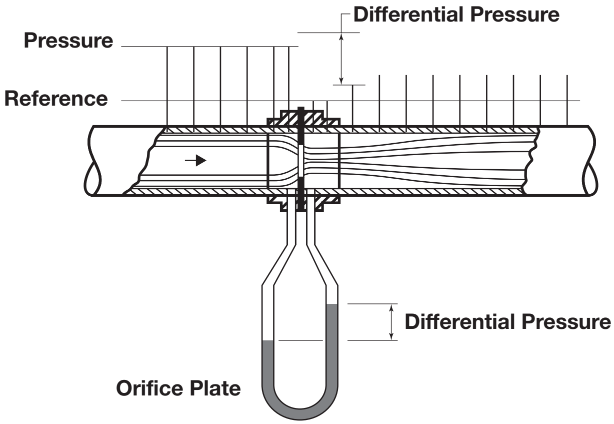


Figure 2

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 operating 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.

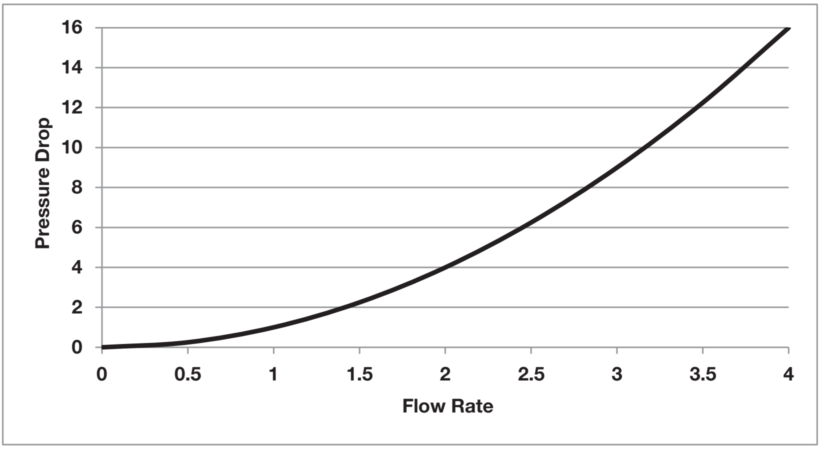


Figure 3

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. Typical turndown of a DP transmitter is 10:1.
2. Limited low flow measurement. There is a minimum flow rate which generates a pressure drop that can be measured with any differential pressure transmitter. 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

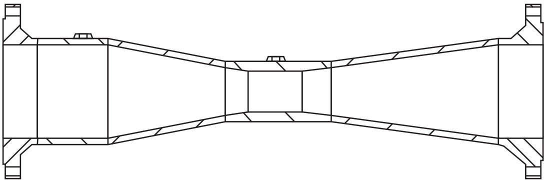
   — Absolute temperature

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 4.

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.



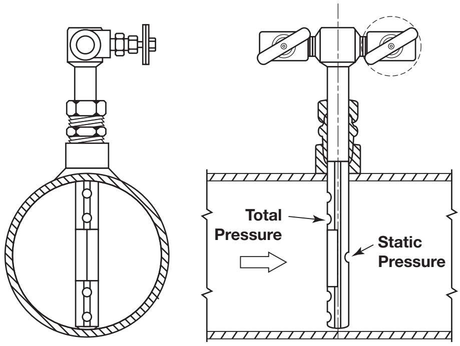
**Venturi Flow Element**

**Figure 4**

### Averaging Pitot Tube

The averaging pitot tube can be an effective differential pressure flow measurement device. It is an insertion device that measures the average velocity across the pipe as shown in the illustration below. While this type of instrument is effective for liquid and steam flow, it has limitations with gas 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 5.

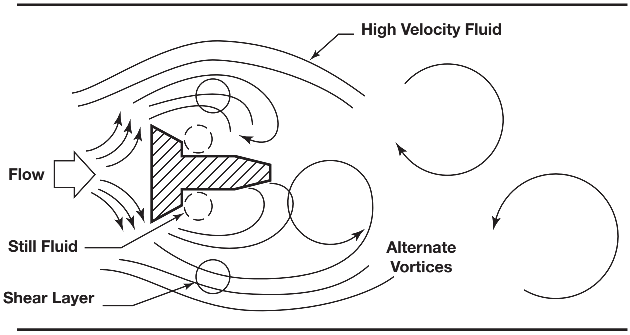


**Averaging Pitot Tube**

**Figure 5**

### 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 6.



**Vortex Shedding**

**Figure 6**

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. This is why some vortex flow meters are reported to drop off at the low end. 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. Sometimes the pipe size is reduced in order to increase the velocity through the vortex flow meter to improve low flow sensitivity. This complicates an installation—especially if done as a retrofit on an existing installation.

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. They are also known to continue spinning after the flow has stopped resulting in high flow measurements.

Many applications for turbine flow meters are for smaller, in-line flow bodies where pressure and temperature are fairly constant. Because of the moving parts the gas does need to be clean.

### 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.

When there is flow, the time for a pulse to go between the downstream and upstream transducer will be longer than the time from the upstream to the downstream transducer. The faster the velocity the greater this difference in time. This time difference can then be used to calculate the velocity and flow in the pipe at operating conditions. Measurement of both pressure and temperature is used to obtain mass flow.

The accuracy of an ultrasonic flow meter can be improved by providing multiple sets of transducers or paths which measure the flow in different areas of the pipe.

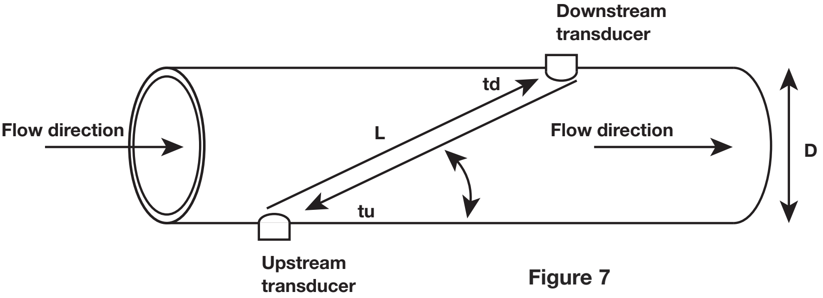


Figure 7

### Coriolis

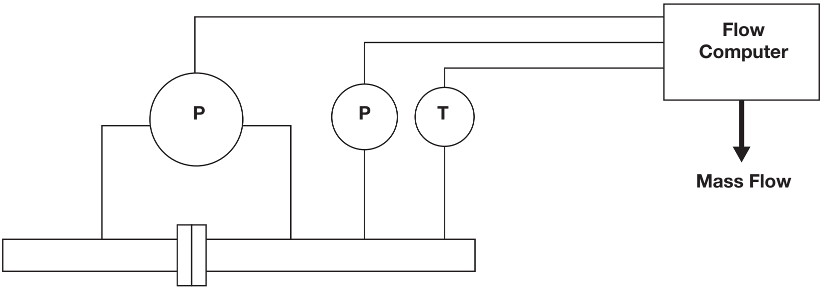
Coriolis is a direct form of mass flow measurement, which does not rely upon the physical properties of the fluid. When first developed, Coriolis flow meters did not have the sensitivity for gas flow measurement; however, the technology has improved and Coriolis is now used to measure gas flows.

There are a variety of designs of Coriolis Mass Flow Meters. These include single straight tube, multiple straight tube, curved tube, S-tube and other variations. They work on the basic principle that the the Coriolis force is dependent on the mass flow through an oscillating sensor tube.

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 with limitations in size. 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 at operating conditions 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 8 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 8

## Multi-Variable Transmitters

A multi-variable transmitter combines the function of the three transmitters ($\Delta P$, 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 in flow 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 application. 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.

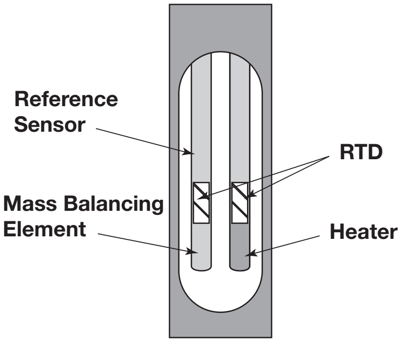
1. Mass flow measurement. Thermal mass flow transmitters provide a measurement of the mass flow rate of the gas based upon heat transfer. The gas flows past a heated surface creating a cooling effect. Heat transfer is caused by the mass (or molecular) flow of the gas providing a mass flow measurement. 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 10 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 and high turndown requirements.
3. Excellent turndown. The Magnetrol® 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 and calibration of the instrument.
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. Many installations use a compression fitting or a retractable probe assembly for inserting the probe into the pipe.
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 TA2 has the lowest installed cost while providing excellent performance. No additional instrumentation is required to obtain a mass flow measurement.

MAGNETROL offers the TA2 thermal mass flow meter to meet a broad range of user's application requirements:

Model TA2 with
Insertion Probe

Model TA2
with Flow Body

The sensor used with the MAGNETROL Thermal Mass Flow meter is illustrated in Figure 9.



**TA2 Sensor**

**Figure 9**

The sensors on the 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 be concerned which method is used. MAGNETROL has experience with both technologies.

### 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. The temperature difference is set during the calibration to optimize the performance for the specific application. As the flow rate increases, more power is required to maintain this constant temperature difference. Refer to the chart shown in Figure 10. 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.

Changes in power 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.

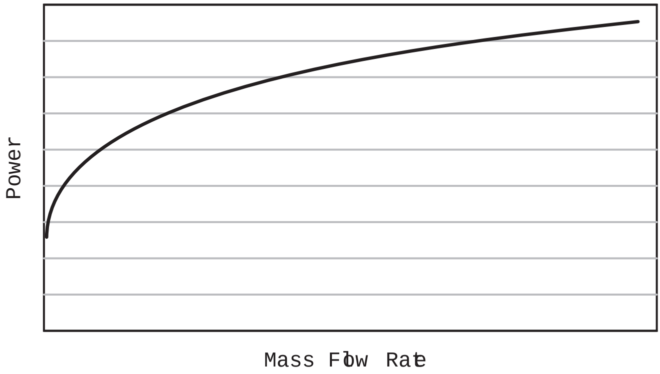


**Figure 10**

There is an inherently non linear relationship between mass flow rate and signal. The instrument linearizes the signal to produce a linear 4-20 mA output signal over the dynamic range of the instrument.

Calibration is an important part of the operation of the TA2. Each instrument is calibrated to establish this relationship between power and mass flow.

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

### 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 was the method utilized in the TA1, the first generation thermal mass flow meter of MAGNETROL.

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.

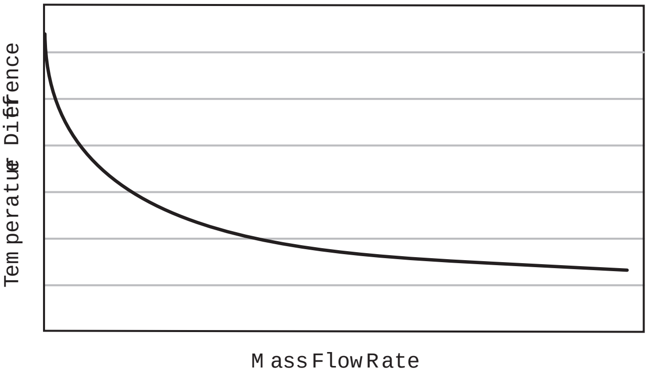


**Figure 11**

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.

## Response Time

One of the main differences between the Constant Temperature Difference and the Constant Power Technologies is the response time. There is some thermal mass which has to heat up or cool down resulting in a slight delay in time between when a change in flow occurs and the instrument reports the flow rate.

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 maintain a constant temperature difference between the reference RTD and the RTD measuring the temperature of the heater. There is a PID control circuit in the TA2 with parameters set to provide the fastest response possible while maintaining steady operation once flow has been reached. The response time of the TA2 to increasing and decreasing flow is shown below:

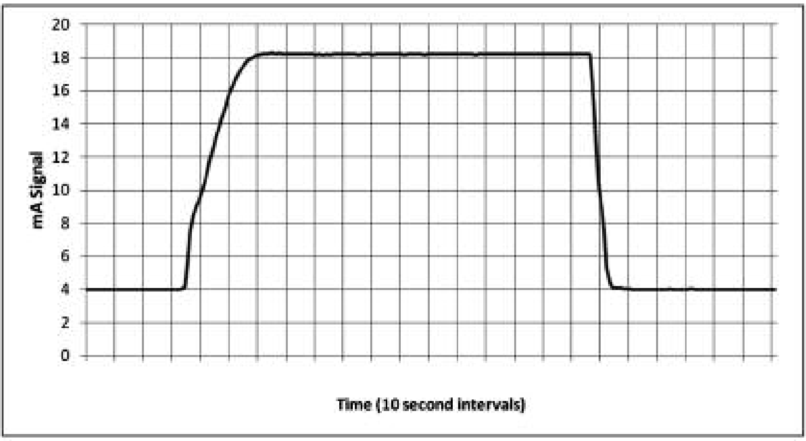


Figure 12

## Temperature Compensation

Thermal Mass Flow Transmitters measure heat transfer and infer the mass flow. This relationship between heat transfer and mass flow is obtained during the calibration which will be discussed in more detail later.

However, the gas properties that affect convective heat transfer are also affected by changing temperature. These properties include thermal conductivity, gas viscosity, density and specific heat.

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 below shows typical curves for the TA2 showing the change in flow rate which occur at different process temperatures due to changes in gas properties.

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

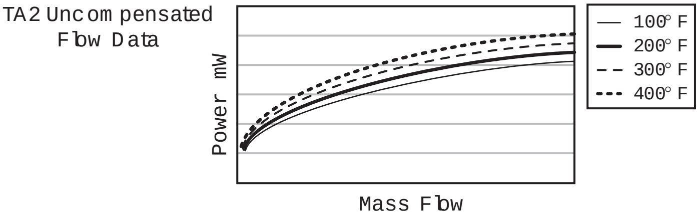


**Figure 13**

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

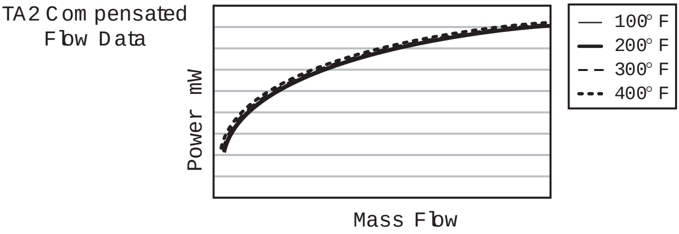


**Figure 14**

These illustrations demonstrate the effectiveness of MAGNETROL 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 cannot provide real time temperature compensation. This is especially a consideration with other manufacturers' 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 advanced real time temperature compensation is an important feature which provides superior performance for the Model TA2.

## Pressure Effects

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

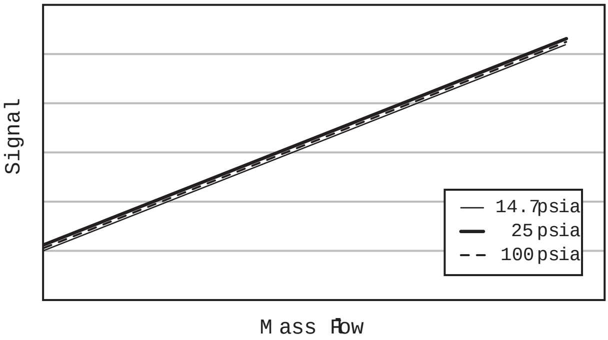


**Figure 15**

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 placing the sensor in a flow bench, flowing a known amount of gas over the sensor and measuring the signal. This is repeated for at least 10 different flow rates. The calibration data of signal and flow rate is then installed 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 provide accurate measurements if used for natural gas. Each instrument is calibrated for a specified gas over the maximum flow rate specified.

It is possible to have two sets of calibration data in the TA2. Thus the same unit can be calibrated on two different gases such as natural gas and Oxygen allowing the user to swap between calibration tables. If the instrument is calibrated for a specific gas, it is also calibrated on air. The gas data goes into one table and the air data into the second table. If the user ever needs to check the calibration on a flow bench, it would be possible to check the air data rather than the more expensive third party calibration for different gases.

Direct calibration on the actual gas is commonly performed and will provide best results. There are occasions where the user is looking for close and repeatable flow measurements. In these cases MAGNETROL can provide an Air Equivalency calibration. Every time we perform a direct calibration on a gas, we also calibrate on air. This has given us an extensive database which compares the velocity of air to the velocity of gas to produce the same signal. The following shows a typical air equivalency curve.

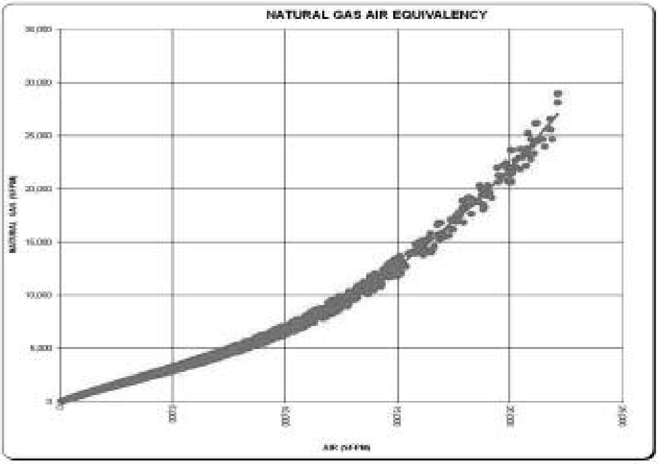


Figure 16

Using this data permits us to calibrate the TA2 on air and then apply this data to adjust for the specified gas. It is also possible for the user to change air equivalency factors in the field for different gases further increasing the flexibility of this instrument.

In some cases it is not possible to flow a gas or gas mixture for the calibration. This can occur with a gas mixture where it is not possible to create the same gas mixture for the calibration. This can also occur for safety reasons where some gases cannot be handled in a flow bench. When either of these two situations occur, MAGNETROL can perform a gas correlation. For these calibrations we calibrate on two different gases with known thermal properties. This defines the heat transfer characteristics of the sensor. By knowing the thermal properties of the gas or gas mixture it is possible to correlate the data from the two individual calibration gases to obtain calibration data for the specified gas.

Each instrument has its own unique calibration. The sensor and the electronics are a matched pair—each has a serial number to enable the units to be matched in the field. Previously, if the probe needs to be replaced, the probe and associated electronics must be calibrated together as a unit. This has been a difficulty with this technology. 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 the keypad and display, HART® or PACT***ware***™ software.

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 Verification

Once a thermal flow meter is calibrated there is the question of how to determine if the unit remains in calibration. One method is to remove the unit and return it to the original manufacturer for recalibration. This requires having a spare flow meter or operating without the flow meter while it is being recalibrated. The actual cost of the recalibration can become expensive.

There are better methods. Some manufacturers claim that the calibration of their flow meters can be verified by simulating a signal and checking that the output matches the expected flow. However, all this does is to check that the transmitter is performing the correct calculations; there is no check of the sensor.

From our experience we believe that the TA2 requires a one time calibration to establish the relationship between heat transfer and mass flow. This is a one time, permanent calibration unless something happens to the sensor. When TA2s have been returned, we find that the new calibration data matches the original calibration.

MAGNETROL understands the user's desire to verify calibration and has developed a method of checking both the transmitter and the sensor. These are simple tests which can be performed in the Instrument Shop and do not require returning the TA2 to MAGNETROL.

- The transmitter can be checked by simulating an input and verifying that the TA2 calculates the flow shown on the calibration certificate. This can easily be done using the keypad and display, using HART, or PACT***ware*** software.
- It is more difficult to check the operation of the sensor. Consider that the TA2 measures heat transfer. The sensor can be checked by creating a condition which produces a known and repeatable amount of heat transfer. This is done at two points—in still air to check no flow and in a water bath to simulate a high flow. This test can be done at some future date and when the values compare with initial values the user can be assured that the heat transfer characteristics of the flow meter are the same and the TA2 remains in calibration.

This calibration verification test can easily be performed in the Instrument Shop. The initial, base line values are determined during the original calibration. These values are stored in the TA2 memory and are found on the calibration certificate. When the verification test is made, the TA2 firmware provides simple step by step procedures for conducting the test. The validation test can also be performed using HART or PACT***ware***.

## Calibration vs. Configuration

Sometimes 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, zero and span of the 4-20 mA signal, units of measurement, installation factors. The user has full capability to configure the TA2 to fit the application.

## Accuracy

The accuracy of the TA2 is well accepted in the industry. Our stated accuracy is ± 1% of reading plus 0.5% of full scale. In reality the accuracy will be better than this. MAGNETROL uses a spline curve where the calibration curve goes directly through the data points. The following curve shows actual calibration data points, allowable error with other data points taken in between the calibration data points. This shows that the accuracy is better than 1% of reading over a turndown rate of 65 to 1.

This also shows that the greater the number of data points the better the overall accuracy. MAGNETROL uses a minimum of 10 data points and sometimes up to 30 data points depending upon the calibration range. Other manufacturers may only use a zero flow point and 4 calibration data points yet claim the same accuracy.

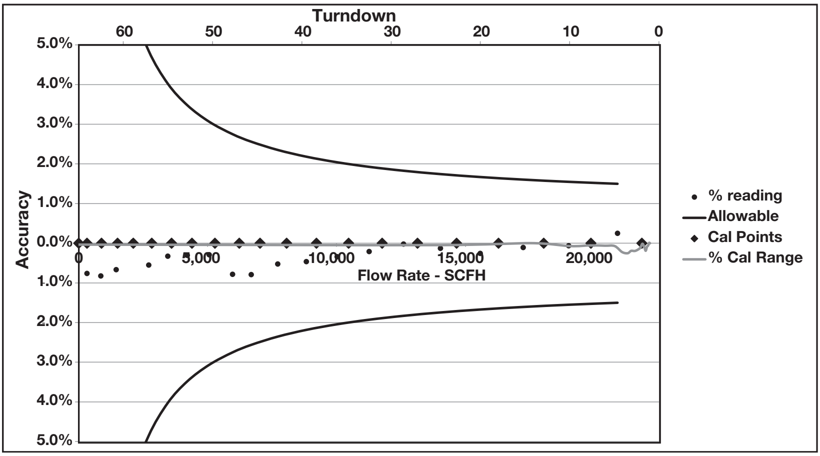


Figure 17

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.

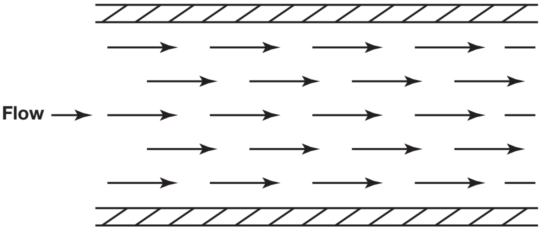
## Flow Profile

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 18.

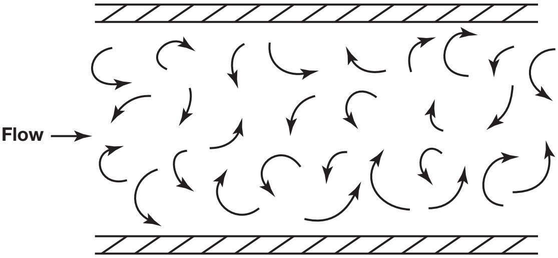
The fluid moves in layers with each layer sliding over the other. The velocity of the fluid at the wall is zero and increases as the distance from the wall increases as shown in Figure 20.



**Laminar Flow**

**Figure 18**

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 19.



**Turbulent Flow**

**Figure 19**

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

Reynolds Number is defined as:

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

Reynolds Number shows the relationship between:

V = Velocity

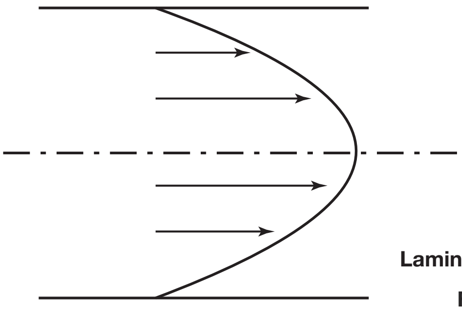
D = Diameter

$\rho$ = Density

$\mu$ = 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.

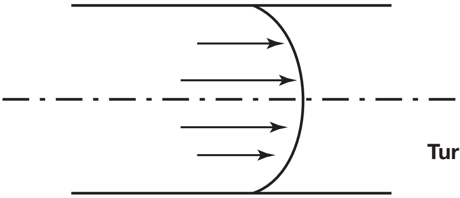
The flow profile in the pipe for laminar flow and turbulent flow are considerably different. With laminar flow the flow moves straight ahead without mixing. The velocity at the wall is zero and the velocity profile across the pipe will look something like Figure 20. Because there is no mixing, the velocity at the centerline is much greater than the average velocity.



**Laminar Flow Profile**

**Figure 20**

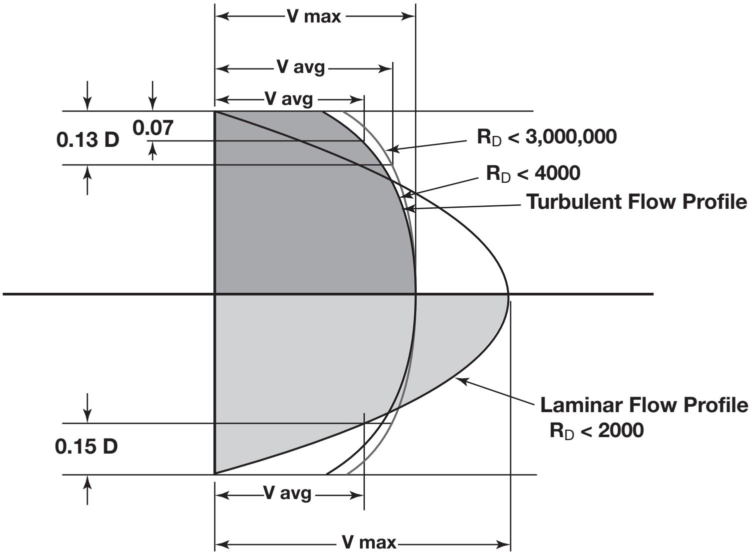
A fully developed turbulent flow profile is shown in Figure 21. Virtually all gas flow applications will be in the turbulent flow area.



**Turbulent Flow**

**Figure 21**

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 22.



**Laminar vs. Turbulent Flow Profile**

**Figure 22**

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.

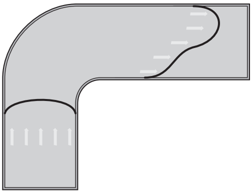
The center line velocity in turbulent flow is approximately 20% greater than the average velocity. The lower portion of Figure 20 shows a laminar flow profile — the centerline velocity is approximately twice the average velocity.

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 slightly different velocity profile 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 velocity will have minimal effect on the flow profile. The disadvantage is that the centerline velocity of a fully developed turbulent flow profile is theoretically 20% higher than the average velocity. This 20% factor between center line velocity and average velocity is taken into account in the calculations of the TA2.

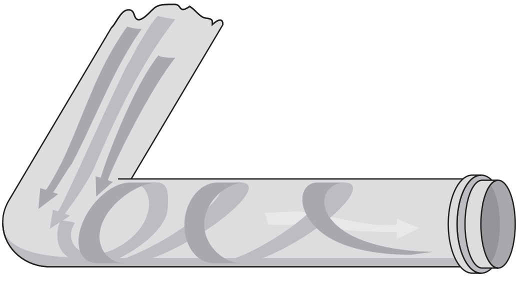
These flow profiles are based on what is referred to as a fully developed turbulent flow profile. This flow profile will naturally develop within a long straight section on pipe. As the gas flows around an elbow, the momentum causes the gas velocity on the outside of the elbow to increase and the velocity on the inside to decrease. This is shown in Figure 23.



**Flow Profile Around Single 90° Elbow**

**Figure 23**

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 24.

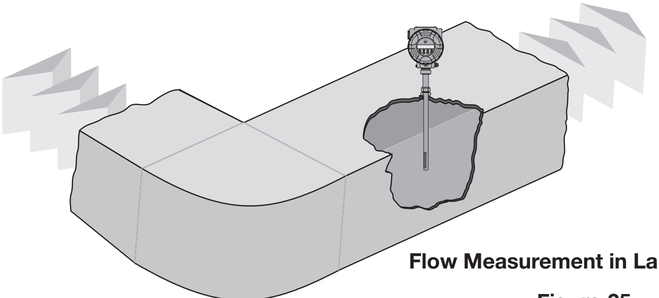


**Swirl Flow Profile**

**Figure 24**

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 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 25. The flow profile in the duct is far from ideal, however repeatable flow measurements are obtainable and can be used for the combustion control system.



**Flow Measurement in Larger Ducts**

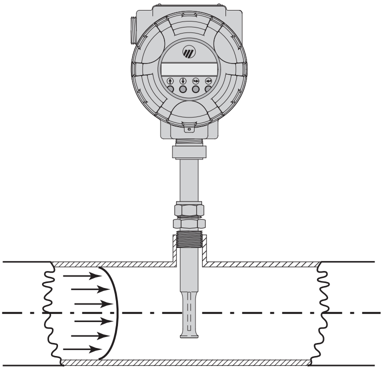
**Figure 25**

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 than 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 compression fitting shown in the Figure 26 below.



**Typical Probe Installation**

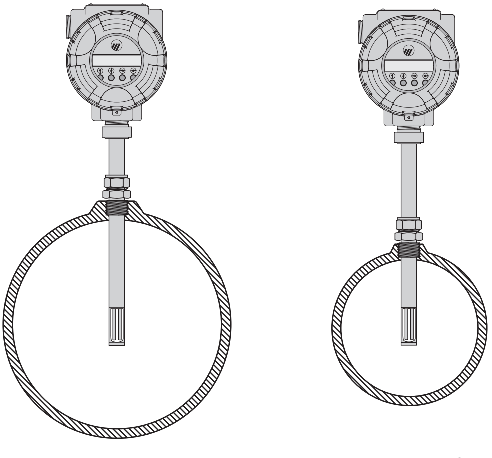
**Figure 26**

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 tightened and 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 is long enough and the velocity range is covered, the same instrument can be used in multiple pipe sizes, or an additional unit kept as a spare. Refer to Figure 27.



**Probe Installation in Different Pipe Sizes**

**Figure 27**

Hot tap Retractable Probe Assembly is also available for the 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 most 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. MAGNETROL uses nominal pipe dimensions found in various handbooks; however ASME permits tolerance in wall thickness which can effect pipe ID.
3. Standard conditions are not always standard. The TA2 permits the user to select the desired standard conditions. The 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 TA2 has the ability to correct the flow measurements for flow profile.
5. Inserting a probe in a tee. Calibration is typically done in a pipe. If the probe is inserted in a tee, the flow profile has changed and the dimensions of a tee are larger than the dimensions of a pipe. This combination can account for errors up to 20%.

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. The effect of condensed moisture on the flow measurement is shown below.

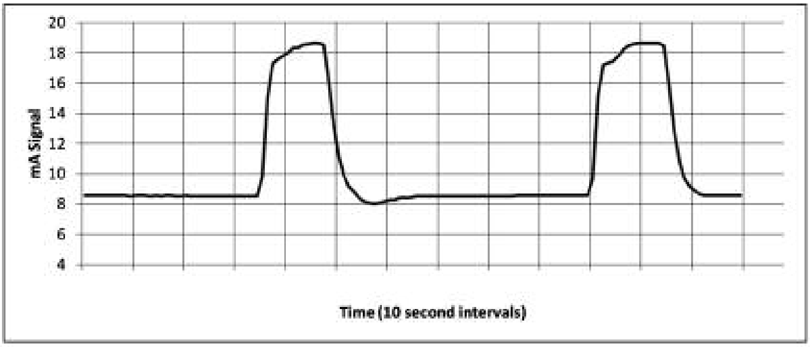


Figure 28

Increasing the damping will greatly reduce the amplitude of the spikes. A moisture knock out pot will provide a reduction in velocity and a change in flow direction forcing entrained droplets to drop out of the gas stream. Another consideration is applications where the gas is saturated with moisture and the ambient temperature is colder than the process temperature. In these cases, condensation may occur on the probe, form a drop which will flow down the probe. If the probe is installed at the top of a pipe, the drop of moisture could flow down the probe and contact the heated sensor. A good general guideline for installing a TA2 in an application containing high amounts of moisture is to install the probe at an angle. This way any drops of liquid which form on the probe will drop off due to gravity.

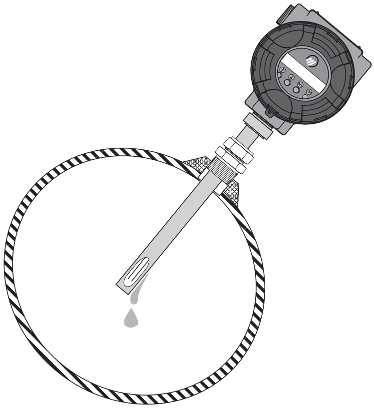


Figure 29

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 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. The use of a Retractable Probe Assembly or simple ball valve with compression fitting permits the probe to be removed during normal operation.

## 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. Can be used for detecting and identifying general location of leaks. Government estimates that leakage can account for 20–30% of compressed air generation. Eliminating a small ¼" leak can result in cost savings up to $4,000 in a year.
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. Knowing the natural gas usage of individual combustion sources can help identify efficiency leading to reduced fuel usage. The composition of natural gas may vary slightly during the year. These changes in heat transfer characteristics of the gas are minor and will not have any noticeable affect on TA2 performance.
4. Green House Gas Emissions. The EPA requires many facilities to report yearly their green house gas emissions from each combustion source. A TA2 is an ideal method of determining the natural gas usage and then follow the EPA guidelines to calculate the green house gas emissions.

## 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 a consistent gas composition such as natural gas, 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 those applications with varying gas compositions, a TA2 will provide a relative flow measurement. It can be used to provide an indication of changes and magnitude in flow rate as well as duration of a release to the flare. Often a TA2 will be used to monitor the flow to the flare from individual production units with a different technology flow meter measuring the main flare flow for environmental reporting or obtaining a mass balance. Considering that the flow meter is used for for flow monitoring rather than flow measurement consideration should be given to a simple calibration rather than trying to calibrate for an exact gas mixture.

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 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 caused by the insertion of the probe. This can cause a considerable error in the flow measurement. The TA2 automatically adjust the blockage factor based upon the flow area.
3. Self-Diagnostics. The TA2 has extensive self diagnostics to insure that the meter is operating properly and within the calibrated range of the instrument. These tests include automatic check of RTD drift, insuring sensor is operating within range, plus other operational/ performance verification. If a problem is detected the TA2 will identify the issue and will also store information in a history log in the unit.
4. Software. The 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 use factors in the flow meter to adjust for flow profile or other installation variables.
6. Two 4–20 mA outputs—An option available on the TA2 is providing a second mA output. This will most commonly be configured for temperature although it is possible to configure for a different flow range to provide better resolution.
7. Selectable STP conditions. The TA2 permits the user to select STP conditions utilized at their facility. Without having this option, flow errors of approximately 8% can occur.
8. HART. The TA2 provides HART communication with a full operational DD which permits the user to do anything over HART which can be accessed via the key pad and display. HART communications is also used with PACT***ware*** software where non-proprietary software can be used for configuration.

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 + 32
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

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