Measurement of Gas Flow

Gas Laws

It is prudent to discuss Gas Laws before one can fully understand how the flow of gas is measured. The term "gas law" refers to the thermodynamic equation of a state of a gas, which is an equation relating the pressure, the volume, the absolute temperature, and the number of moles. The equation of the state of a gas is valid relation when and only when the gas is in a state of thermodynamic equilibrium; the pressure and the temperature are then constant and uniform throughout the volume occupied by the gas. Important to understand is the real relationship between mass, temperature and pressure. Real gases closely follow the Ideal Gas Law which says that pressure, temperature and volume of a gas are all interrelated.

$PV = nRT$

where:

P =the pressure of the gas
V =the volume that the gas occupies
n =the number of molecules of the gas (ie. Mass of the gas)
R =ideal gas constant
T =the temperature of the gas

The Ideal Gas Law defines the volume that a gas will occupy under specific conditions. For example, a fixed mass of gas occupies a volume of 1 liter at a temperature of 0C and a pressure of 1 atmosphere (or 760mmHg). If the pressure is increased and the temperature held constant, the volume must decrease. If the temperature is increased and the pressure is held constant, the volume must increase. If the temperature is reduced and the volume is held constant at 1 liter, the pressure must decrease also. The only constant that did not change in any of these examples is the mass of the gas; it has remained constant because the volume has not been opened; gas has not been added and gas has not escaped. For this reason, it is not useful to use volumetric measurements of gas if the pressure and temperature of the gas cannot be held constant.

The measurement of mass flow, or molar flow, is the measurement of molecular weight of the gas over time. This is usually measured in units of mass per unit of time; as in grams/minute. However, gases are usually defined in volumetric units per unit of time, for example liters per minute (LPM) or cubic centimeters per minute (CCM). But, since volume is dependant on pressure and temperature, it is necessary to normalize the measurement to conditions known as standard temperature and pressure (STP) to allow definition of gas flow in volumetric units. Hence, the terms SCFM, SLPM and SCCM are used for mass flow measurements, defined in volumetric units, where the "S" stands for "standard conditions" of reference temperature and pressure. Usually, these reference conditions are defined as 0°C temperature and 760mmHg (1 atm) pressure but may be specified at other conditions as well dependant upon the industry and engineering staff needs.

Using these reference conditions, it is possible to take an exact mass flow and reference it to a more traditional measurement without losing accuracy. For example, a 500 lb/hr flow of nitrogen can be translated into standard cubic feet per minute (SCFM) using the following relationship:

$Qs = \dot{m}/(p)s$

where $(p)s$ = the density of the gas at standard conditions
$\dot{m}$ = the mass flowrate
Qs = the standard mass flow rate, ie. SCFM

In many applications, only the volumetric flow rate referenced to actual pipe conditions is known. To convert actual (ACFM) to standard conditions (SCFM), the flowing relationship can be used:

$Qs = Qa \times (Pa/Ps) \times (Ts/Ta)$

where:
Pa = actual pressure
Ps = standard pressure
Ts = standard temperature
Ta = actual temperature
Qa = the actual flow rate, ie. ACFM

More Properties of Gases for discussion

According to Avogadro's hypothesis (year 1811), equal volumes of different gases contain the same number of molecules under the same conditions (pressure and temperature). This made it possible to determine how many times heavier a molecule of one gas is than another. The "mole" or the gram-molecular weight is the molecular weight expressed in grams. One mole of any compound has been found to contain 6.023 x 10^{23} molecules. This is called the Avogadro constant. Another definition of the term mole is: The mole is the number of (pure) substance containing the same number of chemical units as there are atoms in exactly twelve grams of C^{12}. In one mole, there are 6.023 x 10^{23} atoms.

Mass is the only property independent of changes in temperature, pressure, velocity, density, and any other factor of the process fluid (gas).

The most fundamental method to measure mass flow of gases is the gravimetric method. This method is a measurement of a gases molar mass displaced over a time period. However, in practice there are problems with this methodology. It is extremely difficult and time consuming to measure the mass flow rate of a gas in this way. For example, think of how complicated it would be to evacuate all gas (using a mechanical vacuum pump) from a known, closed volume then measure and record the weight of this closed & evacuated volume, then, after flowing a gas into this volume for some defined time period, re-weigh the volume with a very accurate, high resolution scale to determine how much mass of the gas has flowed into the known volume. Of course, the person performing this exercise must also know the properties of the gas, specifically the gases molecular weight. This is the most fundamental mass flow measurement; mass (of a gas in this case) moved over time. While an extremely difficult and time consuming task that is filled with uncertainty due to potential handling, timing and weight measurement errors, this method is used by some calibration laboratories as a “Primary Standard of Mass Flow” to calibrate transfer standards (sometimes called working standards) that are in turn easily used day to day for calibrations of “field” measurement devices.

Another way to measure the flow of a gas is to measure the heat capacity of the molecules of the gas. Heat capacity is defined as follows:

$$C = \frac{dq}{dT}$$

where:

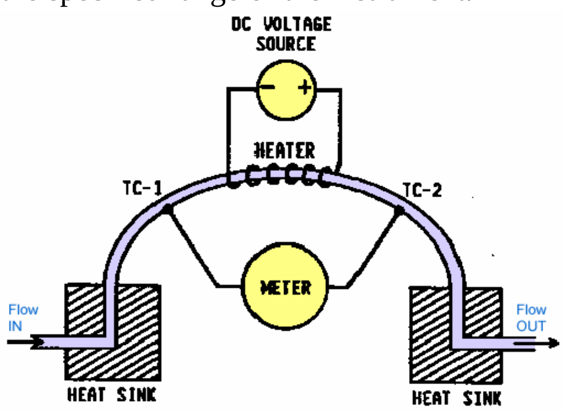
dq = the quantity of heat required to produce the temperature increment dT.

If the gas consists of a singe substance with definite chemical composition and physical state, C is proportional to the total quantity of gas passing through the measurement device. The heat capacity of 1 gram is the specific heat and the heat capacity of one mole is sometimes called the molar heat capacity.

Operating principal of the “heated tube” mass flow meter

Electronic mass flow meters use thermodynamic principals to measure true mass flow rate without the need for corrections of pressure and temperature variations.

The gas to be measured is passed through a precision manufactured sensor tube. Heat (Q) from the heater is applied to the gas molecules, through the wall of the precision sensing tube. When gas is not flowing, the temperature differential between the temperature sensors, TC1 and TC2 is equal. As gas begins to flow, heat is carried away from TC1 by the gas molecules and more heat is sensed at the downstream temperature sensor TC2. This temperature differential (TC2-TC1) is measured, each as a part of a Wheatstone bridge circuit. Because the temperature differential between the two sensors is directly proportional to the mass (m) flow of the gas, an accurate and repeatable flow measurement is obtained without concern for pressure or temperature fluctuations within the specified range of the instrument.



Heated tube mass flow meters can accommodate virtually any type of clean dry gas. If the flow range remains the same, a correlation (K) factor is used to relate the calibration of nitrogen (a typical inert calibration gas) to the actual gas. This K factor is derived experimentally or calculated from the gas density and coefficient of specific heat:

$$K = (p)Cp$$

where:

p =gas density (g/liter)

Cp =coefficient of specific heat cal/gram °C

Final Note: Volumetric Vs Mass flow meters:

Measuring Gas — By Volume or Mass?

by Corte Swearingen

December 24, 2003 — Variable area flowmeters (also known as rotameters) and thermal mass flowmeters are two of the most popular methods for measuring gas flow. However, in both technologies, there are advantages and disadvantages.

Application Examples

For companies working in markets where gas flow is a factor, the number of choices from flowmeter manufacturers and distributors can seem overwhelming. Let's take a simple example of a shop that needs to measure nitrogen in a laboratory environment to ensure that the amount of N2 gas entering the research equipment stays at 350 mL/min. Let us assume that the amount of pressure required to "push" the gas through this piece of equipment varies, but averages to around 15 psi.

The researcher — a person not all that familiar with flow monitoring instrumentation — pulls out an instrumentation catalog and glances at the choices for gas flow: variable area meters; thermal mass flowmeters; differential pressure meters; turbine meters; impeller-style meters; etc. The list is long. Which one to choose?

Thinking that perhaps simplicity is best, our researcher selects a variable area meter with a built-in valve. Using this device, the researcher is now able to read the flowrate and adjust it manually using the built-in valve. The flowrate is checked by matching the spherical float inside the glass flowmeter tube to a scale marking on the tube wall that represents the flow of Nitrogen.

Our researcher feels confident that the nitrogen flow to the instrument is being measured in an elegant and inexpensive manner. However, while the researcher may believe the flow to the instrument is being maintained at 350 mL/min, as the flowmeter indicates, the actual flow to the instrument could be off by 35 percent or more.

The one issue our researcher failed to notice is that the variable area meter was calibrated with the flowmeter outlet at atmospheric pressure. In other words, zero psi of backpressure. This is the normal way most variables area meters are calibrated. However, our researcher's equipment is producing a variable backpressure, depending on the state of other downstream equipment. Herein lies the problem. This varying backpressure is causing the gas density and viscosity to change. Because the gas density and viscosity is varying from the calibration gas density and viscosity, the readout on the flowtube is no longer accurate. Had the researcher ordered the variable area meter compensated for the 15 psi of backpressure, the instrument would have been accurate for the application (assuming the temperature of the Nitrogen equaled the calibration temperature at the factory, usually 70 F).

Now, let's suppose a researcher is blending two gases together and the blend ratio needs to be constant even though there will be pressure and temperature variations in the gas flow lines. The researcher picks a two-frame, variable-area flowmeter that has two flowtubes installed along with a manual valve for each tube. There are two separate inlets and a common outlet. By varying the valves and watching the floats in the flow tubes, the researcher is able to control the blend of each gas. In this example, the application requires a constant ratio blend of air and Oxygen. Do you think this application will be accurate? Would you have thought about using this method for the gas blending application?

Actually, the use of a variable-area blending system will work just fine providing, as mentioned before, both the gases being blended are at a constant temperature and equal to that of the calibration gas temperature. In addition, the backpressure at the blender's common outlet must be constant and equal to the calibration backpressure. If this is the case, the variable-area blending system can actually be a very good economical choice. However, in our above application example, we have two gas lines that vary in temperature and pressure. In this case, it is impossible to accurately control a constant blend ratio using a dual-tube, variable-area blending apparatus.

The bottom line in this application is that the researcher needs to control the gas blending by the gas mass and the variable area system can only control the bending of the gases volumetrically. The researcher, in this instance, would have been much better off with two thermal mass flowmeters for the gas blending application instead of the variable-area flowtube system.

Volumetric vs. Mass Flow

Because variable-area meters monitor and control flow volumetrically and thermal mass meters monitor and control the mass of the gas, let's look at a very concrete example that will give you an instant understanding of the difference volumetric and mass flows.

A device that measures volumetric flow is measuring the flow volume per unit time. A volumetric measuring device cannot tell when the line temperature and pressure changes (or at least ignores that information).

For example, let's suppose we have a helium line that passes through a cycling furnace. As the furnace turns off and on, the air in the line will change temperature. Let's also suppose that this change happens very quickly to that when the furnace is on, the air in the line heats up rapidly and when the furnace turns off, the air in the line cools down immediately. Let's also suppose that the furnace is cycling on and off frequently but randomly.

Now, if we use this line to fill up several balloons with 250 ml/min of helium using a volumetric monitoring device, we will find that while all the balloons will initially be the same size, once the gas temperature in the balloons equilibrates, they will all be different sizes. This happens, of course, because while the volume reading on the flowmeter may have been the same for each balloon, the actual mass of helium delivered into the balloons varied as the temperature changed in the helium line.

Had we monitored 250 ml/min of mass flow into the balloons instead of volumetric flow, the balloons would have been different sizes initially but once the helium inside reached equilibrium temperature, the balloons would all be the same size. This is because we filled each balloon with the same total mass of helium gas, even though the gas temperature varied from balloon to balloon.

With this example, you can see how critical it is, depending on your application, to monitor and control mass flow over volumetric flow. If you were doing an experiment based on chemical reactions, monitoring the volumetric flow as opposed to the mass flow could be disastrous. However, there are many cases where monitoring the mass flow is not required and volumetric flow will work just fine. As an end-user, it is important to understand the difference between volumetric and mass flow monitoring and to know which you may need to monitor for a certain application.

For gas flow measurement applications at one standard temperature and no back pressure on the meter outlet, one could select a volumetric meter and receive satisfactory results so long as the temperature and/or pressure never changes. Where temperatures and pressure fluctuate and cannot be precisely controlled, select a mass flow meter that automatically compensates for those changes.

Finally, all mass flow rate specifications MUST include a definition of STP (standard temperature and pressure). Without this important piece of information, measuring and defining gas flows in volumetric units will lead to poor correlation and wide variability of test results.

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