A FLOW TUTORIAL – PART 1

What's in a Unit? (Flow Measurement - Part 1)

So you want to measure flow? The answer would seem to be to purchase a flowmeter. With fluid flow defined as the amount of fluid that travels past a given location, this would seem to be straightforward — any flowmeter would suffice. However, consider the following equation describing the flow of a fluid in a pipe.

$Q = A \times v$

Q is flow rate, A is the cross-sectional area of the pipe, and v is the average fluid velocity in the pipe. Putting this equation into action, the flow of a fluid traveling at an average velocity of a 1 meter per second through a pipe with a 1 square meter cross-sectional area is 1 cubic meter per second. Note that Q is a volume per unit time, so Q is commonly denoted as the "volumetric" flow rate.

Now consider the following equation:

$W = \rho \times Q$

Where W is flow rate (again - read on), and rho is the fluid density. Putting this equation into action, the flow rate will be 1 kilogram per second when 1 cubic meter per second of a fluid with a density of 1 kilogram per cubic meter is flowing. (The same can be done for the commonly-used "pounds". Without getting into details — a pound is assumed to be a mass unit.) Note that W is a mass per unit time, so W is commonly denoted as the "mass" flow rate.

Now — which flow do you want to measure? Not sure? In some applications, measuring the volumetric flow is the thing to do. Consider filling a tank. Volumetric flow may be of interest to avoid overflowing a tank where liquids of differing densities can be added. (Then again, a level transmitter and high level switch/shutoff may obviate the need for a flowmeter.) Consider controlling fluid flow into a process that can only accept a limited volume per unit time. Volumetric flow measurement would seem applicable.

In other processes, mass flow is important. Consider chemical reactions where it is desirable to react substances A, B and C. Of interest is the number of molecules present (its mass), not its volume. Similarly, when buying and selling products (custody transfer) the mass is important, not its volume.

FTB-909 Turbine, $1005, shown with FLSC-61 Signal Conditioner, $325, see page F-76 and F-77.

A FLOW TUTORIAL – PART 2

What's in a Unit? (Flow Measurement - Part 2)

Having discovered that there are two types of flow rates (volumetric and mass), it should not be a surprise that some flowmeters measure mass (W) while other flowmeters measure volume (Q). However, it is not quite that simple. Repeating the equations from Part 1 (for convenience), it can be seen that, assuming A is constant, Q can be determined by measuring the average fluid velocity v. Further, assuming that rho is constant, W can be determined from Q.

Q = A x v
W = rho x Q

Summarizing, some flowmeters measure volumetric flow, some flowmeters measure velocity from which the volumetric flow is determined, and some flowmeters measure mass flow. In addition, when the density is known or assumed, mass flow can be determined from the volumetric flow, and the volumetric flow can be determined from the mass flow.

So you just wanted to measure flow — did you now? It all seemed so logical and simple at the time. Stick around — it gets worse.

Some flowmeters use other principles to infer flow. The most common of these measurements measure the velocity head (1/2 rho v x v) to infer the volumetric flow. Notice that these flowmeters do NOT measure volume, do NOT measure mass, and do NOT measure velocity — but rather measure a combination of density and the square of velocity! Would it surprise you to discover that this is a description of (commonly-applied) head flowmeters, such as orifice plates, venturis, nozzles...? Further, in many applications, the inferred volumetric flow is used to determine the mass flow. Errors can enter the measurement process during each measurement and with each assumption. Is it any surprise that plant engineers often have difficulty closing material balances in their plants?

Summarizing (again), some flowmeters measure volume, some flowmeters measure mass, some flowmeters measure velocity, and some flowmeters measure inferentially. Understand the difference, but also understand that careful attention to detail can result in an inferential measurement that is better than the others.

A FLOW TUTORIAL – PART 3

What's in a Unit? (Flow Measurement - Part 3)

Volumetric flow is expressed in units that reflect a volume per unit time. The example in Part 1 determines cubic meters and cubic feet per unit time to be volumetric flow units. Gallons and liters per unit time are also volumetric flow units.

Mass flow is expressed in units that reflect a mass per unit time. The other example in Part 1 determines kilograms and pounds per unit time to be mass flow units. (Without getting into details — a pound is assumed to be a mass unit.) Note that the units of time are independent of whether volumetric or mass flow is measured.

Let's have a quiz.

Are the following volumetric or mass liquid flow units?

gallons per minute
cubic feet per second
liters per minute
kilograms per hour
pounds per hour
grams per minute

Can one have a cubic foot of feathers?
yes/no

Can one have a gallon of feathers?
yes/no

Can one have a kilogram of feathers?
yes/no

If you answered volumetric to the first three questions, mass to the next three questions, and yes to the last three questions, you are on track.

Consider purchasing fuel for your car. How does a US gallon of gasoline purchased on a hot summer day in Las Vegas, Arizona compare with a US gallon of gasoline purchased on a cold winter night in Anchorage, Alaska? It was determined that a gallon is a volumetric unit, so logic would indicate that the same volume of gasoline was purchased. Yet the temperature difference would cause their densities, and hence their masses, to be different. Using this logic, more mass would be obtained by purchasing gasoline in colder weather. Thinking locally, one might conclude that it is more economical to purchase gasoline during the wee hours of the morning when the temperature is coldest.

As you might suspect, such is not the case. Gasoline pumps compensate for density variation that occurs due to temperature, and in doing so, they measure the amount (mass) of gasoline dispensed. Yet, a gallon of cold gasoline will occupy less volume than when hot. In essence, the measurement of a gallon of gasoline actually refers to its volume at a given temperature (such as 60 degF). As such, this is really a mass measurement unit because it refers to the flow of a specific substance at a given temperature,

Returning to the quiz, let's not be so hasty with the first three questions. They could be incomplete!

A FLOW TUTORIAL – PART 3.1

What's in a Unit? (Flow Measurement - Part 3.1)

Part 3 discussed the use of volumetric units (such as gallons) to infer mass when the composition and temperature is known. The example given was that of purchasing a gallon of gasoline in a hot and cold climate. The assertion was that a gallon of gasoline purchased in hot and cold climates might have different sizes due to their differing temperatures, but their masses should be the same because the retail flowmeter is temperature compensated.

A number of e-mails questioning this assertion and further investigation resulted in the interesting discovery that retail gasoline flowmeters are not temperature-compensated in the United States, but are temperature-compensated in Canada. In other words, either the measured volume (in the US) or the measured temperature-corrected volume (in Canada) is used to infer mass.

Consider the following general analysis:

1. Air temperature differences between hot and cold climates are large. In addition, air temperature fluctuations between day and night in a given location can be large.
2. There is a significant difference between ground temperatures in hot and cold climates. However, ground temperature fluctuations between day and night in a given location is very small. Ground temperature fluctuation between summer and winter in a given location is relatively small.
3. Gasoline will be warm when it leaves the refinery, but will cool in transport to the retailer's underground tank. Given time in the tank, the temperature of the gasoline will approach the ground temperature.
4. Flowmeter calibration is performed using standard weights, implying a calibration to mass.

These statements imply that despite wide air temperature fluctuations, the temperature of the gasoline pumped through the flowmeter should be nearly the same as the ground temperature. Because the ground temperature does not fluctuate very much, the temperature variation of the gasoline will be small throughout the year, so the mass of a gallon of gasoline should not vary much throughout the year from a given tank. Following this logic, the mass of a gallon of gasoline sold in Alaska should be the same as one sold in Nevada.

Fluctuations in gasoline temperature cause gasoline density changes. The magnitude with which these changes affect measurement accuracy can be quantified by performing an uncertainty analysis to determine if temperature compensation is appropriate. An uncertainty analysis for this measurement would likely reveal a number of sources of measurement uncertainty, such as (but not limited to) the effects of ambient air temperature, gasoline temperature leaving the refinery, transport time from the refinery to the tank, ground temperature, tank level prior to filling, the volume of gasoline in the flowmeter piping, flowmeter piping temperature, frequency of use, and composition changes. As a minimum, such analysis would likely reveal that the consumer would not be advised to purchase gasoline from a tank that was just filled with warm gasoline. A detailed analysis may reveal other significant issues.

While this is perhaps more information than one would like to know about the subject, this discussion clearly illustrates the need to understand the process — and that the same process may be different in different locations. Sometimes ... it's just not so easy.

A FLOW TUTORIAL – PART 3.2

What's in a Unit? (Flow Measurement - Part 3.2)

A brief review — Part 3 addressed mass flow measurement, volumetric flow measurement, and inferred mass flow measurement. The measurement of gasoline was given as an example of the inferred mass flow measurement (using volumetric units). Comments resulted in Part 3.1 that addressed some issues associated with retail gasoline measurements. This sparked a flurry of comments regarding how gasoline is measured at the pump.

This issue attempts to tie the comments together, so reading this issue without having read previous issues may prove difficult.

Gasoline pumps in the USA measure volume and are calibrated using volumetric means. In other words, they are true volumetric devices — they measure volume and indicate gallons. Even the New York Times offered advice to the consumer on this one with "... buy gasoline during the coolest time of the day — early morning or late evening — while the gasoline is most dense..." (New York Times, September 24, 2001, Empowered II Smart Energy Management, A clean car is an efficient car, page 7).

Gasoline pumps in Canada measure volume. This volume is then compensated for the actual temperature to indicate the volume of the gasoline as if it were a certain temperature. The compensated volume is an implied mass measurement. I suspect (but do not know) that these pumps are calibrated using volumetric means that are temperature compensated. In other words, they are inferred mass measurement devices and are calibrated as such — they measure volume and indicate in (temperature-compensated) liters.

In Canada, the inferred mass of the gasoline received should be the


All models shown smaller than actual size.

See page F-81.

FTB795, $1008

FTB792, $538

FTB794, $768

FTB791, $528

FTB793, $548

same (within the limitations of the equipment) regardless of gasoline temperature. Note however that composition differences (and additives) may cause the density at a given temperature to be different than its nominal value. As an example, a 1% increase in gasoline density from its nominal value does not affect the actual volume measured, but will cause the inferred mass measurement to be 1% lower than the actual mass flow.

My comments on some readers' responses follow:

One reader questioned whether the "wee hours of the am" would be the time when the gasoline would be at its lowest temperature in an underground tank. Thermal lag for underground gasoline storage tanks is an issue, but may not be significant. For science class, my daughter measured the temperatures 1 meter above and 1 meter below grade in the fall/winter (in the New York area). I seem to remember the ground temperature changing by only 1-2 degC over a period of months. The above ground temperature changed by 20 degC (or more?) during the same period. This issue is likely to be significant for above ground storage tanks (as suggested by other readers). Note however that filling the tank may cause larger (transient) effects caused by such issues as the quantity and temperature of the gasoline prior to fill, and the quantity and temperature of gasoline added.

Not being able to sell compressed natural gas measured with a Coriolis mass flowmeter in kg or lbm (pounds mass) because it was not considered 'marketable' to the the public illustrates resistance to change. By the way, when will gasoline be sold by the kg or lbm — or better yet, by the BTU or Joule (as suggested by another reader)? I suspect that it will not be soon.

The comments and observations about beating the measurement were amusing. Society allows people to (reasonably) operate in their own self-interest. Parting with less money for a product is clearly in the purchaser's self-interest. (Engineers sometimes call this an "optimization problem", but that is an issue for another day.) Comments on how to beat the system were inevitable.

The safety point regarding gasoline expansion causing explosions and fires (after topping off a gas tank in a cold climate and then parking in a warm garage) is important. Virtually everything is potentially dangerous — even a small puddle of water that turns to ice...

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