Flow Measurement

FUNDAMENTALS

Flowmetering terms can often seem cryptic. Here are definitions of some of the most commonly used.

ACCURACY

Accuracy is a quantity defining the limit that errors will not exceed. This value should include the combined effects of conformity, hysteresis, deadband, and repeatability errors. When applied to flowmeters, accuracy is specified in one of two different ways; % of full scale or % of rate.

% OF FULL SCALE

A % of full scale accuracy specification defines an expanding error envelope. For a flowmeter with a flow range of 0 to 100 gpm and accuracy of 1%, FS will read +/-1gpm anywhere in its operating range. This corresponds to +/-1% of rate at full scale and +/-10% of rate at 10% of full scale.

% OF RATE

A % of rate accuracy specification defines a constant error envelope. For the previous flowmeter with the same flow range and an accuracy of 1% of rate, the reading will be +/-1% of actual flowrate anywhere in the meters operating range. As a result, at full scale the reading will be +/-1 gpm and at 10 gpm it will be +/- 0.1 gpm.

Figure 1 contains graphs that illustrate the difference in % of rate and % of span accuracy statements.

REPEATABILITY

Repeatability is the closeness of agreement between consecutive measurements of the same flow. This can also be specified as a % of full scale or a % of rate.

RANGEABILITY

Rangeability refers to the minimum and maximum measurable flowrates. For example, if the maximum flowrate is 100 gpm and the minimum flowrate is 10 gpm, the rangeability is 10% to 100%.

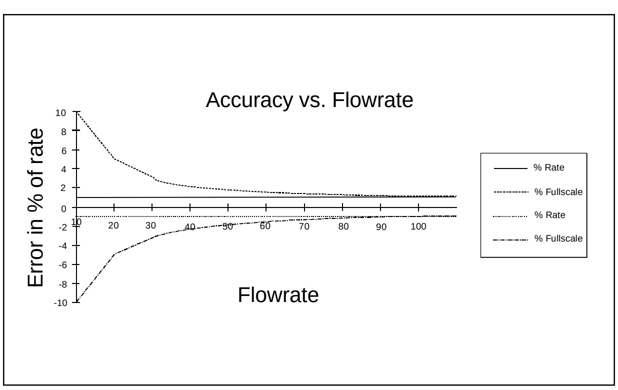

FIGURE 1 % of Rate vs. % of Span Accuracy

TURNDOWN

Turndown conveys the same information as rangeability but in a slightly different way. Turndown is the ratio of maximum flow to minimum flow. For the same flowmeter we used in the rangeability example, the turndown would be 100/10 to 1 or 10 to 1.

VISCOSITY

For a newtonian fluid, viscosity is the same as consistency and is the resistance offered by the fluid to deformation. Viscosity will be stated as either absolute or kinematic viscosity. Absolute viscosity is the fundamental viscosity measurement of a fluid and has units of Poises in the cgs system. Kinematic viscosity is equal to absolute viscosity divided by the fluid density and has units of Stokes in the cgs system.

REYNOLDS NUMBER

Reynolds Number is dimensionless quantity that is proportional to the ratio of inertia forces to viscous forces in a flow system. The proportional constant is the characteristic length of the system. For Pipe Reynolds Number, the characteristic length is the pipe diameter. Reynolds Number is a convenient parameter by which to compare different flow systems. Pipe Reynolds Number can be found by using the following equations:

$$R = [DV/\nu]\rho$$

or $[DV/u]$

where R = Reynolds Number

D = inside pipe diameter (ft or m)

V = fluid velocity (ft/s or m/s)

ν = kinematic viscosity (ft2/s or stokes)

ρ = fluid density (lb/ft3 or kg/m3)

u = absolute viscosity (lb/ft s or poises)

Many convenient hybrid forms of the Reynolds Number equation exist. One such equation for liquid is:

$$R = C^*Q(GPM)\ \nu(cSt)$$

Where C is the constant from Table 1. Table 1 is valid for schedule 40, pipe.

TABLE 1 Values of C for Schedule 40 Pipe

Pipe Size	C
3/4"	3837
1"	3014
1.5"	1964
2"	1530
3"	1031
4"	785

For other than schedule 40, pipe C is equal to:

C = 3162/pipe ID (inches)

VOLUMETRIC VS. MASS FLOWRATE

When measuring a flowrate, there are two fundamental types of measurements; volumetric and mass flowrate. Volumetric flowrate is a measure of the volume of liquid flowing through the metering device. The units for this type of flow measure indicate that it is volumetric, i.e. GPM (Gallons Per Minute). Most flowmeters measure volume of a fluid by measuring the velocity through a known area. These meters include orifice plates, fluidic flowmeters, and magnetic flowmeters.

Mass flowmeters measure the mass of the fluid flowing through the meter. The units for this type of meter indicate that it is a mass-based measurement, i.e. #/hr. The use of mass flowmeters is limited because of the relatively high cost of the meters and application restrictions.

Often, a volumetric flowmeter is used in conjunction with a flow computer to calculate the mass flowrate. If the volumetric flowrate, denoted by Q is multiplied by the density of the fluid, the result will be the mass flowrate, denoted by W.

$$W = \rho Q$$

where W is the mass flowrate:

ρ is the fluid density at flowing conditions

Q is the volumetric flowrate

Tables 2 and 3 give the conversion factors for volumetric and mass flowrates respectively.

TABLE 2 Equivalents of Volumetric Flowrate

UNKNOWN → / *KNOWN ↓*

Volumetric Flowrate	Ft^3/sec	Ft^3/min	Ft^3/hr	GPM	GPH	L/min
Ft^3/sec	1	60	3600	448.9	26,930	1,699
Ft^3/min	0.01667	1	60	7.481	448.9	28.32
Ft^3/hr	0.0002778	0.1667	1	0.1247	7.481	0.472
GPM	0.002228	0.1337	8.022	1	60	3.786
GPH	0.00003713	0.002228	0.1337	0.01667	1	0.06311
L/min	0.0005885	0.03531	2.119	0.2642	15.85	1

TABLE 3 Equivalents of Mass Flowrate

UNKNOWN → / *KNOWN ↓*

Mass Flowrate	lbm/sec	lbm/min	lbm/hr	gm/sec	gm/min	Kg/hr
lbm/sec	1	60	3600	453.6	27,220	1,633
lbm/min	0.01667	1	60	7.560	453.6	27.22
lbm/hr	0.0002778	0.1667	1	0.1260	7.560	0.4536
gm/sec	0.0022205	0.1323	7.938	1	60	3.600
gm/min	0.00003675	0.002205	0.1323	0.01667	1	0.0600
Kg/hr	0.0006125	0.03675	2.205	0.2778	16.67	1

TYPICAL MASS FLOW CALCULATIONS- Liquid Flow Measurement, Linear Meter

If the mass flow is desired for a liquid, the volumetric flowrate must be multiplied by the density of the fluid. There are basic approaches to this problem. The first and simplest approach is to assume the density is constant and multiply the volumetric flowrate by this value. This approach is described by the following equation:

$$W = \rho_{(const)}Q$$

However, the density of a fluid can often vary significantly over temperature. These variations in density will cause errors in the calculated mass flow. To correct for density variations over temperature, it is common to measure both the flowrate and temperature of the liquid. The temperature is used to determine the density at flowing conditions. Often, the density versus temperature relationship will be stored in a characterizer block. Figure 2 shows a typical configuration for computing mass flowrate for a liquid with varying density. The following equation describes this approach:

$$W = \rho_{(calc)}Q$$

LIQUID FLOW MEASUREMENT - Square Law Meter

If the flow transmitter is an orifice plate, you can also calculate mass flow by taking density into account. However, if you are going to calculate the flowing density, it is best to correct the basic orifice calculation for changes in density also. The basic orifice equation for liquid is:

$$Q = \frac{K' [P_1 - P_2]^{1/2}}{(\rho)^{1/2}}$$

Multiplying this equation by density results in:

$$W = \rho Q = K' [\rho (P_1 - P_2)]^{1/2}$$

In these equations, the quantity $(P_1 - P_2)$ is the differential pressure measured by the differential pressure transmitter. When performing a mass flow calculation, do not take the square root of the flow signal in the transmitter. Figure 3 shows a typical configuration for performing mass flow computation on a liquid orifice meter.

STEAM FLOW MEASUREMENT - Linear Meter and Square Law Meter

Mass flow calculations for steam are performed in much the same way as for liquids. The major difference between liquid and steam, or even matter gas flows, is that the flowing density of steam and gas are dependent on both temperature and pressure. If the steam to be metered is sufficiently superheated, then it can be treated as an ideal gas and the density can be calculated. Many times, however, this is not the case.

When the steam cannot be treated as an ideal gas, an attempt must be made to characterize the density of the steam in a usable manner. One thing that helps in this situation is that the pressure of the steam is often controlled. If the pressure is being controlled, then the density of the steam at the pressure can be characterized over the expected temperature range. Once this is achieved, the actual calculation of mass flow is the same as it was with a liquid.

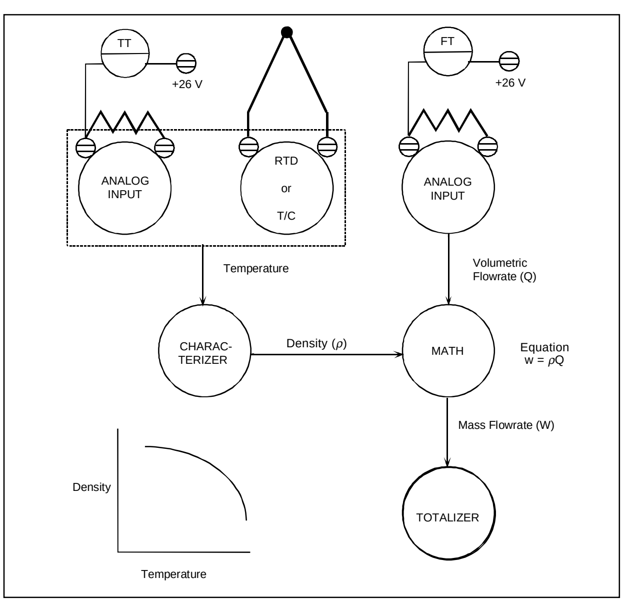

FIGURE 2 Mass Flow Calculation Liquid\Saturated Steam (Linear Meter)

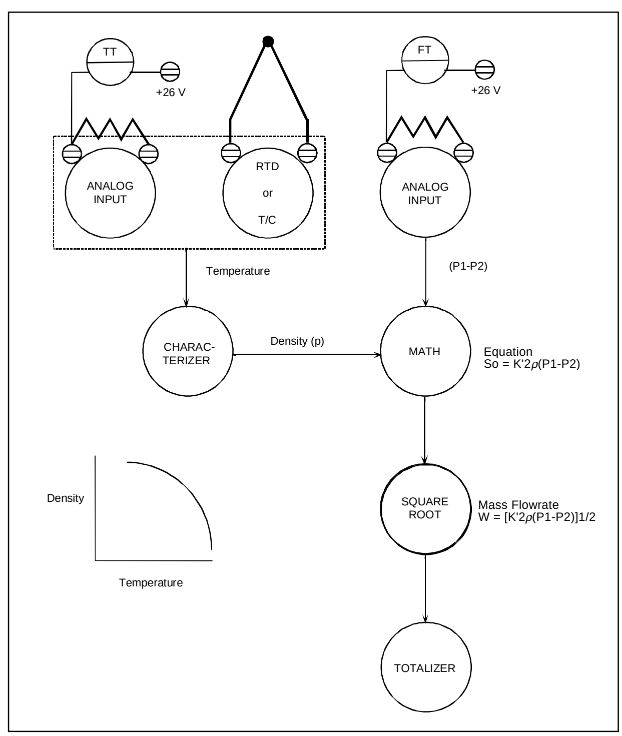

FIGURE 3 Mass Flow Calculation Liquid\Saturated Steam (Square Root Meter)

GAS FLOW MEASUREMENT - Linear Meter

For gases and superheated steam, it is necessary to use both the flowing temperature and the flowing pressure to calculate mass flowrate. The temperature and pressure are used to calculate the density at flowing conditions. The ideal gas law is used to determine the density from the pressure and temperature. It is useful to do an example problem to demonstrate the procedure.

Calculate the mass flowrate of natural gas through a linear meter given the following information:

flow range	0-5000 #/hr
operating pressure	100 psia
operating temperature	80°F

From this information we calculate the density at normal or base conditions. We use the ideal gas law from the Fluid & Gas Properties section, and the value of R from Table 1.

$$R = 96.4\ (\text{ft-lbf})/(\text{lbm-°R})$$

$$\rho = \frac{p(\text{psfa})}{R\,T(°R)}$$

convert psia to psfa

$$(100)144 = 14{,}400\ \text{psfa}$$

convert °F to °R

$$80 + 460 = 540°R$$

$$\rho = \frac{14{,}400}{(96.4)(540)} = 0.2766\ \text{lbm/ft3}$$

To determine the required range of the transmitter in volumetric units, divide the full scale flowrate by the base density.

$$5000/0.2766 = 18{,}076.6\ \text{acfh or } 301.3\ \text{acfm}$$

From this, the transmitter range is 0 to 301.3 acfm. The pressure transmitter range is 0 to 200 psia and the temperature transmitter range is 0 to 150°F.

To compensate the measured flowrate for deviations from the base density, we multiply it by the ratio of the actual density to the base density.

$$\rho_{act} = \frac{\rho_{act}}{(96.4)(460+T_{act})}$$

$$\rho_b = \frac{\rho_b}{(96.4)(460+T_b)}$$

$$\frac{\rho_{act}}{\rho_b} = \frac{\rho_{act}(460+T_b)}{p_b\,(460+T_{act})}$$

$$W = \frac{\rho_{act}}{\rho_b} Q$$

This equation must now be converted to a form that can be entered into the Moore 352 Single-Loop Digital Controller. The form of the equation needs to match:

$$S_O = \frac{G_O(G_A S_A + B_A)(G_B S_B + B_B) + B_O}{(G_C S_C + B_C)}$$

In this equation, the flow signal will be S_A, the pressure signal will be S_B and the temperature signal will be S_C. For this application, the following coefficients are known:

$G_A = 1$
$B_A = 0$
$B_O = 0$

We need to calculate the other coefficients. To calculate the bias values, use this approach.

$$B_X = \frac{V_{Xmin}\,G_X}{V_{Xmax} - V_{Xmin}}$$

where V_{Xmin} is the minimum value of the variable
V_{Xmax} is the maximum value of the variable

The values of the variable must be in the proper units (e.g. °F must be entered in °R). For the first try, assume that G_X is equal to 1. If the calculated value of B_X is greater than 3.000, then the value of G_X can be changed to ensure that B_X is within the proper range.

Since the pressure transmitter is an absolute transmitter, and referenced to 0.0 psia, we do not need to calculate a bias term for it. We also do not need to worry that its output is psia and not psfa, because we are interested in the ratio of the actual pressure to the base pressure, not the absolute value of it.

To calculate the bias term for the pressure, we use the previous format:

$$B_C = \frac{460\ (1)}{(610\text{-}460)} = 3.066$$

Since 3.066 is greater than 3.00, we need to change the value of G_C. Try changing the value of G_C to 0.5. Changing this gain will be compensated for when we calculate G_O.

$$B_C = \frac{460}{150}(0.5) = 1.533$$

Finally calculate G_O.

$$G_O = \frac{\dfrac{G_C\,(T_b - T_{LRV}) + B_C}{(T_{URV} - T_{LRV})}}{\dfrac{G_B\,(P_b - P_{LRV}) + B_C}{(P_{URV} - P_{LRV})}}$$

$$G_O = \frac{0.5\,\dfrac{(80 - 0)}{(150 - 0)} + 1.533}{1.0\,\dfrac{(100 - 0)}{(200 - 0)} + 0} = 3.599$$

$= 3.599$

This is too large to be entered as a gain. The values of gains must be between 0.30 and 3.00. To overcome this, we can enter a gain of 1.5 for G_A and a gain of 2.340 for G_O. We have now determined all of the coefficients for the math block.

$G_O = 2.340$ $B_O = 0$
$G_A = 1.500$ $B_A = 0$
$G_B = 1.000$ $B_B = 0$
$G_C = 0.500$ $B_C = 1.533$

GAS AND SUPERHEATED STEAM FLOW MEASUREMENT - Square Root Meter

To compensate a gas or superheated steam flow that is being measured by a square root meter, the procedure is very similar to that of a linear meter. Basically, the only difference is that a square root meter is compensated for changes in density before the square root is taken. The equation for mass flow of a square root meter is:

$$W = K''[\rho(P_1 - P_2)]^{1/2}$$

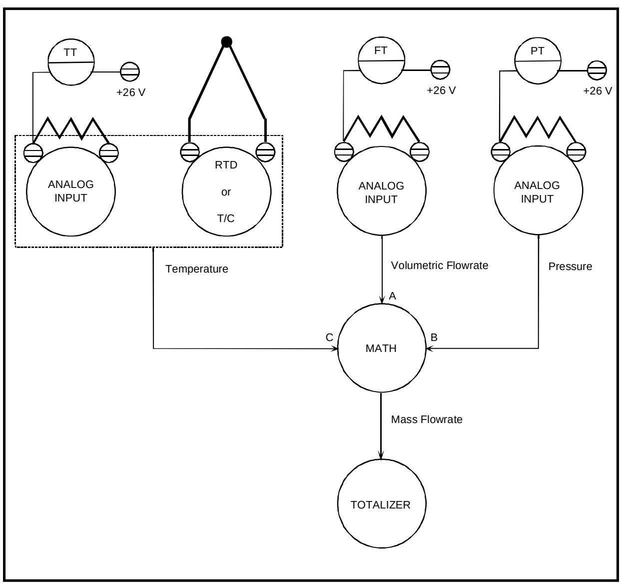

FIGURE 4 Mass Flow Calculation - Gas\Superheated Steam (Linear Meter)

As with linear meters, orifice meters are sized upon a set of base conditions, so the density term is in effect combined with K" to produce K"'. To correct for changes in density, we multiply the value $(P_1 - P_2)$ by the ratio of ρ_{act} to ρ_b. This results in the following equation:

$$W = K''' [\rho_{act}/\rho_b(P_1 - P_2)]^{1/2}$$

This calculation is performed exactly the way it was for the linear meter with the differential pressure signal being used for the flow signal. After the signal is compensated for density changes, the square root is taken. A typical configuration is shown in Figure 5.

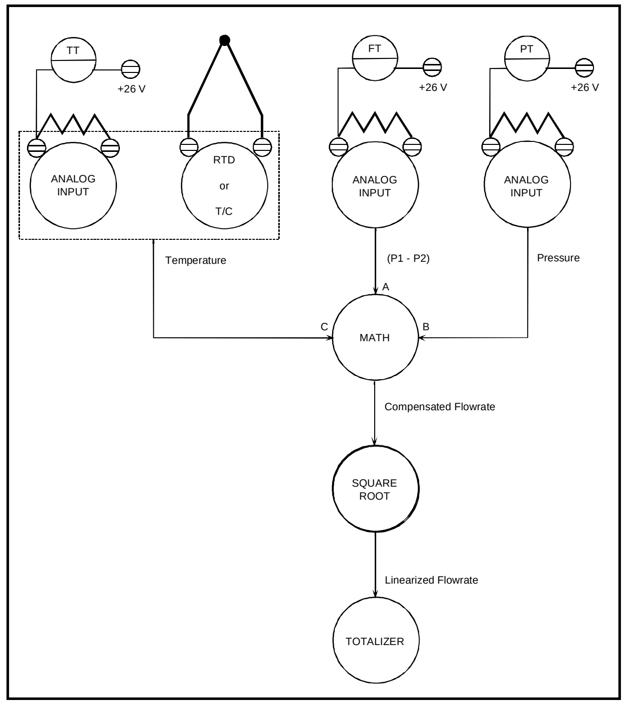

FIGURE 5 Mass Flow Calculation - Gas\Superheated Steam (Square Root Meter)