Reference Manual
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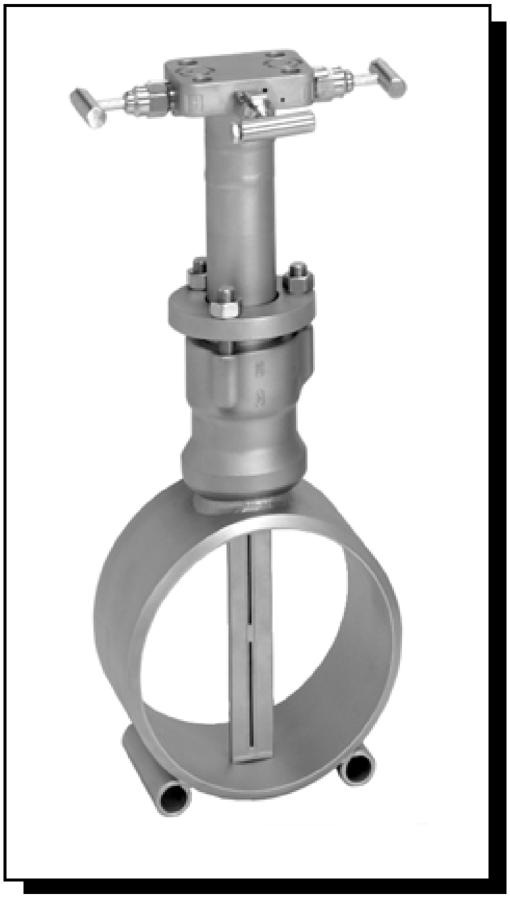
Rosemount 485 Annubar® Flow Handbook



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Section 1 Fluid Flow Theory

INTRODUCTION

The Emerson Process Management DP-Flow Engineering Department has prepared this book to provide all of the information necessary to accurately measure fluid flow using the Rosemount 485 Annubar primary element.

Fluid flow measurement involves many variables. In this handbook fluid properties that affect flow measurement are discussed and defined. We hope this will bring all readers to a point where they are comfortable with the flow equations which follow. The flow equations are developed from Bernoulli's Theorem, which is the application of the law of conservation of energy to fluid flow. These equations are then developed and modified for use with 485 Annubar Flow Sensors. After all the terms have been defined and the equations developed, you are then ready to do the precise flow calculations necessary to apply an Annubar and an associated secondary readout instrument to your flow situation.

We realize that many intricacies of fluid flow have been neglected in this book. We feel that we have presented enough theory and data for you to accurately measure fluid flow using the Annubar Flow Sensor. For difficult flow measurement problems, contact your local Emerson Process Management representative for assistance.

PHYSICAL FLUID PROPERTIES

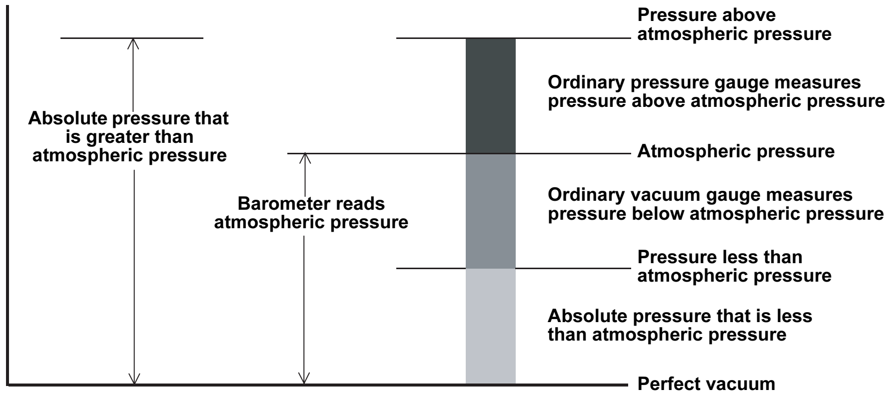
To solve any flow problem a knowledge of the physical properties of the fluid is required. Appendix A gives fluid property data for the most common fluids. Definitions and descriptions of the most common properties are given below.

Pressure

Pressure is the force exerted by a fluid per unit area. The most common unit of pressure measurement is pounds force per square inch (lbf/in^2 or psi) in the English system of units and pascal or kilopascal (Pa or kPa) in the SI system of units.

In most flow problems (especially gas flow problems), the absolute pressure must be used in the calculations. However, most pressure gages measure a pressure that is referenced to atmospheric pressure (atmospheric pressure = 0 psig or 0 kPa g). To obtain absolute pressure, the atmospheric pressure must be added to the gage pressure. Vacuum gages measure a pressure that is lower than atmospheric pressure. To obtain absolute pressure, the vacuum pressure must be subtracted from the atmospheric pressure. All of these pressure terms are described in detail below and the relationship between these pressures is shown graphically in Figure 1-1.

Figure 1-1. Pressure Relationships



Absolute zero pressure, or a perfect vacuum, would exist if all molecules were removed from an enclosed space. In reality, this is impossible to achieve, but it does serve as a convenient reference for pressure measurement.

Atmospheric pressure is the amount of pressure exerted by the atmosphere above absolute zero pressure. The “standard” atmospheric pressure used in this handbook is 14.696 psia (101.325 kPa). It is important to realize that atmospheric pressure at any one location varies with day to day weather conditions. More important, the atmospheric pressure changes rapidly with elevation above sea level. The following table gives the U.S. Standard Atmosphere (1962) for various altitudes above sea level.

Table 1-1. Atmospheric Pressure by Altitude

Altitude		Atmospheric Pressure	
feet	meters	psia	bar
0	0	14.696	1.01
500	152.4	14.433	0.995
1000	304.8	14.173	0.977
1500	457.2	13.917	0.959
2000	609.6	13.664	0.942
2500	762.0	13.416	0.925
3000	914.4	13.171	0.908
3500	1066.8	12.930	0.891
4000	1219.2	12.692	0.875
4500	1371.6	12.458	0.859
5000	1524.0	12.227	0.843
6000	1828.8	11.777	0.812
7000	2133.6	11.340	0.782
8000	2438.4	10.916	0.753
9000	2743.2	10.505	0.724
10000	3048.0	10.106	0.697
15000	4572.0	8.293	0.572
20000	6096.0	6.753	0.466

Example:

A manometer at an elevation of 5,000 feet above sea level measures 10 inches of mercury vacuum. Express this pressure in absolute terms (psia).

Solution:

From Table 1-1 on page 1-2, the average atmospheric pressure at 5,000 feet elevation is 12.227 psia.

10 inches of mercury = 4.912 psia.

(2.036" Hg @ 0°C = 1 psi - see Appendix B Unit and Conversion Factors)

Absolute pressure = 12.227 - 4.912 = 7.315 psia.

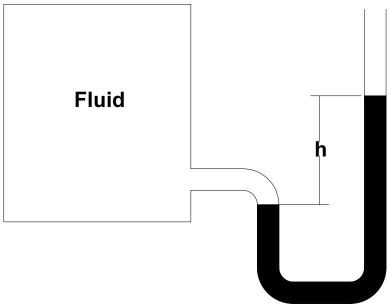
Differential pressure is just what the name implies, a difference between two pressures. Frequently, a differential pressure is measured with a pressure transmitter or a manometer which contains water, mercury, alcohol, oil, or other fluids. The differential pressure can be calculated by the relation:

$$\Delta P = \rho h$$

where:

ΔP = differential pressure in lbf/ft^2
ρ = density of the fluid in lbm/ft^3
h = elevation difference of the fluid in feet

Figure 1-2. Differential Pressure



Commercial instruments used for indicating or recording the differential pressure operate using various principles; such as variable reluctance, capacitance, or strain gage. These instruments generally give the true differential pressure without the need for additional corrections.

Temperature

Although temperature is a property which is familiar, an exact definition is difficult. Temperature is a measure of the degree of hotness or coldness of a substance. Temperature scales are defined such that the temperature of boiling water at standard atmospheric pressure is 212 °F (100 °C) and the freezing temperature of water is 32 °F (0 °C).

Most flow problems require that the temperature be expressed in absolute units. The absolute temperature of a substance is the measure of the temperature intensity of the substance above the datum known as “absolute zero.” According to kinetic theory, all molecular activity ceases at absolute zero. The Rankine and Kelvin temperature scales are based on absolute zero.

Absolute zero temperature is -459.69 °F (-273.15 °C).

Thus:

$°R = °F + 459.69$

Where:
°R = degrees Rankine
°F = degrees Fahrenheit

$°K = °C + 273.15$

Where:
°K = degrees Kelvin
°C = degrees Celsius

In most engineering work, the value of 459.69 is rounded off to 460 so that degrees Rankine is approximated as:

$°R = °F + 460$

It is important that absolute temperatures be used in gas flow problems.

Density, Specific Weight, Specific Gravity

Density is defined as the mass of a substance per unit volume. Density is usually expressed in pounds-mass-per cubic foot (lbm/ft^3) or kilograms per cubic meter (kg/m^3).

Specific Weight is defined as the weight, due to the gravitational pull of the earth, of a substance per unit volume. Specific weight is expressed in pounds-force per cubic foot (lbf/ft^3) or Newtons per cubic meter (N/m^3). As can be seen, specific weight and density are not synonymous terms. Only at locations where the local acceleration of gravity is equal to the standard acceleration of gravity ($g_c = 32.1740$ ft/s^2 or $g_c = 9.807$ m/s^2) does the numerical value of specific weight equal the numerical value of density.

Specific Gravity is defined as the ratio of the density of one substance to the density of a second or reference substance. The reference substance depends on whether the flowing media is liquid or gas.

For liquids, water at either 60 °F (15°C) or 77 °F (25 °C) is used as the reference substance. The density of distilled water at 60 °F is 62.3707 lbm/ft^3. The density of distilled water is 25 °C is 997 kg/m^3.

The determination of the specific gravity of a liquid can be made by comparing the weights of equal volumes of the liquid and water. If the quality of the work justifies it, these weights may be corrected for the buoyancy of air as well as for temperature effects. For most commercial work, the specific gravities of liquids are obtained with hydrometers. The scales of hydrometers are graduated to read directly in specific gravities, in degrees Baume or in degrees API (American Petroleum Institute). The relationship between specific gravity and degrees Baume is defined by the following formulas:

1. For liquids heavier than water: $^{\circ}\mathrm{B} = 145 - \left(\frac{145}{\left(\frac{\mathrm{SpGr60}}{60^{\circ}\mathrm{F}}\right)}\right)$

2. For liquids lighter than water: $^{\circ}\mathrm{B} = \left(\frac{140}{\left(\frac{\mathrm{SpGr60}}{60^{\circ}\mathrm{F}}\right)}\right) - 130$

3. For use in the American petroleum industry, the following relation between degrees API and specific gravities is used:

$$'\mathrm{API} = \left(\frac{141.5}{\left(\frac{\mathrm{SpGr60}}{60^{\circ}\mathrm{F}}\right)}\right) - 131.5$$

In the above equations, the term “Sp Gr 60/60” means that the specific gravity value to be used is that which exists when the temperatures of the reference liquid (water) and of the oil, or other liquid, are both at 60 °F.

For gases, air is used as the reference fluid. However, instead of a ratio of densities, the ideal specific gravity of a gas is defined as the ratio of the molecular weight of the gas of interest to the molecular weight of air. The molecular weight of air is 28.9644.

The reason for not using the ratio of the densities is that the effects of pressure and temperature on the densities of gases vary from one gas, or gas mixture, to another. Thus, even though the densities may be determined at very nearly identical ambient conditions and the resulting values adjusted to a common basis of pressure and temperature, an error may be incurred when the resulting ratio is used at a state differing from the common basis. The magnitude of this error is likely to increase as the state of use departs further and further from the common starting basis. On the other hand, so long as the composition of the gas used undergoes no change, the ratio of molecular weights will remain the same regardless of changes of pressure, temperature, and location.

For a more complete discussion or real and ideal specific gravities, see Appendix C Related Calculations.

Viscosity

Absolute viscosity may be defined simply as the temporary resistance to flow of a liquid or gas. It is that property of a liquid or gas which tends to prevent one particle from moving faster than an adjacent particle. The viscosity of most liquids decreases with an increase in temperature, but the viscosity of gases increases with an increase in temperature.

In the English System of units, the absolute viscosity has units of lbm/ft-sec. However, it is common practice to express the value of the viscosity in poise or centipoise (1 poise = 100 centipoise). The poise has units of dyne seconds per square centimeter or of grams per centimeter second. Less confusion will exist if the centipoise is used exclusively for the unit of viscosity. For this reason, all viscosity data in this handbook are expressed in centipoise, which is given the symbol μ_{cp}.

If it is necessary to express the viscosity in the English System of units, the following conversion factors should be used.

Poise x 0.067197 = lbm/ft-sec

Centipoise x 0.00067197 = lbm/ft-sec

The Annubar primary element is a head-type meter and requires fluid to convey the DP signal to the meter. For this reason a practical viscosity limit of 50 centipoise should be followed.

Kinematic viscosity or kinetic viscosity is the absolute viscosity divided by the density of the fluid at the same temperature.

$$\nu_{cs} = \frac{\mu_{cp}}{36.13\rho} \qquad \nu_{cs} = \frac{\mu_{cp}}{\rho}$$

(36.13 converts to lbm/ft^3 to gm/cm^3)

Like the units of absolute viscosity, the units of kinematic viscosity are usually expressed in metric units. To be consistent and to reduce confusion, the kinematic viscosities used in this handbook will have units of centistokes (cm^2/sec) and will be denoted υ_{cs}.

There is no name for kinematic viscosities in the English System of units, but the following conversion factor can be used:

υ_{cs} x 0.00001076 = υ(ft^2/s)

NATURE OF FLUID FLOW IN PIPES

In the foregoing sections on the physical properties of fluids, subjects were discussed that had to do with the type of fluid being used. However, one property of fluid flow which is independent of the type of fluid is velocity.

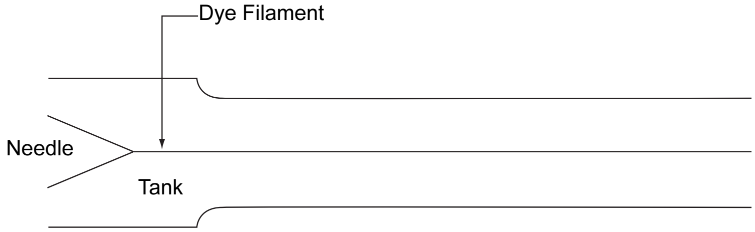
Flow Patterns

Depending upon the magnitude of the velocity, three distinct flow regimes can be encountered. These three types of flows are known as laminar, transition, and turbulent.

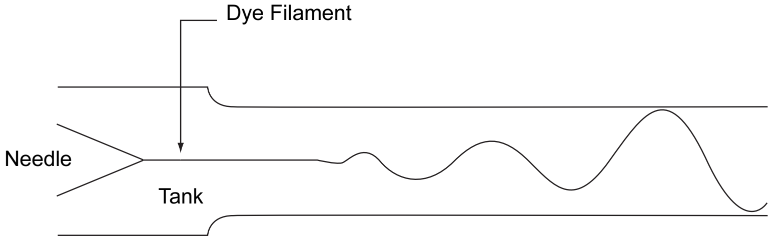
The classic experiment of introducing dye into a flowing stream was first conducted by Reynolds in 1883. The experiment consists of injecting a small stream of dye into a flowing liquid and observing the behavior of the dye at different sections downstream of the injection point. Figure 1-3 shows the three possible types of flow with the dye injected.

Figure 1-3. Types of Flow Development

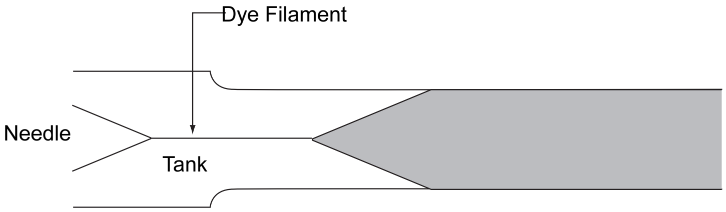
Laminar occurs when the velocity is small and the dye remains in a straight line.



Transition occurs at a slightly higher velocity than laminar flow. The dye does not remain in a straight line and does not spread throughout the pipe.



Turbulent occurs at velocities above transition flow. The dye spreads throughout the pipe as shown below. It is this type of flow which is important to the general user. Turbulent flow is, by far, the most common type of flow encountered in pipes.



Average Velocity

Unless it is stated otherwise, the term velocity will refer to the average velocity in the pipe. The average velocity is determined by the continuity equation for steady state flow.

$$W = \rho AV \qquad \left(\frac{lbm}{s}\right) = \left(\frac{lbm}{ft^3}\right)(ft^2)\left(\frac{ft}{s}\right) \qquad \left(\frac{kg}{s}\right) = \left(\frac{kg}{m^3}\right)(m^2)\left(\frac{m}{s}\right)$$

This equation states that for steady state flow, the mass rate of flow lbm/sec (kg/s) at any point in the pipeline can be calculated from the product of the density lbm/ft^3 (kg/m^3), the cross-sectional area of the pipe ft^2 (m^2), and the average velocity ft/s (m/s).

Reynolds Number

The work that Osborne Reynolds accomplished in the late 1800's led to a flow parameter that now carries his name, e.g. the Reynolds Number. His work showed that the nature of flow in a pipe depends on the pipe diameter (D), the density (ρ), viscosity, and the velocity of the fluid.

$$R_D = \frac{D\nu\rho}{\mu} = \frac{(\mathrm{ft})\left(\frac{\mathrm{ft}}{\mathrm{s}}\right)\left(\frac{\mathrm{lbm}}{\mathrm{ft}^3}\right)}{\left(\frac{\mathrm{lbm}}{\mathrm{ft}\cdot \mathrm{s}}\right)} \qquad R_D = \frac{D\nu\rho}{\mu} = \frac{(\mathrm{m})\left(\frac{\mathrm{m}}{\mathrm{s}}\right)\left(\frac{\mathrm{kg}}{\mathrm{m}^3}\right)}{\left(\frac{\mathrm{kg}}{\mathrm{m}\cdot \mathrm{s}}\right)}$$

As can be seen, the Reynolds Number has no dimensions and it may be considered as the ratio of dynamic forces to viscous forces.

For the three types of flow previously discussed, it has been found that generally laminar flow exists below a Reynolds Number of 2000. Transition flow generally exists between a Reynolds Number range of 2000 to 4000. However, the values of 2000 and 4000 are not precisely fixed. The laminar flow range can terminate between a Reynolds Number range of 1200 to 13000 depending on the smoothness of the pipe. If heat is added to the pipe, laminar flow can be extended to even higher Reynolds Numbers. The turbulent flow exist above pipe Reynolds numbers from 4,000 to 13,000.

Since the product is dimensionless, the numerical value will be the same for any given set of conditions, so long as all the separate factors are expressed in a consistent system of units. This makes the Reynolds Number an ideal correlating parameter. Therefore, the flow coefficient of flow meters are generally expressed as functions of Reynolds Number.

Although the combination $DV\rho / \mu$ is the classical expression for the Reynolds Number, there are several other equivalent combinations. First, the ratio ρ/ μ may be replaced by $1 /\upsilon$ giving:

$$R_D = \frac{DV}{\upsilon}$$

Also, the volume rate of flow (ft^3/s or m^3/s) is $Q = \pi(D^2/4)V$, thus another alternate combination for Reynolds Number is:

$$R_D = \frac{4Q\rho}{\pi D_{ft}\mu} \qquad R_D = \frac{4Q\rho}{\pi D_m\mu}$$

Also, the mass rate of flow (lbm/s or kg/s) is $W = Q\rho$ so that a third alternate combination is:

$$R_D = \frac{4W}{\pi D_{ft}\mu} \qquad R_D = \frac{4W}{\pi D_m\mu}$$

If the viscosity (μ) is given in centipoise, the last combination for Reynolds Number becomes:

$$R_D = \frac{1895W}{D_{ft}\mu_{cp}} \qquad R_D = \frac{1298W}{D_m\mu_{cp}}$$

The pipe Reynolds Number (R_D) can be calculated by using any of the following equations:

Liquid:

$$R_D = \frac{3160 \cdot GPM \cdot G}{D \cdot \mu_{cp}} \qquad R_D = \frac{21230 \cdot LPM \cdot G}{D \cdot \mu_{cp}}$$

Gas:

$$R_D = \frac{0.4831 \cdot SCFH \cdot G}{D \cdot \mu_{cp}} \qquad R_D = \frac{432 \cdot NCMH \cdot G}{D \cdot \mu_{cp}}$$

Liquid, Gas and Steam:

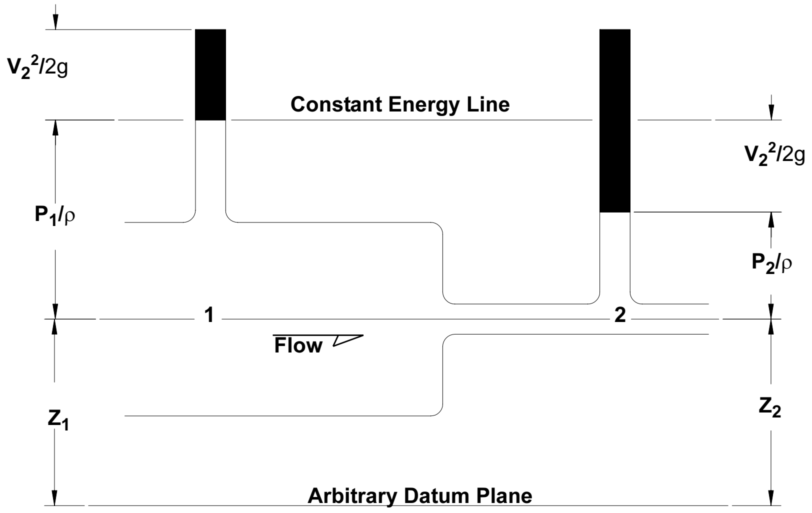
$$R_D = \frac{6.316 \cdot \left(\frac{lbm}{hr}\right)}{D \cdot \mu_{cp}} \qquad R_D = \frac{353.6 \cdot \left(\frac{kg}{hr}\right)}{D \cdot \mu_{cp}}$$

where:
G = specific gravity of flowing fluid (air = 1.0, water = 1.0)
GPM = U.S. gallons per minute
kg/hr = flowrate of fluid in kilograms per hour
LPM = flowrate of fluid in liters per minute
NCMH = flowrate of gas in normal cubic meters per hour
SCFH = flowrate of gas in standard cubic feet per hour

Bernoulli's Theorem

Bernoulli's Theorem is a means of expressing the application of The Law of Conservation of Energy to the flow of fluids in a pipe. The total energy at any location in the pipe, above some arbitrary datum, is equal to the sum of the elevation head, the velocity head, and the pressure head.

Figure 1-4. Bernoulli's Theorem



In a steady incompressible flow, without friction, the sum of the velocity head, pressure head, and elevation head is a constant along any streamline (see Figure 1-4). Assuming that the elevation difference between two measuring points is negligible ($Z_1 = Z_2$), Bernoulli's Equation can then be written:

Equation 1-1.

$$\left(\frac{V_1^2}{2g}\right) + \left(\frac{P_1}{\rho}\right) = \left(\frac{V_2^2}{2g}\right) + \left(\frac{P_2}{\rho}\right)$$

where,
V = velocity, ft/s (m/s)
g = gravitation constant, ft/s^2 (m/s^2)
P = pressure, lbf/ft^2 (kPa)
ρ = density, lbm/ft^3 (kg/m^3)
A = area, ft^2 (m^2)

Since Bernoulli's Theorem states that the flow is steady, the continuity equation must apply. The continuity equation states that the mass rate of flow between two points must be constant.

Equation 1-2.

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2$$

since the flow is incompressible ($\rho_1 = \rho_2$), *Equation 1-3* reduces to:

Equation 1-3.

$$A_1 V_1 = A_2 V_2$$

solving for V_1 in *Equation 1-4*:

Equation 1-4.

$$V_1 = \frac{A_2 V_2}{A_1}$$

and substituting into *Equation 1-1*:

$$\frac{1}{2g}\left(\frac{A_2 V_2}{A_1}\right)^2 + \left(\frac{P_1}{\rho}\right) = \left(\frac{V_2^{\ 2}}{2g}\right) + \left(\frac{P_2}{\rho}\right)$$

$$\frac{V_2^2}{2g} - \frac{1}{2g}\left(\frac{A_2 V_2}{A_1}\right)^2 = \left(\frac{P_1}{\rho}\right) + \left(\frac{P_2}{\rho}\right)$$

$$\frac{V_2^2}{2g} - \left(1 - \left(\frac{A_2}{A_1}\right)^2\right) = \frac{P_1 - P_2}{\rho}$$

$$V_2^2 = 2g\left(\frac{P_1 - P_2}{\rho}\right)\left[\frac{1}{1 - \left(\frac{A_2}{A_1}\right)^2}\right]$$

$$V_2 = \sqrt{2g\frac{P_1 - P_2}{\rho}}\sqrt{\frac{1}{1 - \left(\frac{A_2}{A_1}\right)^2}}$$

Again, using the continuity equation, the theoretical mass rate of flow would be:

Equation 1-5.

$$W_{theo} = \rho A_2 V_2 = A_2\sqrt{2g\rho(P_1 - P_2)}\sqrt{\frac{1}{1 - \left(\frac{A_2}{A_1}\right)^2}}$$

The theoretical equation for volumetric flow is:

Equation 1-6.

$$Q_{theo} = A_2 V_2 = A_2\sqrt{\frac{2g\rho(P_1 - P_2)}{\rho}}\sqrt{\frac{1}{1 - \left(\frac{A_2}{A_1}\right)^2}}$$

By definition the discharge coefficient of a flow meter is the ratio of the actual rate of flow to the theoretical rate of flow.

Equation 1-7.

$$C = \frac{W_{actual}}{W_{theoretical}} = \frac{Q_{actual}}{Q_{theoretical}}$$

Therefore, the actual volumetric flow for liquid is:

Equation 1-8.

$$Q_{actual} = Q = A_2C\sqrt{\frac{2g\rho(P_1 - P_2)}{\rho}}\sqrt{\frac{1}{1 - \left(\frac{A_2}{A_1}\right)^2}}$$

By defining the flow coefficient K of an Annubar primary element as:

$$K = \frac{C}{\sqrt{1 - \left(\frac{A_2}{A_1}\right)^2}}$$

The volumetric flow *Equation 1-8* reduces to:

Equation 1-9.

$$Q = KA_2\sqrt{\frac{2g(P_1 - P_2)}{\rho}}$$

In a like manner, the mass rate of flow reduces to:

Equation 1-10.

$$W_{actual} = W = KA_2\sqrt{2g\rho(P_1 - P_2)}$$

By using consistent units *Equation 1-9* can be checked as follows:

$$Q = ft^2\sqrt{\frac{ft\left(\frac{lbf}{ft^2}\right)}{s^2\left(\frac{lbf}{ft^3}\right)}} = \frac{ft^3}{s} \qquad Q = m^2\sqrt{\frac{(m)\left(\frac{kgf}{m^2}\right)}{s^2\left(\frac{kgf}{m^3}\right)}} = \frac{m^3}{s}$$

Likewise, *Equation 1-10* is:

$$W = ft^2\sqrt{\frac{ft}{s^2}\frac{lbm}{ft^3}\frac{lbf}{ft^2}} = \frac{lbm}{s} \qquad W = m^2\sqrt{\frac{m}{s^2}\frac{kgm}{m^3}\frac{kgf}{m^2}} = \frac{kgm}{s}$$

NOTE:
In the above units conversion, lbf is set equal to lbm. This is only true at standard gravity (g_c = 32.174 ft/sec2). However, for measurements on the surface of the earth, the assumption of lbf = lbm is fairly good.

It is also interesting to note that this assumption leads to the historical name "head-type meters". By using the following:

$$h = \frac{\frac{lbf}{ft^2}}{\frac{lbm}{ft^3}} = ft \qquad h = \frac{\frac{kgf}{m^2}}{\frac{kgm}{m^3}} = m$$

Where h is feet (meters) of head of flowing fluid, equation (2-9) can be written as:

$$Q = KA\sqrt{2g\frac{\left(\frac{lbf}{ft^2}\right)}{\left(\frac{lbm}{ft^3}\right)}} = KA\sqrt{2gh} \qquad Q = KA\sqrt{2g\frac{\left(\frac{kgf}{m^2}\right)}{\left(\frac{kgm}{m^3}\right)}} = KA\sqrt{2gh}$$

The equation $Q = KA\sqrt{2gh}$ will be recognized as the well known hydraulic equation for liquids.

Actual and Standard Volumetric Flowrate for Gases

The most common unit of volumetric measurement in English Units is the cubic foot. The most common unit in SI units is the cubic meter. Many others exist, such as the cubic inch, the gallon (231 cubic inches), and the barrel (42 gallons); but these are generally defined as portions of a cubic foot.

In Equation 1-9 the volumetric flow (Q) can be calculated in ft^3/s (m^3/s) if all the other parameters have the consistent set of units shown. The most important aspect of this equation is that the volumetric flow is given in actual units.

Example:

> Suppose a flowmeter is operating according to Equation 1-10, and that the equation shows that the flowrate is 5 ft^3/s. Also suppose that the fluid can be poured or dumped into one (1) cubic foot containers. At the end of one second, five containers would be full of fluid. In other words, the equation gave the flowrate in actual cubic feet per second.

For gases, especially fuel gases, the cubic foot is still the unit of measurement. However, a cubic foot of gas has no absolute or comparative value unless the pressure and temperature of the gas are specified. Common sense tells us that the amount of matter within a one cubic foot space at a pressure of 1000 psia is greater than the amount of matter within that space if the pressure is atmospheric. Since the fuel gas industry is interested in selling energy, which is the amount of heat that can be generated by that cubic foot of gas, and that the amount of energy is directly proportional to the number of molecules (matter) within the cubic foot space, it is easy to see why the pressure and temperature of the gas are specified.

Since it is the amount of matter (mass) that is required to be measured as the gas flows along the pipeline, the actual volumetric flowrate terms do not lend themselves to this task easily.

Example:

> Suppose a gas in a pipeline at 140 kPa abs and 5 °C is flowing at 50 actual m^3/s; it is not obvious that the same amount of matter (mass) would flow through a pipeline at 5100 kPa abs and 30.8 °C if the flowrate was 1.54 actual m^3/s.

Because of the inability to compare the amounts of mass of a gas in actual volumetric terms, the standard volumetric term was developed. The most common unit of gaseous measurement is the amount of a gas that would be contained in a one cubic foot enclosure at standard conditions. Standard conditions can be defined as any combination of temperature and pressure. Some common standard sets are provided in the table below.

Table 1-2. Standard Conditions

Temperature	Pressure
60 °F	14.73 psia
68 °F	14.73 psia
0 °C	101.393 kPa abs

The approximate conversion from actual volumetric flowrate to standard volumetric flowrate is accomplished by the BOYLES-CHARLES law. These laws state the following:

1. If an ideal gas were contained within an enclosure at constant temperature, the pressure would increase in proportion to the volume decrease. Example: the pressure would double if the volume was reduced by half. The equation takes the form of:

   $$P_1V_1 = P_2V_2$$

   Which states that the product of the pressure and volume at one condition must equal the product of the pressure and volume at any other condition provided the temperature is the same at both conditions.
2. Again, if an ideal gas were contained within an enclosure of constant volume, the pressure would increase in proportion to the absolute temperature increase. The equation for this process takes the form:

   $$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

   Which states that the ratio of the pressure and temperature at any one condition must equal the ratio of the pressure and temperature at any other conditions provided the volume of the container has not changed.

Both of these laws can be combined to form a single equation:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

If, instead of considering actual volumes, the flowrate (actual volume per unit time) is used, the equation becomes:

$$\frac{P_1Q_1}{T_1} = \frac{P_2Q_2}{T_2}$$

Since $Q_1 = \frac{V_1}{t}$ and $Q_2 = \frac{V_2}{t}$ where t is a common unit of time (hours, minutes or seconds).

Now, if P_1 and T_1 are always considered to be at the standard specified conditions of 14.73 psia and 60°F (101.393 kPa A and 0 °C), the flowrate Q_1 is the standard volumetric flowrate Q_S.

$$\frac{14.73Q_s}{460 + 60} = \frac{P_fQ_A}{T_f + 460} \qquad \frac{101.325Q_s}{273.15 + 0} = \frac{P_fQ_A}{T_f + 273.15}$$

This equation allows the standard volumetric flowrate (Qs) to be calculated from any actual volumetric flowrate (QA) where the pressure and temperature are known.

$$Q_s = \frac{P_f}{14.73} \cdot \frac{460 + 60}{T_f + 460} \cdot Q_A \qquad Q_s = \frac{P_f}{101.325} \cdot \frac{273.15 + 0}{T_f + 273.15} \cdot Q_A$$

In an example on page 1-12, two actual volumetric flowrates were given, and it was stated that the amount of mass flowing was the same. To check this, the standard volumetric can be calculated for each flowrate:

Flowrate #1:

$$Q_A = 50\frac{ft^3}{s}$$

$$P_f = 20psia$$

$$T_f = 40°F$$

$$Q_s = \frac{20}{14.73}\cdot\frac{460+60}{460+40}\cdot 50$$

$$Q_s = 70.6SCFS$$

$$Q_A = 50\frac{m^3}{s}$$

$$P_f = 140kPaabs$$

$$T_f = 5°C$$

$$Q_s = \frac{140}{101.325}\cdot\frac{273.15+0}{273.15+5}\cdot 50$$

$$Q_s = 67.8NMCS$$

Flowrate #2

$$Q_A = 1.5\frac{ft^3}{s}$$

$$P_f = 750psia$$

$$T_f = 102.5°F$$

$$Q_s = \frac{750}{14.73}\cdot\frac{460+60}{460+102.5}\cdot 1.5$$

$$Q_s = 70.6SCFS$$

$$Q_A = 1.54\frac{m^3}{s}$$

$$P_f = 5100kPaA$$

$$T_f = 39.2°C$$

$$Q_s = \frac{5100}{101.325}\cdot\frac{273.15+0}{273.15+39.2}\cdot 1.54$$

$$Q_s = 67.8NMCS$$

As can be seen, the two actual volumetric flowrates are identical in terms of standard volumetric flowrates. However, only ideal gases have been considered so far. Real gases deviate from the Boyles-Charles relationships. The amount of deviation depends upon pressure, temperature, and type or composition of the gas. The deviation is known as the compressibility factor of the gas. For most flow conditions, the conversion to standard volumetric flowrate using only the Boyles-Charles relationship will be accurate within a few percent. To be correct, the Boyles-Charles relationship must be modified as follows:

$$\frac{P_1V_1}{Z_aT_1} = \frac{P_2V_2}{Z_fT_2}$$

Where Z is the compressibility factor at each pressure and temperature condition. This modification leads to the following:

$$Q_s = \frac{P_f}{14.73}\cdot\frac{460+60}{T_f}\cdot\frac{Z_b}{Z_f}\cdot Q_A$$

$$Q_s = \frac{P_f}{101.325}\cdot\frac{273.15+0}{T_f}\cdot\frac{Z_b}{Z_f}\cdot Q_A$$

Where:

Z_b=compressibility factor at base or standard conditions and is generally considered to be unity (Z_b=1.000).

Z_f=compressibility factor at P_f and T_f.

More discussion on compressibility factors can be found in “Ideal and Real Specific Gravity” on page D-1.

Actual and Standard Volumetric Flowrate for Liquids

In general, liquid flowrates are not converted into standard volumetric flowrates. They are usually expressed in actual volumetric terms.

However, some industries do convert actual liquid flows to standard liquid flows. The petroleum industry is probably the largest industry which does convert its actual volumes to standard volumes. This is done primarily because that industry is concerned with the selling and buying of energy. The energy content of a barrel of oil at 1000 °F is less than the energy content of a barrel of oil at 60 °F because the oil expands with temperature. Since the energy content is directly proportional to the amount of matter (mass) within the barrel, the temperature (thermal) expansion is considered.

Industries which convert liquids to standard volumetric flows have generally established 60 °F as the reference temperature. To convert actual volumetric flow to standard volumetric flows, the following equation can be used.

$$Q_s = Q_A \frac{\rho_A}{\rho_s}$$

Where,

Q_S = standard volumetric flowrate

Q_A = actual volumetric flowrate

ρ_A = density of fluid at actual flowing conditions

ρ_S = density of fluid at standard or base conditions

As can be seen, the conversion to standard volumetric flow can be accomplished simply by multiplying the density ratio. One alternate that is commonly encountered is that the conversion is accomplished by multiplying by the ratio of the specific gravities. That is:

$$Q_s = Q_A \frac{G_f}{G_s}$$

Where,

G_f=specific gravity at flowing conditions

G_S=specific gravity at base conditions

Since specific gravity is defined as the ratio of the density of the fluid to the density of the fluid to the density of water at 60°F, these conversions are identical.

Section 2 Annubar Primary Element Flow Calculations

ANNUBAR PRIMARY ELEMENT FLOW EQUATIONS

The Annubar primary element flow equations are all derived from the hydraulic equations which are shown on page 1-11. For a detailed example of a derivation of an Annubar primary element equation, see the Rosemount 485 Annubar Flow Test Data Book (document number 00821-0100-4809).

Equation 2-1. : Volume rate of flow - Liquids (Actual Conditions)

$$Q_a = C' \cdot \sqrt{h_w} \qquad \text{OR} \qquad h_w = \left(\frac{Q_a}{C'}\right)^2$$

where:

$$C' = F_{na} \cdot K \cdot D^2 \cdot F_{aa} \cdot \sqrt{\frac{1}{G_f}}$$

NOTE:
For description of standard volumetric flow equations, see page 1-12.

Equation 2-2. : Mass rate of flow - Liquids

$$W = C' \cdot \sqrt{h_w} \qquad \text{OR} \qquad h_w = \left(\frac{W}{C'}\right)^2$$

where:

$$C' = F_{na} \cdot K \cdot D^2 \cdot F_{aa} \cdot \sqrt{\rho_f}$$

Equation 2-3. : Mass rate of flow - Gas and Steam

$$W = C' \cdot \sqrt{h_w} \qquad \text{OR} \qquad h_w = \left(\frac{W}{C'}\right)^2$$

where:

$$C' = F_{na} \cdot K \cdot D^2 \cdot Y_a \cdot F_{aa} \cdot \sqrt{\rho_f}$$

Equation 2-4. : Volume rate of flow - Gas (Standard Conditions)

$$Q_s = C' \cdot \sqrt{h_w \cdot P_f} \qquad \text{OR} \qquad h_w = \frac{1}{P_f} \cdot \left(\frac{Q_s}{C'}\right)^2$$

where:

$$C' = F_{na} \cdot K \cdot D^2 \cdot Y_a \cdot F_{pb} \cdot F_{tb} \cdot F_{tf} \cdot F_g \cdot F_{pv} \cdot F_{aa}$$

Equation 2-5. : Volume rate of flow - Gas (Actual Conditions)

$$Q_a = C' \cdot \sqrt{h_w} \qquad \text{OR} \qquad h_w = \left(\frac{Q_a}{C'}\right)^2$$

where:

$$C' = F_{na} \cdot K \cdot D^2 \cdot Y \cdot F_{aa} \cdot \sqrt{\frac{1}{\rho_f}}$$

For a detailed description of each term in the above equations, see "Nomenclature" on page 2-6. Please note that each of the above equations has a C' constant. It is not intended that the C' constant of one equation is equal to the C' constant of another equation. The numerical value of any C' constant is the product of the appropriate factors for that equation only.

The following tabulations of the flow equations will serve as handy work pads. Also, the table numbers where the necessary information can be found are given in the headings of these tabulations. Several completed examples of flow calculations are given beginning on page 2-11.

NOTE
The 485 Annubar primary element needs no correction for the Reynolds Number.

Table 2-1. Equation for Liquid – Volume Rate of Flow

Rate of Flow	Unit Conversion Factor	Annubar Flow Coefficient	Internal Pipe Diameter	Thermal Expansion Factor (Table A-11)	Flowing Specific Gravity	Differential Pressure
	Annubar Flow Constant C^I					
Q_a	$= F_{na}$	$\cdot\ K$	$\cdot\ D^2$	$\cdot\ F_{aa}$	$\cdot\ \sqrt{\frac{1}{G_f}}$	$\cdot\ \sqrt{h_w}$
GPM	5.6664		$(in)^2$			inch H_2O at 68 °F
GPH	339.99		$(in)^2$			inch H_2O at 68 °F
GPD	8159.7		$(in)^2$			inch H_2O at 68 °F
BPH (42 gal)	8.0949		$(in)^2$			inch H_2O at 68 °F
BPD (42 gal)	194.28		$(in)^2$			inch H_2O at 68 °F
ft^3/min	0.75749		$(in)^2$			inch H_2O at 68 °F
CFH	45.4494		$(in)^2$			inch H_2O at 68 °F
CFM	0.7575		$(in)^2$			inch H_2O at 68 °F
Imp. GPM	4.7183		$(in)^2$			inch H_2O at 68 °F
LPH	4.00038		$(mm)^2$			kPa
LPM	6.6673E-02		$(mm)^2$			kPa
LPS	1.1112E-03		$(mm)^2$			kPa
m^3/D	9.6012E-02		$(mm)^2$			kPa
m^3/H	4.0005E-03		$(mm)^2$			kPa
m^3/M	6.6675E-05		$(mm)^2$			kPa
m^3/s	1.1112E-06		$(mm)^2$			kPa

Table 2-2. Liquid – Mass Rate of Flow

Rate of Flow	Unit Conversion Factor	Annubar Flow Coefficient	Internal Pipe Diameter	Thermal Expansion Factor (Table A-11)	Flowing Specific Gravity	Differential Pressure
	Annubar Flow Constant C^I					
W =	F_{na} ·	K ·	D^2 ·	F_{aa} ·	$\sqrt{\rho_f}$ ·	$\sqrt{h_w}$
PPD	8614.56		$(in)^2$			inch H_2O at 68 °F
PPH	358.94		$(in)^2$			inch H_2O at 68 °F
PPM	5.9823		$(in)^2$			inch H_2O at 68 °F
PPS	0.0997		$(in)^2$			inch H_2O at 68 °F
T(met)/hr	1.2645E-04		$(mm)^2$			kPa
kg/D	3.03471		$(mm)^2$			kPa
Kg/H	0.12645		$(mm)^2$			kPa
kg/M	2.1074E-03		$(mm)^2$			kPa
kg/S	3.5124E-05		$(mm)^2$			kPa

Table 2-3. Gas and Steam– Mass Rate of Flow

Rate of Flow	Unit Conversion Factor	Annubar Flow Coefficient	Internal Pipe Diameter	Annubar Expansion Factor	Thermal Expansion Factor (Table A-11)	Flowing Specific Gravity	Differential Pressure
	Annubar Flow Constant C^I						
W =	F_{na} ·	K ·	D^2 ·	Y_a ·	F_{aa} ·	$\sqrt{\rho_f}$ ·	$\sqrt{h_w}$
PPD	8614.56		$(in)^2$				inch H_2O at 68 °F
PPH	358.94		$(in)^2$				inch H_2O at 68 °F
PPM	5.9823		$(in)^2$				inch H_2O at 68 °F
PPS	0.0997		$(in)^2$				inch H_2O at 68 °F
T(met)/hr	1.2645E-04		$(mm)^2$				kPa
kg/D	3.03471		$(mm)^2$				kPa
Kg/H	0.12645		$(mm)^2$				kPa
kg/M	2.1074E-03		$(mm)^2$				kPa
kg/S	3.5124E-05		$(mm)^2$				kPa

Table 2-4. Volume Rate of Flow at STD Conditions - Gas

Rate of Flow	Unit Conversion Factor	Annubar Flow Coefficient	Internal Pipe Diameter	Annubar Expansion Factor	Pressure Base Factor	Temperature Base Factor	Flowing Temperature Factor	Specific Gravity Factor	Supercomp Factor (Table 8)	Thermal Expansion Factor (Table 9)	Flowing Specific Gravity	Differential Pressure
Annubar Flow Constant C^I												
Q_a =	F_{na} ·	K ·	D^2 ·	Y_a ·	F_{pb} ·	F_{tb} ·	F_{tf} ·	F_g ·	F_{pv} ·	F_{aa} ·	$\sqrt{\rho_f}$ ·	$\sqrt{h_w}$
SCFD	8116.1		$(in)^2$									H_20 @ 68° F
SCFH	338.17		$(in)^2$									H_20 @ 68° F
SCFM	5.6362		$(in)^2$									H_20 @ 68° F
NL/H	11.34700		$(mm)^2$									kPa
NL/M	0.18912		$(mm)^2$									kPa
NM^3/D	0.27234		$(mm)^2$									kPa
NM^3/H	1.1347E-02		$(mm)^2$									kPa
NM^3/M	1.8912E-04		$(mm)^2$									kPa
NM^3/S	3.1520E-06		$(mm)^2$									kPa

Table 2-5. Volume Rate of Flow at Act Conditions

Rate of Flow	Unit Conversion Factor	Annubar Flow Coefficient	Internal Pipe Diameter	Annubar Expansion Factor	Thermal Expansion Factor (Table 9)	Flowing Specific Gravity	Differential Pressure
	Annubar Flow Constant C^I						
Q_a =	F_{na} ·	K ·	D^2 ·	Y_a ·	F_{aa} ·	$\sqrt{\frac{l}{\rho_f}}$ ·	$\sqrt{h_w}$
ACFD	8614.56		$(in)^2$				H_20 @ 68° F
ACFH	358.94		$(in)^2$				H_20 @ 68° F
ACFM	5.9823		$(in)^2$				H_20 @ 68° F
AL/H	126.4434		$(mm)^2$				kPa
AL/M	2.10739		$(mm)^2$				kPa
Am^3/D	3.03473		$(mm)^2$				kPa
Am^3/H	0.12645		$(mm)^2$				kPa
Am^3/M	2.1074E-03		$(mm)^2$				kPa
Am^3/S	3.5124E-05		$(mm)^2$				kPa

NOMENCLATURE

D	Internal diameter of pipe, inches (mm)
F_{aa}	Thermal Expansion Factor. This factor corrects for the flowing area change of the pipe at the Annubar location due to temperature effects. For 316 stainless steel Annubar primary elements mounted in carbon steel pipe, F_{aa} = 1.0000 for temperatures between 31 and 106 °F. See Table B-1 on page B-3 which includes thermal expansion factors for various pipe materials at several temperatures.
F_g	Specific Gravity Factor. This factor corrects the flow equation whenever the gas is not air. The factor can be calculated as: $F_g = \sqrt{\frac{1}{G}}$ where, G = specific gravity of flowing gas, air = 1.000. For a more complete description of specific gravity, see “Density, Specific Weight, Specific Gravity” on page 1-4 and Appendix D: Related Calculations.
F_{na}	Units Conversion Factor. This factor is used to convert the flow rate to the desired set of units. Appendix D: Related Calculations shows an example of how the numerical value of F_{na} is derived from the hydraulic equation for a given set of input units.
F_{pb}	Pressure Base Factor. The Pressure Base Factors are calculated to give gas volumes at a pressure base of 14.73 psia (101.325 kPa abs). The pressure base factor can be calculated as: $F_{pb} = \frac{14.73}{\text{base pressure, psia}}$ OR $F_{pb} = \frac{101.325}{\text{base pressure, kPa abs}}$
F_{pv}	Supercompressibility Factor. The Supercompressibility Factor accounts for the deviation from the “ideal gas” laws. In the flow equations, gas volumes are assumed to vary with pressure and temperature in accordance with Boyle’s and Charles' laws (the “ideal gas” laws). Actually, the volume occupied by individual gases deviate, by a slight degree, from the volumes which the “ideal gas” laws indicate. The amount of deviation is a function of the composition of the gas and varies primarily with static pressure and temperature. The actual deviation may be obtained by a laboratory test conducted on a sample of the gas, carefully taken at line conditions of pressure and temperature. The National Bureau of Standards, Circular 564, gives the compressibility factor (Z) of air and other pure gases. The relationship between supercompressibility factor and compressibility factor is as follows: $F_{pv} = \sqrt{\frac{1}{Z}}$ Table A-9 on page A-12 gives an abbreviated listing of the supercompressibility factors for air. Practical relationships have been established by which this deviation can be calculated and tabulated for natural gases containing normal mixtures of hydrocarbon components, considering the presence of small quantities of carbon dioxide and nitrogen and also relating the deviation to the heating value of gas. The A.G.A. manual (NX-19), “Determination of Supercompressibility Factors for Natural Gas”, should be used for determination of F_{pv}.
F_{tb}	Temperature Base Factor. The Temperature Base Factors are calculated to give gas volumes at a base temperature of 60 °F (520°R) for English Units. In order to adapt the flow equation for use in SI units, the factor is calculated similarly at 16 °C (289.15 K). The factor can be calculated as: $F_{tb} = \frac{\text{temperature base (°F)} + 460}{520}$ OR $F_{tb} = \frac{\text{temperature base (°C)} + 273.15}{288.15}$
F_{tf}	Flowing Temperature Factor. The units conversion factor (F_{NA}) for volumetric flow of gases at standard conditions has been calculated assuming that the gas temperature flowing around the Annubar primary element is 60 °F (520 °R) or 16 °C (289 K). If measurement is made at any other flowing temperature, then the flowing temperature factor must be applied. The factor can be found in Table A-8 on page A-11 or calculated as: $F_{tf} = \sqrt{\frac{520}{\text{flowing temperature (°F)} + 460}}$ OR $F_{tf} = \sqrt{\frac{288.15}{273.15 + \text{flowing temperature (°C)}}}$
G	Specific Gravity of Flowing Liquid. Ratio of the density of the flowing fluid to the density of water at 60°F which is 63.3707 lbm/ft^3. See Table A-4 on page A-6 for specific gravities of various liquids.
h_w	Differential pressure produced by the Annubar primary element. For this handbook, the differential pressure is expressed as the height, in inches, of a water column at 68 °F at standard gravity (g_c = 32.174 ft/sec^2). In SI Units, the differential pressure is expressed in kPa. h_w = inches H_2O at 68 °F (kPa)
K	Flow Coefficient. Equation 2-8 on page 2-9 defines the flow coefficient of an Annubar primary element. It is related to the diameter of the pipe and is generally expressed as a function of Reynolds Number. See “Reynolds Number” on page 1-8 for an explanation of Reynolds Number.

P_f Flowing Pressure. This is the static pressure, in absolute units, existing in the pipe. For this handbook, the pressures are expressed in psia (kPa abs).

Q_a Actual Volumetric Flow Rate. This term is the flow rate of the fluid passing the Annubar primary element in actual volume units per units of time. Examples are actual cubic feet per hour (ACFH), GPM, Am^3/h, etc.

Q_s Standard (Normal) Volumetric Flow Rate. This term is the flow rate of the fluid passing the Annubar primary element in standard volume units per unit of time. For some gases, especially fuel gases, the cubic foot is the unit of measurement. However, a cubic foot of gas has no absolute or comparative value unless the pressure and temperature of the gas are specified. A common unit used for evaluating rates of flow is standard cubic foot per hour (SCFH). This unit states how many cubic feet of gas per hour would be flowing around the Annubar primary element if the flowing pressure and temperature were equal to the base pressure and temperature. For this handbook, the base pressure is 14.73 psia (101.56 kPa abs) and the base temperature is 60 °F (520 °R) or 0 °C (273 K).

ρ_f Flowing Density. For this handbook, the densities are expressed in lbm/ft (kg/m^3). Appendix A: Fluid Properties and Pipe Data gives densities of various fluids.

Y_A Expansion Factor. When a gas flows around an Annubar primary element, the change in velocity is accompanied by a change in density. The expansion factor must be applied to correct for this change. The expansion factor also accounts for small changes in the internal energy of the molecules due to the temperature difference between the upstream and downstream pressure ports of the Annubar primary element. The variation of the expansion factor is small and the ratio of specific heats for commercial gases is sufficiently constant to warrant using a constant ratio of specific heat. Use the following algorithm to calculate the value of the gas expansion factor. This equation adjusts for density and internal energy effects of the gas as it flows around the Annubar primary element.

Equation 2-6. : Gas Expansion Factor

$$Y_a = 1 - (Y_1(1-B)^2 - Y_2)\frac{h_w}{P_f \Upsilon}$$

where:

Equation 2-7. : Blockage Equation

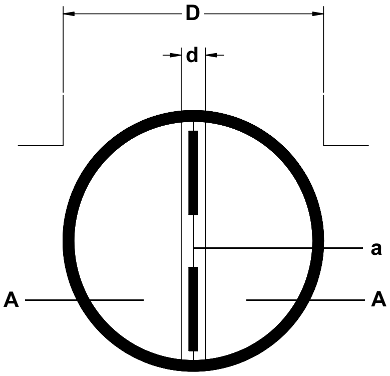
$B = \frac{4d}{\pi D}$ = Blockage
D = Internal Pipe Diameter in inches (cm)
d = See Table 2-7 on page 2-10
h_w = Differential pressure in inches (mm) of water column
P_f = Flowing line pressure in psia (kPa abs)
γ = Ratio of specific heats
Y_1= 0.011332 in English Units (0.31424 SI Units)
Y_2= 0.00342 in English Units (0.09484 SI Units)

Examples of gases with a specific heat ratio of 1.4 are: air, CO, H_2, NO, N_2 and O_2. Examples of gases with a specific heat ratio of 1.3 are: natural gas, ammonia, CO_2, Cl_2, H_2S, N_2O, SO_2, and steam.

Y_a is needed in all gas flow equations and requires the differential pressure be calculated first. If the differential pressure is not known, Y_a is assumed to be 1.000 and the differential pressure is calculated. Iteration is then necessary to determine a final value.

W Mass Rate of Flow. This term is the flow rate of the fluid passing the Annubar primary element in mass units per unit time.

Figure 2-1. Typical Cross Section



a = Annubar projected area = $d \cdot D$

A = Pipe inside area = $\frac{\pi D^2}{4}$

$B = \frac{a}{A} = \frac{4d}{\pi D}$

Flow Coefficient Reynolds Number Dependency

When the 485 Annubar primary element is used within the acceptable Reynolds Number range defined by Rosemount in Table 2-7 on page 2-10, the Annubar Primary element's flow coefficient will be independent of changing Reynolds Number. Any variations in the K-value with changing Reynolds Number are due to scatter and fall within ±0.75% of the published K-value.

A 485 Annubar primary element’s K-factor independence of Reynolds number allows the user to measure a large range of Reynolds Numbers without need of a correction factor for changing Reynolds Numbers. The 485 Annubar primary element K-factor independence can be attributed to a constant separation point along the edges of its T-shaped sensor and the probe's ability to take a proper average of its sensing slots.

Flow Coefficient Theory

Rosemount was the first company to identify and utilize the theoretical equations linking self-averaging pitot tube flow coefficients to pipe blockage. This K-to-Blockage theoretical link establishes a higher degree of confidence in 485 Annubar K-factors than in flow meters that use only an empirical data base for determining their flow coefficients.

Signal

The signal generated by an Annubar can be divided into two major parts:

- the differential pressure contribution due to the Annubar 's shape (H_S)
- the differential pressure contribution due to the Annubar’s blockage in the pipe (H_b).

Shape Differential

An Annubar primary element placed in an infinitely large pipe (with no confining walls) will still produce a differential pressure. This differential pressure is nearly twice that of a standard pitot tube, and is the result of a reduced low pressure on the downstream side. The upstream, or high pressure is caused by the fluid impacting the front of the Annubar primary element and is known as the stagnation pressure. The downstream, or low pressure is caused by the fluid traveling past the Annubar primary element, creating suction on the rear side. This suction phenomenon can be attributed to boundary layer flow separation.

Blockage Differential

An Annubar primary element is an obstruction in the pipe and therefore, reduces the cross-sectional area through which the fluid can pass. This reduced area causes the fluid to accelerate and hence, reduces its pressure. Therefore, the downstream pressure measurement of an Annubar primary element will be affected by the Annubar's blockage in the pipe.

Since an Annubar primary element uses the internal diameter of the pipe it is being inserted into as a throat diameter in its calculation of a flow rate, the Annubar primary element K-factor must compensate for the amount of obstructed area the sensor itself causes in the pipe. This is analogous to the velocity of approach factor for an orifice plate or a venturi meter.

By writing a mass balance and an energy balance around the Annubar primary element, and by dividing the differential pressure produced by the Annubar primary element into H_s and H_b, one can derive the relationship between the Annubar primary element K-factor and the Annubar primary element's blockage in the pipe. The derivation involves partial differential pressure components, and the integration of a K-blockage equation. The result is the following K vs. Blockage equation:

Equation 2-8. : K vs. Blockage

$$K_A = \frac{(1 - C_2B)}{\sqrt{1 - C_1(1 - C_2B)^2}}$$

The constants C_1 and C_2 must be determined experimentally. Once C_1 and C_2 are determined, the equation above becomes the theoretical link between the Annubar primary element K-factor (K) and the Annubar primary element's blockage in the pipe (B). The values for constants C_1 and C_2 are shown in the table below:

Table 2-6. 485 Sensor Constants

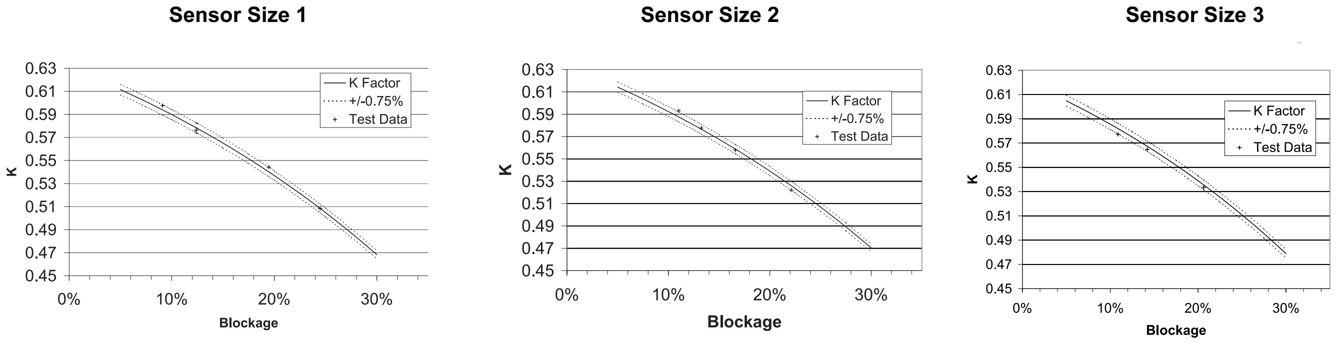
Coefficient	Sensor Size 1	Sensor Size 2	Sensor Size 3
C_1	– 1.515	– 1.492	– 1.5856
C_2	1.4229	1.4179	1.3318

The Importance of the Flow Coefficient, or K vs. B Theory

As with any other meter, the 485 Annubar primary element's accuracy is only as good as its flow coefficient (K-factor). Rosemount has tested a representative sample of flowmeters and empirically determined flow coefficients. For Annubars, these flow coefficients are plotted against the meter's blockage. Curve fitting techniques combined with flow coefficient theory are applied to the base line data to generate equations that predict flow coefficients in untested line sizes and untested Reynolds Number ranges. Please see the 485 Annubar Flow Test Data Book (document number 00821-0100-4809, Rev AA) for a more detailed discussion of this topic.

Provided the theory is based on the proper physics, these relationships are immune to minor variation in test data. Using a theoretical basis (in addition to empirical testing) for the prediction of untested flow coefficients provides a much higher degree of confidence in the untested values. The graphs in Figure 2-2 show that empirical data agree with a plot of the K vs. Blockage Equation.

Figure 2-2. K vs. BLOCKAGE



Operating Limitations

For an Annubar primary element to operate accurately, the flowing fluid must separate from the probe at the same location (along the edges of the T-shape sensor). Drag coefficients, lift coefficients, separation points, and pressure distributions around bluff bodies are best compared by calculating the “rod” Reynolds Number. There is a minimum rod Reynolds Number at which the flowing fluid will not properly separate from the edges of a T-shape sensor. The minimum rod Reynolds Numbers for the Rosemount 485 are:

Table 2-7. Reynolds Number and Probe Width

Sensor Size	Probe Width (d)	Minimum Reynolds Number
1	0.590-in. (1.4986 cm)	6000
2	1.060-in (2.6924 cm)	12500
3	1.935-in (4.915 cm)	25000

Above these rod Reynolds Numbers 485 Annubar primary elements will operate accurately.

To determine the rod Reynolds Number at any given flowrate, use the following relationship:

$$Re_{rod} = \frac{dV\rho}{12\mu} \qquad \text{OR} \qquad Re_{rod} = \frac{dV\rho}{100\mu}$$

where,
ρ = fluid density in lbm/ft^3 (kg/m^3)
d = probe width in inches (cm)
V = velocity of fluid in feet per second (m/s)
μ = fluid viscosity in lbm/ft-sec (kg/m-s)

When determining the minimum operating flow rate for an Annubar primary element, one should also consider the capability of the secondary instrumentation (differential pressure transmitters, manometers, etc.).

The upper operating limit for 485 Annubar primary elements is reached when any one of the following criteria is met:

1. The fluid velocity reaches the structural limit of the Annubar.
2. The fluid velocity reaches a choked flow condition at the Annubar (gas).
3. Cavitation occurs on the downstream side of the Annubar.

Flow Calculation Examples:

Problem:

Oil with a specific gravity of 0.825 is flowing at a rate of 6000 GPM. The 20-in. standard wall (ID = 19.26-in.) carbon steel pipeline has a pressure of 75 psig and a temperature of 100°F. What is the differential pressure (h_w) that a Sensor Size 2 485 Annubar primary element would measure?

Solution:

$$h_w = \left(\frac{Q_a}{C'}\right)^2$$

(from Equation 2-1 on page 2-1)

Qa = 600 GPM

$$C' = F_{na} \cdot K \cdot D^2 \cdot F_{aa} \cdot \sqrt{\frac{1}{G_f}}$$

(from Equation 2-1 on page 2-1)

where:

F_{na} = 5.6664

$$K = \frac{(1 - C_2 B)}{\sqrt{1 - C_1 (1 - C_2 B)^2}}$$

(from Equation 2-8 on page 2-9)

where:

$$B = \frac{4d}{\pi D} = \frac{4(1.060)}{19.25\pi} = 0.0701$$

(from Equation 2-7 on page 2-7)

$$C_1 = -1.492$$

(from Table 2-6 on page 2-9)

$$C_2 = 1.4179$$

(from Table 2-6 on page 2-9)

so:

$$K = \frac{(1 - 1.4179 \times 0.0701)}{\sqrt{1 - (-1.492) \times (1 - 1.4179 \times 0.0701)^2}} = 0.6058$$

$$D^2 = 19.26^2 = 370.9476$$

F_{aa} = 1.000

$$\sqrt{\frac{1}{G_f}} = \sqrt{\frac{1}{0.825}} = 1.101$$

so:

$$C = 5.6664 \cdot 0.6058 \cdot 370.9476 \cdot 1.000 \cdot 1.101 = 1401.9625$$

and:

$$h_w = \left(\frac{6000}{1401.9625}\right)^2 = 18.316 \qquad \text{inchH}_2\text{O}$$

Problem:

Oil with a specific gravity of 0.825 is flowing at a rate of 22,700 LPM. The 50 cm inside diameter carbon steel pipeline has a pressure of 517 kPa and a temperature of 38 °C. What is the differential pressure (h_w) that a Sensor Size 2 485 Annubar primary element would measure?

Solution:

$$h_w = \left(\frac{Q_a}{C'}\right)^2$$ *(from Equation 2-1 on page 2-1)*

Qa = 22700 LPM

(from Table 2-2 on page 2-4)

$$C' = F_{na} \cdot K \cdot D^2 \cdot F_{aa} \cdot \sqrt{\frac{1}{G_f}}$$ *(from Equation 2-1 on page 2-1)*

where:

F_{na} = 0.066673

$$K = \frac{(1 - C_2B)}{\sqrt{1 - C_1(1 - C_2B)^2}}$$ *(from Equation 2-8 on page 2-9)*

where:

$$B = \frac{4d}{\pi D} = \frac{4(2.6924)}{50\pi} = 0.0686$$ *(from Table 2-6 on page 2-9)*

(from Table 2-6 on page 2-9)

$$C_1 = -1.492$$

(from Table 2-6 on page 2-9)

$$C_2 = 1.4179$$

so:

$$K = \frac{(1 - (1.4179 \cdot 0.0686))}{\sqrt{1 - ((-1.492) \cdot (1 - (1.4179 \cdot 0.0686))^2)}} = 0.6065$$

$$D^2 = 500^2 = 250000$$

F_{aa} = 1.000

$$\sqrt{\frac{1}{G_f}} = \sqrt{\frac{1}{0.825}} = 1.101$$

so:

$$C' = 0.066673 \cdot 0.6065 \cdot 250000 \cdot 1.000 \cdot 1.101 = 11130.33$$

and:

$$h_w = \left(\frac{22700}{11130.33}\right)^2 = 4.159 \quad \text{kPa}$$

Problem:

Steam at 500 psia and 620 °F is flowing in a 24-in. ID carbon steel pipe. The measured differential pressure on a Sensor Size 3 485 Annubar primary element is 15-in H_2O. What is the flowrate in PPH?

Solution:

$W = C' \cdot \sqrt{h_w}$ *(from Equation 2-2 on page 2-1)*

$C' = F_{na} \cdot K \cdot D^2 \cdot Y_a \cdot F_{aa} \cdot \sqrt{\rho_f}$ *(from Equation 2-3 on page 2-1)*

where:

$F_{na} = 358.94$ *(from Table 2-2 on page 2-4)*

$$K = \frac{(1 - C_2B)}{\sqrt{1 - C_1(1 - C_2B)^2}}$$ *(from Equation 2-8 on page 2-9)*

where:

$B = \frac{4d}{\pi D} = \frac{4(1.920)}{24\pi} = 0.1019$ *(from Equation 2-7 on page 2-7)*

$C_1 = (-1.5856)$ *(from Table 2-6 on page 2-9)*

$C_2 = 1.3318$ *(from Table 2-6 on page 2-9)*

so:

$$K = \frac{(1 - (1.3318 \cdot 0.1019))}{\sqrt{1 - ((-1.5856) \cdot (1 - (1.3318 \cdot 0.1019))^2)}} = 0.5848$$

$D^2 = 24^2 = 576$

$Y_a = 1 - (0.011332(1 - B)^2 - 0.00342)\frac{h_w}{P_f\Upsilon}$ *(from Equation 2-6 on page 2-7)*

where:

$B = \frac{4d}{\pi D} = \frac{4(1.920)}{24\pi} = 0.1019$ *(from Equation 2-7 on page 2-7)*

$H_w = 15\text{in}H_2O$
$P_f = 500\text{psia}$
$\Upsilon = 1.3$

so:

$$Y_a = 1 - (0.011332(1 - 0.1019)^2 - 0.00342)\frac{15}{500 \cdot 1.3} = 0.9999$$

$F_{aa} = 1.008$

ρ_f *per ASME steam tables*

$\sqrt{\rho_f} = \sqrt{0.8413} = 0.9172$

so

$$C' = 358.94 \cdot 0.5848 \cdot 576 \cdot 0.9999 \cdot 1.008 \cdot 0.9172 = 111771.96$$

$$W = 111771.96 \cdot \sqrt{15} = 432890.93 \qquad \mathrm{PPH}$$

Problem:

Steam at 3500 kPa abs and 350 °C is flowing in a 60.96 cm ID carbon steel pipe. The measured differential pressure on a Sensor Size 3 485 Annubar primary element is 7.5 kPa. What is the flowrate in kg/hr?

Solution:)

$$W = C' \cdot \sqrt{h_w}$$ *(from Equation 2-2 on page 2-1)*

$$C' = F_{na} \cdot K \cdot D^2 \cdot Y_a \cdot F_{aa} \cdot \sqrt{\rho_f}$$ *(from Equation 2-3 on page 2-1)*

where:

$F_{na} = 0.12645$

$$K = \frac{(1 - C_2B)}{\sqrt{1 - C_1(1 - C_2B)^2}}$$ *(from Equation 2-8 on page 2-9)*

where:

$$B = \frac{4d}{\pi D} = \frac{4(4.9149)}{60.96\pi} = 0.1027$$ *(from Equation 2-7 on page 2-7)*

(from Table 2-6 on page 2-9)

$C_1 = -1.5856$ *(from Table 2-6 on page 2-9)*

$C_2 = 1.3318$ *(from Table 2-6 on page 2-9)*

so:

$$K = \frac{(1 - 1.3318 \times 0.1027)}{\sqrt{1 - ((-1.5856) \cdot (1 - (1.3318 \cdot 0.1027))^2)}} = 0.5845$$

$$D^2 = 609.6^2 = 371612.16$$

$$Y_a = 1 - (0.31424(1 - B)^2 - 0.09484)\frac{h_w}{P_f\Upsilon}$$ *(from Equation 2-6 on page 2-7)*

where:

$$B = \frac{4d}{\pi D} = \frac{4(4.9149)}{60.96\pi} = 0.1027$$ *(from Equation 2-7 on page 2-7)*

$H_w = 7.5\,\mathrm{kPa}$

$P_f = 3500\,\mathrm{kPaA}$

$\Upsilon = 1.3$

so:

$$Y_a = 1 - (0.31424(1 - 0.1027)^2 - 0.09484)\frac{7.5}{3500 \times 1.3} = 0.9997$$

$F_{aa} = 1.009$ *(from Table B-1 on page B-1)*

$\sqrt{\rho_f} = \sqrt{13.0249} = 3.609$ ρ_f *per ASME steam tables* so

$$C' = 0.12645 \cdot 0.5845 \cdot 371612.16 \cdot 0.9997 \cdot 1.009 \cdot 3.609 = 99986.42$$

$$W = 99986.42 \cdot \sqrt{7.5} = 273824.1\,\mathrm{kg/h}$$

Problem:

Natural gas with a specific gravity of 0.63 is flowing in a 12-in. schedule 80 carbon steel pipe. the operating pressure is 1264 psia. The operating temperature is 120 °F. For a Sensor Size 2 485 Annubar primary element, determine the differential pressure (h_w) for a flowrate of 6 MM SCFH at a base temperature of 60 °F and a pressure of 14.73 psia.

Solution:

$$h_w = \frac{1}{P_f} \cdot \left(\frac{Q_s}{C'}\right)^2$$

$$Q_s = 6000000\,\mathrm{SCFH}$$

$$P_f = 1264\,\mathrm{psia}$$

$$C' = F_{na} \cdot K \cdot D^2 \cdot Y_a \cdot F_{pb} \cdot F_{tb} \cdot F_{tf} \cdot F_g \cdot F_{pv} \cdot F_{aa}$$ *(from Equation 2-4 on page 2-1)*

where:

$F_{na} = 338.17$

$$K = \frac{(1 - C_2 B)}{\sqrt{1 - C_1 (1 - C_2 B)^2}}$$ *(from Equation 2-8 on page 2-9)*

where:

$$B = \frac{4d}{\pi D} = \frac{4(1.060)}{11.37\pi} = 0.1186$$ *(from Equation 2-7 on page 2-7)*

$$C_1 = -1.492$$ *(from Table 2-4 on page 2-5)*

$$C_2 = 1.4179$$ *(from Table 2-4 on page 2-5)*

so:

$$K = \frac{(1 - (1.4179 \cdot 0.1186))}{\sqrt{1 - ((-1.492) \cdot (1 - (1.4179 \cdot 0.1186))^2)}} = 0.5835$$

$$D^2 = 11.376^2 = 129.41$$

The differential pressure h_w is required to calculate Y_a. Since h_w is not known, assume Y_a = 1 and verify the results

$$F_{pb} = \frac{14.73}{\text{base pressure, psia}} = \frac{14.73}{14.73} = 1$$

$$F_{tb} = \frac{\text{temperature base (°F) + 460}}{520} = \frac{60 + 460}{520} = 1$$

$$F_{tf} = \sqrt{\frac{520}{\text{flowing temperature (°F) + 460}}} = \sqrt{\frac{520}{120 + 460}} = 0.9469$$

$$F_g = \sqrt{\frac{1}{G}} = \sqrt{\frac{1}{0.63}} = 1.2599$$

$$F_{pv} = \sqrt{\frac{1}{Z}} = \sqrt{\frac{1}{0.8838}} = 1.0637$$

(Compressibility factor for natura gas from A.G.A Report No. 3

$$F_{aa} = 1.001$$

so:

$$C = 338.17 \times 1.5835 \times 129.41 \times 1 \times 1 \times 1 \times 0.9469 \times 1.2599 \times 1.0637 \times 1.001 = 32436.74$$

$$h_w = \frac{1}{P_f} \cdot \left(\frac{Q_s}{C'}\right)^2 = \frac{1}{1264} \cdot \left(\frac{6000000}{32436.74}\right)^2 = 27.07 \text{inH}_2\text{O}$$

Now the value of Y_a, assumed above, can be checked:

$$Y_a = 1 - (0.011332(1 - B)^2 - 0.00342)\frac{h_w}{P_f \Upsilon}$$

(from Equation 2-6 on page 2-7)

where:

$$B = \frac{4d}{\pi D} = \frac{4(1.060)}{11.37\pi} = 0.1186$$

(from Equation 2-7 on page 2-7)

H_w = 27.07inchH$_2$O

P_f = 1264psia

Υ = 1.3

so:

$$Y_a = 1 - (0.011332(1 - 1186)^2 - 0.00342)\frac{27.07}{1264 \times 1.3} = 1$$

The assumed and calculated value are the same. therefore, the value of h_w = 24.27 inch H_2O is the correct answer.

Problem:

Natural gas with a specific gravity of 0.63 is flowing in a 300 mm ID carbon steel pipe. The operating pressure is 8700 kPA abs and the operating temperature is 50 °C. For a Sensor Size 2 485 Annubar primary element, determine the differential pressure (h_w) for a flowrate of 1700 Nm^3/m at a base temperature of 0 °C and a pressure of 101.325 kPa.

Solution:

$$h_w = \frac{1}{P_f} \cdot \left(\frac{Q_s}{C'}\right)^2$$ *(from Equation 2-4 on page 2-1)*

$$Q_s = 1700 Nm^3/m$$

$$P_f = 8700 kPa$$

$$C' = F_{na} \cdot K \cdot D^2 \cdot Y_a \cdot F_{pb} \cdot F_{tb} \cdot F_{tf} \cdot F_g \cdot F_{pv} \cdot F_{aa}$$ *(from Equation 2-4 on page 2-1)*

where:

$$F_{na} = 0.00018912$$

$$K = \frac{(1 - C_2B)}{\sqrt{1 - C_1(1 - C_2B)^2}}$$ *(from Equation 2-8 on page 2-9)*

where:

$$B = \frac{4d}{\pi D} = \frac{4(26.924)}{300\pi} = 0.1143$$ *(from Equation 2-7 on page 2-7)*

$$C_1 = -1.492$$ *(from Table 2-6 on page 2-9)*

$$C_2 = 1.4179$$ *(from Table 2-6 on page 2-9)*

so:

$$K = \frac{1 - (1.4179 \cdot 0.1143)}{\sqrt{1 - ((-1.492) \cdot (1 - (1.4179 \cdot 0.1143))^2)}} = 0.5856$$

$$D^2 = 300^2 = 90000$$

The differential pressure h_w is required to calculate Y_a. Since h_w is not known, assume $Y_a = 1$ and verify the results.

$$F_{pb} = \frac{101.325}{\text{base pressure, kPa abs}} = \frac{101.325}{101.325} = 1$$

$$F_{pb} = \frac{\text{temperature base (°C)} + 273.15}{288.15} = \frac{0 + 273.15}{288.15} = 0.9479$$

$$F_{tf} = \sqrt{\frac{288.15}{273.15 + \text{flowing temperature (°C)}}} = \sqrt{\frac{288.15}{273.15 + 50}} = 0.9443$$

$$F_g = \sqrt{\frac{1}{G}} = \sqrt{\frac{1}{0.63}} = 1.2599$$

$$F_{pv} = \sqrt{\frac{1}{Z}} = \sqrt{\frac{1}{0.876}} = 1.0684$$

$$F_{aa} = 1.001$$

so:

$$C' = 0.00018912 \cdot 0.5856 \cdot 90000 \cdot 1 \cdot 0.9479 \cdot 1 \cdot 0.9443 \cdot 1.2599 \cdot 1.0684 \cdot 1.001 = 12.0215$$

$$h_w = \frac{1}{P_f} \cdot \left(\frac{Q_s}{C'}\right)^2 = \frac{1}{8700} \cdot \left(\frac{1700}{12.0215}\right)^2 = 2.2986\,\text{kPa}$$

Now the value of Y_a, assumed above, can be checked:

$$Y_a = 1 - (Y_1(1-B)^2 - Y_2)\frac{h_w}{P_f \Upsilon}$$ *(from Equation 2-6 on page 2-7)*

where:

$$B = \frac{4d}{\pi D} = \frac{4(26.924)}{300\pi} = 0.1143$$ *(from Equation 2-7 on page 2-7)*

$H_w = 2.2986\,\text{kPa}$

$P_f = 8700\,\text{kPa}$

$\Upsilon = 1.3$

so:

$$Y_a = 1 - (0.31424 \cdot (1 - 0.1143)^2 - 0.09484)\frac{2.2986}{8700 \cdot 1.3} = 1$$

The assumed and calculated value are the same. therefore, the value of h_w = 2.2986kPa is the correct answer.

Section 3 Installation and Operational

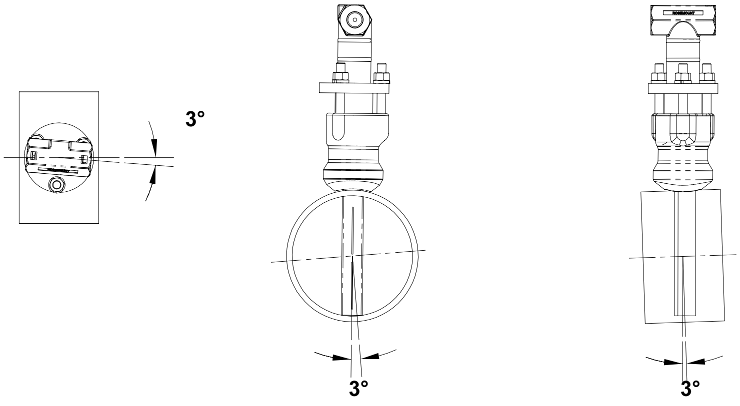
ERRORS

Alignment

The Annubar probe senses a total pressure (impact and static pressure) through the upstream slots and a low pressure through the downstream ports. The impact pressure and the downstream low pressure are affected by the alignment of the sensing slots/ports. A deviation from perpendicular to the axis of the pipe in any direction will affect either or both of the sensed pressures. The published Flow Coefficients were determined experimentally with a carefully aligned Annubar primary element. Changes within the 3° limits will have insignificant effects on the pressures and consequently on the Flow Coefficients. Further changes will cause a shift in the Flow Coefficient.

If, for some reason, an Annubar primary element is not or cannot be installed within the recommended limits the output signal will be repeatable and stable but will be shifted by some unknown amount. This shift can be accounted for by performing an in-line calibration. An in-line calibration entails determining the installed Annubar flow coefficient typically by performing a pitot-traverse of the flow point. After determining a new Flow Coefficient, the Annubar primary element will perform within its normal accuracy specifications.

Figure 3-1. Acceptable Alignment



Sizing

For accurate measurement, the design of the Annubar probe requires that the flow sensing slots/ports be located at specific points in the flow stream. The Annubar primary element is manufactured to ensure proper slot/hole location based on customer-supplied pipe ID and wall dimensions. When the Annubar primary element is installed in the line using the proper fittings, the sensing ports end up at the proper locations. If an Annubar primary element is used in a line which has a different inside diameter or wall thickness than for which it was manufactured, the ports will not be properly located. Using the wrong mounting fittings may also cause a location error.

The result of having the sensing ports improperly located could be an incorrect flow measurement. The reading may be either high or low depending on the individual application.

An Annubar primary element that is installed in an incorrect line size will generate a repeatable signal. A calibration factor can be determined to correct flow measurement allowing normal use of the Annubar primary element.

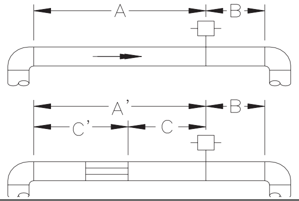
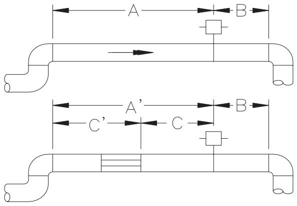
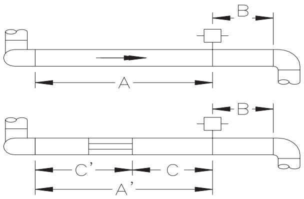
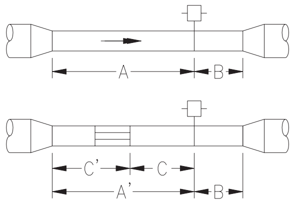
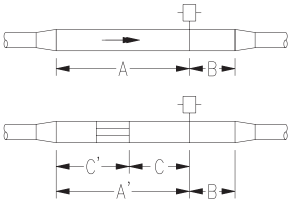
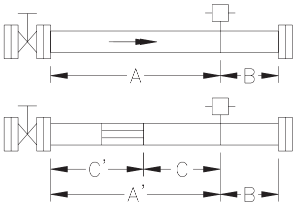
UPSTREAM FLOW DISTURBANCE

The Annubar flow sensor is an averaging head type device. The location of the sensing ports has been mathematically determined using fully developed turbulent flow characteristics. This implies that the flow velocity profile is symmetrical across the pipe in all directions. The averaging functions of the Annubar primary element will not take place if the flow profile is not symmetrical. This will cause a change in the Flow Coefficient from the published information.

The flow profile can be influenced by any upstream device which disturbs the flow. Examples would be valves, elbows, diameter changes, etc. Sufficient length of straight run of pipe upstream of the Annubar primary element will allow the turbulent flow profile to develop. A flow straightener or straightening vanes may be used to reduce the length of straight run required. These are available in several configurations from piping supply houses. Table 3-1 shows minimum straight run requirements with and without the use of flow straighteners.

The Annubar primary element will produce a repeatable signal even if the straight run requirements have not been met. In many control situations, it is necessary to monitor changes in flow rather than to measure flow rate. Here it would not be necessary to have the full amount of straight run. Where flow measurement is necessary without sufficient straight run, an in-line calibration may be necessary to determine the correct Flow Coefficient.

Table 3-1. Straight Run Requirements

	Upstream Dimensions					Downstream Dimensions
	Without Vanes		With Vanes			
	In Plane A	Out of Plane A	A’	C	C’	
1 	8	10	—	—	—	4
	—	—	8	4	4	4
2 	11	16	—	—	—	4
	—	—	8	4	4	4
3 	23	28	—	—	—	4
	—	—	8	4	4	4
4 	12	12	—	—	—	4
	—	—	8	4	4	4
5 	18	18	—	—	—	4
	—	—	8	4	4	4
6 	30	30	—	—	—	4
	—	—	8	4	4	4

INSTRUMENT LINES AND CONNECTIONS LEAKAGE

Flow measurement using an Annubar primary element or any other type of head device depends on comparing two pressures generated by the flow past the device. This difference is called a differential pressure or DP The magnitude of this DP is small and quite often less than one (1) psi. Any leaks in the instrument lines or connections will change the DP output of the Annubar primary element. In applications with static pressure above atmospheric pressure a leak in the pressure lines will cause a low DP to be seen by the secondary instrumentation.

FLOW PARAMETER CHANGES

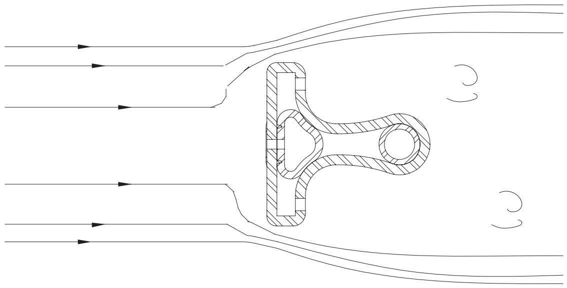
The Annubar primary element will function over an extremely wide range of flow conditions. Measuring flow with an Annubar primary element requires care in determining the flowing conditions so that the secondary instrumentation provides usable readings.

A precise flow calculation is performed as part of the application of an Annubar primary element and secondary instrumentation. If any of the following parameters change, the flow calculation is no longer valid. Significant changes in fluid temperature, density, specific gravity, velocity and pressure are some of the parameters that will cause errors in flow measurement unless a new flow calculation is done. A new flow calculation can then provide necessary information for calibrating the secondary instrumentation.

DIRT ACCUMULATION

One inherent advantage of an Annubar primary element over devices such as an orifice plate is its ability to function in flows carrying dirt and grease. The shape of the Annubar primary element causes most foreign material to flow around the probe rather than accumulate on it. The material that does impact on the probe does not significantly affect performance unless, under extreme cases, some of the sensing ports are completely obstructed or the outside shape is drastically changed by buildup.

Figure 3-2. Particulate Deflection



There are two methods of cleaning the Annubar primary element to restore performance. Mechanical cleaning is the more certain method, but does require removal of the Annubar primary element. Purging the Annubar primary element is effective if the accumulation covers the sensing ports or blocks the inner passages of the Annubar primary element.

In applications where a large amount of foreign material exists, it may be necessary to perform a routine preventative maintenance removal of the Annubar primary element for cleaning. The outer surfaces should be cleaned with a soft wire brush. The outer internal passages should be cleaned with a soft wire brush and compressed air. If necessary, a solvent for dissolving foreign material may be appropriate.

Purging the Annubar primary element with an external fluid source under a higher pressure is an effective means of retaining clear pressure pathways in the Annubar primary element.

The following precautions should be taken:

1. The purging fluid must be compatible with the process fluid and shouldn't cause other problems such as contamination.
2. The purging fluid should be preheated or pre-cooled if the temperature difference of the fluid and the process exceeds 150°F (66°C).
3. The differential pressure transmitter or meter should be isolated from the purge fluid to prevent over-ranging.
4. Continuous purging is not recommended.

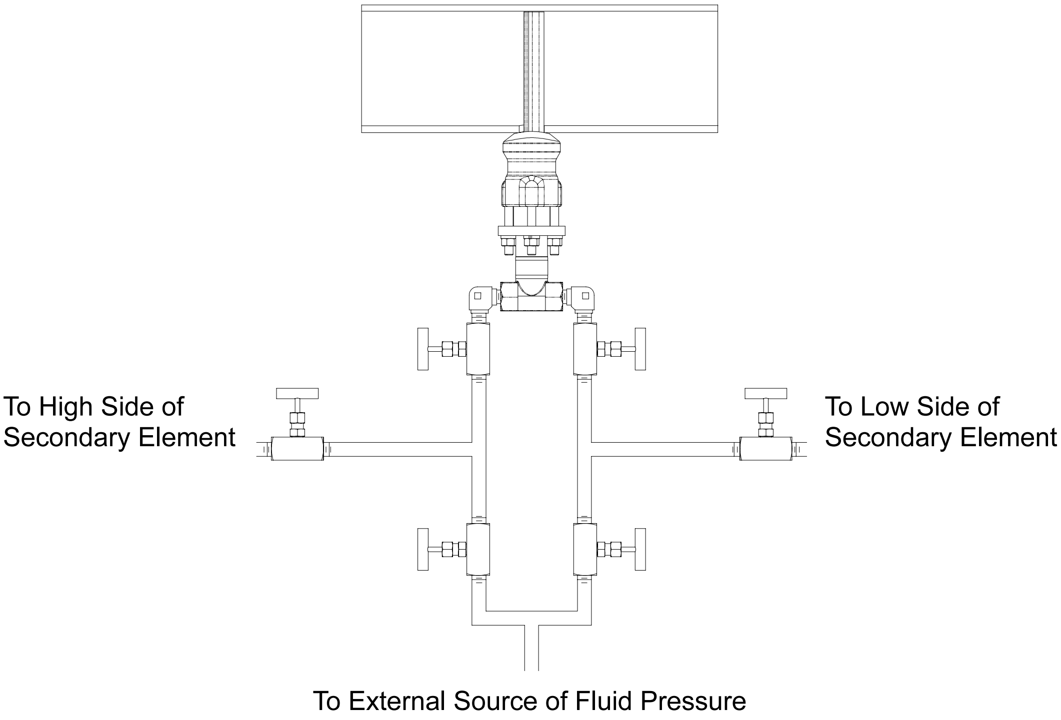
The length of time between purges, or the cycle time as well as the length of the purge cycle must be determined experimentally. There are no general guidelines as conditions, fluids, and systems affect the specific function of a purge system.

Purging may be done in several ways. One is to provide an external source of fluid pressure which can be valved into the instrument lines.

Blow-down of the Annubar primary element is a method of purging. This method uses process line pressure to clean the Annubar primary element. Some means of opening the instrument lines are required. During blow-down, the process fluid flows out of the Annubar primary element, carrying any debris with it.

Care must be taken to protect the secondary instrumentation from high pressures and temperatures when purging an Annubar primary element.

Figure 3-3. Impulse Tube Arrangement for Purge



GAS ENTRAPMENT

Flow measurement with an Annubar primary element or any head type device involves measuring and comparing pressures of very low magnitude or very little differences. Problems causes by leaks and liquid legs have been previously mentioned. Problems may also be caused by gas entrapment while measuring flow in a liquid line.

The effect of having air entrapped in an instrument line is that of building in a shock absorber. In all flow situations the Annubar DP signal fluctuates because of flow turbulence. The entrapped gas is compressible and therefore absorbs a portion of the signal at the secondary instrumentation. A liquid filled line would not have any tendency to absorb part of the signal.

Entrained air in impulse lines also leads to head errors. Low density gas in impulse lines diplaces liquid creating measurement offset.

It is important to follow the installation recommendations for placement of the Annubar primary element and instrumentation to minimize gas entrapment. Periodic bleeding of the secondary instrumentation and lines may be necessary.

FLOW PARAMETER LIMITATIONS

The Annubar primary element will function in a wide variety of fluid flow situations. There are two specific situations in which the Annubar primary element should not be used. The first is in flows where the viscosity approaches or exceeds 50 centipoise. The second is in a situation with two phase flow. This is true of liquid/gas, liquid/solid and gas/solid situations. Examples would be quality steam, slurries and foam. If there is doubt about any application, consult an Emerson Process Management representative.

Appendix A Fluid Properties and Pipe Data

FLUID PROPERTIES

Table A-1. Density of Superheated Steam and Compressed Water Density, ρ, lbm/ft^3

Temp	1	2	5	10	20	50	100	200	500	750	1000
°F	psia	psia	psia	psia	psia	psia	psia	psia	psia	psia	psia
32	62.42	62.42	62.42	62.42	62.42	62.42	62.42	62.46	62.54	62.58	62.62
40	62.42	62.42	62.42	62.42	62.42	62.42	62.42	62.46	62.54	62.58	62.62
60	62.37	62.37	62.37	62.37	62.37	62.37	62.37	62.42	62.46	62.50	62.58
80	62.23	62.23	62.23	62.23	62.23	62.23	62.23	62.27	62.31	62.38	62.42
100	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.04	62.07	62.15	62.19
120	.002901	61.73	61.73	61.73	61.73	61.73	61.73	61.77	61.81	61.84	61.88
140	.002804	.005619	61.39	61.39	61.39	61.39	61.39	61.43	61.46	61.50	61.58
160	.002713	.005435	60.98	60.98	61.01	61.01	61.01	61.01	61.09	61.13	61.20
180	.002628	.005263	.01321	60.55	60.57	60.57	60.57	0.61	60.68	60.72	60.75
200	.002548	.005101	.01280	.02575	60.10	60.13	60.13	60.13	60.21	60.24	60.31
220	.002472	.004950	.01241	.02495	59.59	59.60	59.60	59.67	59.70	59.77	59.81
240	.002402	.004807	.01205	.02420	.04885	59.10	59.10	59.10	59.17	59.24	59.28
260	.002334	.004672	.01171	.02351	.04738	58.51	58.55	58.55	58.62	58.69	58.72
280	.002271	.004545	.01139	.02285	.04602	57.94	57.94	59.97	58.04	58.07	58.14
300	.002211	.004425	.01108	.02223	.04473	.1140	57.31	57.34	57.41	57.47	57.54
320	.002154	.004311	.01079	.02165	.04352	.1107	56.63	56.66	56.75	56.82	56.88
340	.002100	.004203	.01052	.02109	.04239	.176	.2213	55.96	56.05	56.12	56.18
360	.002149	.004100	.01026	.02057	.04131	.1047	.2146	55.22	55.31	55.40	55.46
380	.002000	.004002	.01002	.02007	.04029	.1019	.2084	54.47	54.56	54.65	54.71
400	.001954	.003908	.009781	.01960	.03933	.09938	.2026	.4238	53.74	53.82	53.91
420	.001909	.003819	.009557	.0914	.03841	.09696	.1973	.4104	52.88	52.97	53.08
440	.001866	.003734	.009343	.01871	.03753	.09466	.1923	.3982	51.98	52.08	52.17
460	.001826	.003653	.009139	.01830	.03670	.09249	.1876	.3870	50.99	51.13	51.23
480	.001787	.003575	.008944	.01791	.03590	.09042	.1832	.3766	1.049	50.08	50.20
500	.001750	.003500	.008756	.01753	.03514	.08845	.1790	.3670	1.008	48.97	49.12
520	.001714	.003429	.008576	.01717	.03441	.08657	.1750	.3580	.9728	1.603	47.94
540	.001680	.003360	.008405	.01682	.03371	.08477	.1712	.3496	.9413	1.530	46.64
560	.001647	.003294	.008239	.01649	.03304	.08305	.1676	.3416	.9128	1.468	2.142
580	.001615	.003230	.008080	.01617	.03240	.08140	.1642	.3341	.8870	1.415	2.035
600	.001585	.003169	.007927	.01587	.03178	.07982	.1609	.3270	.8633	1.367	1.947
620	.001555	.003111	.007780	.01557	.03119	.07830	.1577	.3202	.8413	1.325	1.871
640	.001527	.003054	.007638	.01529	.03061	.07683	.1547	.3137	.8209	1.287	1.804
660	.001499	.002999	.007501	.01501	.03006	.07543	.1518	.3076	.8010	1.252	1.746
680	.001473	.002947	.007369	.01475	.02953	.07408	.1490	.3017	.7840	1.219	1.693
700	.001446	.002896	.007242	.01449	.02902	.07278	.1464	.2960	.7671	1.189	1.645
720	.001423	.002847	.007119	.01425	.02852	.07152	.1438	.2906	.7510	1.161	1.601
740	.001400	.002799	.007000	.01401	.02804	.07030	.1413	.2854	.7359	1.135	1.560
760	.001376	.002753	.006885	.01378	.02758	.06913	.1389	.2804	.7215	1.111	1.523
780	.001354	.002709	.006774	.01335	.02713	.06800	.1366	.2755	.7077	1.087	1.488
800	.001333	.002666	.006666	.01334	.02670	.06690	.1344	.2709	.6946	1.065	1.455
820	.001312	.002624	.006562	.01313	.02628	.06584	.1322	.2664	.6820	1.045	1.424
840	.001292	.002584	.006461	.01293	.02587	.06482	.1301	.2521	.6700	1.025	1.394
860	.001272	.002454	.006363	.01273	.02548	.06382	.1281	.2579	.6584	1.006	1.367
880	.001253	.002507	.006268	.01254	.02509	.06286	.1261	.2539	.6473	.9877	1.340
900	.001235	.002470	.006175	.01235	.02472	.06192	.1242	.2500	.6366	.9703	1.315
920	.001217	.002434	.006086	.01217	.02436	.06101	.1224	.2462	.6263	.9537	1.291
940	.001199	.002399	.005998	.01200	.02401	.06013	.1206	.2425	.6163	.9377	1.269
960	.001182	.002365	.005914	.01183	.02367	.05928	.1187	.2389	.6068	.9223	1.247
980	.001166	.002332	.005832	.01167	.02334	.05845	.1172	.2355	.5975	.9075	1.266
1000	.001150	.002300	.005752	0.1151	.02302	.05764	.1155	.2321	.5885	.8933	2.061
Sat Steam	.002998	.005755	.01360	.02603	.04978	.1175	.2257	.4372	1.078	1.641	2.242
Sat. Water	61.96	61.61	60.94	60.28	59.42	57.90	56.37	54.38	50.63	48.33	46.32
T_{sat} °F	101.74	126.07	162.24	193.21	227.96	281.02	327.82	381.80	467.01	510.84	544.58

Table A-2. Properties of Saturated Water

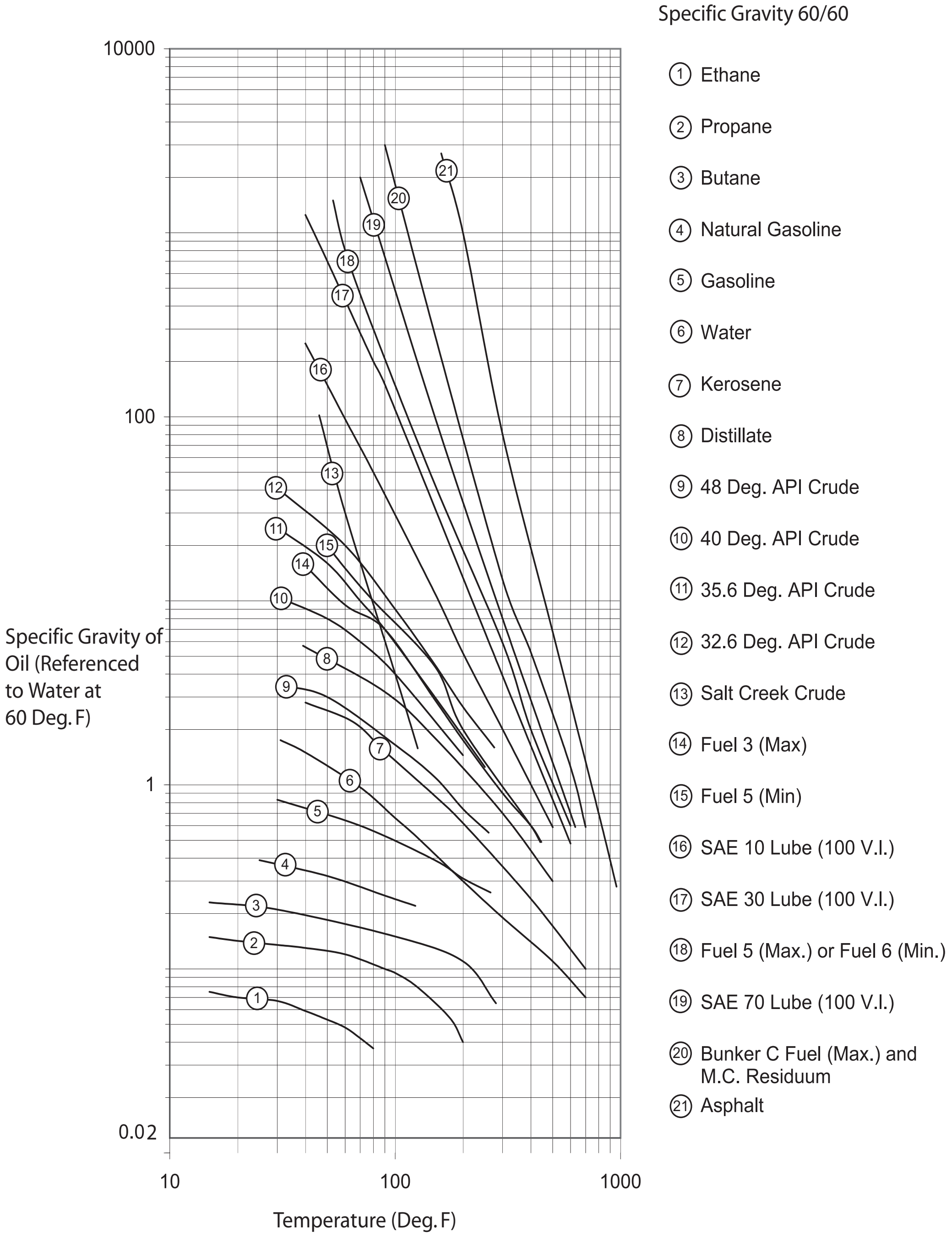
Temp	Density	Specific	Viscosity	Temp	Density	Specific	Viscosity	Temp	Density	Specific	Viscosity	Temp	Density	Specific	Viscosity
°F	lbm/ft^3	G_f	Centipoise	°F	lbm/ft^3	G_f	Centipoise	°F	lbm/ft^3	G_f	Centipoise	°F	lbm/ft^3	G_f	Centipoise
32	62.4140	1.007	1.75	66	62.3344	.9994	1.03	160	60.9932	.9779	.394	330	56.2960	.9026	.163
33	62.4167	1.007	1.72	67	62.3275	.9993	1.02	165	60.8909	.9763	.380	335	56.1220	.8998	.160
34	62.4191	1.008	1.69	68	62.3205	.9992	1.00	170	60.7862	.9746	.366	340	55.9458	.8970	.157
35	62.4212	1.008	1.66	69	62.3132	.9991	.988	175	30.6789	.9729	.353	345	55.7674	.8941	.155
36	62.4229	1.008	1.63	70	62.3058	.9990	.975	180	60.5693	.9717	.341	350	55.5859	.8912	.152
37	62.4242	1.009	1.61	71	62.2981	.9988	.962	185	60.4573	.9693	.330	355	55.4042	.8883	.150
38	62.4252	1.009	1.58	72	62.2902	.9987	.950	190	60.3430	.9675	.319	360	55.2192	.8853	.147
39	62.4258	1.009	1.55	73	62.2822	.9986	.937	195	60.2265	.9656	.309	365	55.0320	.8823	.145
40	62.4261	1.009	1.53	74	62.2739	.9984	.925	200	30.1076	.9637	.300	370	54.8424	.8793	.143
41	62.4261	1.009	1.50	75	62.2654	.9983	.913	205	59.9866	.9618	.291	375	54.6506	.8762	.141
42	62.4257	1.009	1.48	76	62.2568	.9982	.902	210	59.8635	.9598	.282	380	54.4563	.8731	.139
43	62.4251	1.009	1.45	77	62.2479	.9980	.890	215	59.7382	.9578	.274	385	54.2597	.8700	.137
44	62.4241	1.009	1.43	78	62.2389	.9979	.879	220	59.6108	.9558	.267	390	54.0606	.8668	.135
45	62.4229	1.008	1.41	79	62.2297	.9977	.868	225	59.4813	.9537	.259	395	53.8590	.8635	.133
46	62.4213	1.008	1.38	80	62.2203	.9976	.857	230	59.3497	.9416	.252	400	53.6548	.8603	.131
47	62.4194	1.008	1.36	81	62.2107	.9974	.847	235	58.2161	.9494	.246	405	53.4481	.8569	.129
48	62.4173	1.007	1.34	82	62.2009	.9973	.837	240	58.0804	.9472	.239	410	53.2387	.8536	.127
49	62.4149	1.007	1.32	83	62.1910	.9971	.826	245	58.9428	.9450	.233	415	53.0267	.8502	.126
50	62.4122	1.007	1.30	84	62.1809	.9970	.816	250	58.8031	.9428	.228	420	52.8119	.8467	.124
51	62.4092	1.006	1.28	85	62.1706	.9968	.807	255	58.6614	.9405	.222	425	52.5942	.8433	.122
52	62.4059	1.006	1.26	90	62.1166	.9959	.761	260	58.5177	.9382	.217	430	52.3737	.8397	.121
53	62.4024	1.005	1.24	95	61.0585	.9950	.718	265	57.3720	.9359	.212	435	52.1503	.8361	.119
54	62.3986	1.004	1.22	100	61.9964	.9940	.680	270	57.2244	.9335	.207	440	51.9238	.8325	.118
55	62.3946	1.004	1.20	105	61.9307	.9929	.645	275	57.0747	.9311	.203	445	51.6942	.8288	.116
56	62.3903	1.003	1.19	110	61.8612	.9918	.612	280	57.9231	.9287	.198	450	51.4615	.8251	.115
57	62.3858	1.002	1.17	115	61.7884	.9907	.582	285	57.7695	.9262	.194	455	51.2255	.8213	.114
58	62.3810	1.002	1.15	120	61.7121	.9894	.555	290	57.6139	.9237	.190	460	50.9862	.8175	.112
59	62.3760	1.001	1.14	125	61.6326	.9882	.529	295	57.4563	.9212	.186	465	50.7434	.8136	.111
60	62.3707	1.000	1.12	130	61.5500	.9868	.505	300	56.2966	.9186	.183	470	50.4971	.8096	.110
61	62.3652	.9999	1.10	135	61.4643	.9855	.483	305	56.1350	.9161	.179	475	50.2472	.8056	.109
62	62.3595	.9998	1.09	140	61.3757	.9840	.463	310	56.9713	.9134	.176	480	49.9935	.8016	.108
63	62.3535	.9997	1.07	145	61.2842	.9826	.444	315	56.8056	.9108	.172	485	49.7359	.7974	.106
64	62.3474	.9996	1.06	150	61.1899	.9811	.426	320	56.6378	.9081	.169	490	49.4744	.7932	.105
65	62.3410	.9995	1.04	155	61.0928	.9795	.410	325	56.4680	.9054	.166	495	49.2087	.7890	.104

Table A-3. Viscosity of Water and Steam, in Centipoise (μ)(1)

Temp	1	2	5	10	20	50	100	200	500	1000
°F	psia	psia	psia	psia	psia	psia	psia	psia	psia	psia
Sat Steam Sat. Water	.677 .010	.524 .010	.368 .011	.313 .012	.225 .012	.197 .013	.164 .014	.138 .015	.111 .017	.094 .019
1000	.030	.030	.030	.030	.030	.030	.030	.030	.030	.031
950	.029	.029	.029	.029	.029	.029	.029	.029	.029	.030
900	.028	.028	.028	.028	.028	.028	.028	.028	.027	.027
850	.026	.026	.026	.026	.026	.026	.026	.026	.025	.056
800	.025	.025	.025	.025	.025	.025	.025	.025	.026	.026
750	.024	.024	.024	.024	.024	.024	.024	.024	.025	.025
700	.023	.023	.023	.023	.023	.023	.023	.023	.023	.024
650	.022	.022	.022	.022	.022	.022	.022	.022	.023	.023
600	.021	.021	.021	.021	.021	.021	.021	.021	.021	.021
550	.020	.020	.020	.020	.020	.020	.020	.020	.020	.019
500	.019	.019	.019	.019	.019	.019	.019	.018	.018	.0103
450	.018	.018	.018	.018	.018	.018	.018	.017	.115	.116
400	.016	.016	.016	.016	.016	.016	.016	.016	.131	.132
350	.015	.015	.015	.015	.015	.015	.015	.152	.153	.154
300	.014	.014	.014	.014	.014	.014	.182	.183	.183	.184
350	.013	.013	.013	.013	.013	.228	.228	.228	.228	.229
200	.012	.012	.012	.012	.300	.300	.300	.300	.300	.301
150	.011	.011	.427	.427	.427	.427	.427	.427	.427	.428
100	.680	.680	.680	.680	.680	.680	.680	.680	.680	.680
50	1.299	1.299	1.299	1.299	1.299	1.299	1.299	1.299	1.299	1.299
32	1.753	1.753	1.753	1.753	1.753	1.753	1.753	1.753	1.753	1.753

(1) Values below line are for water.

Figure A-1. Viscosity of Water and Liquid Petroleum Products



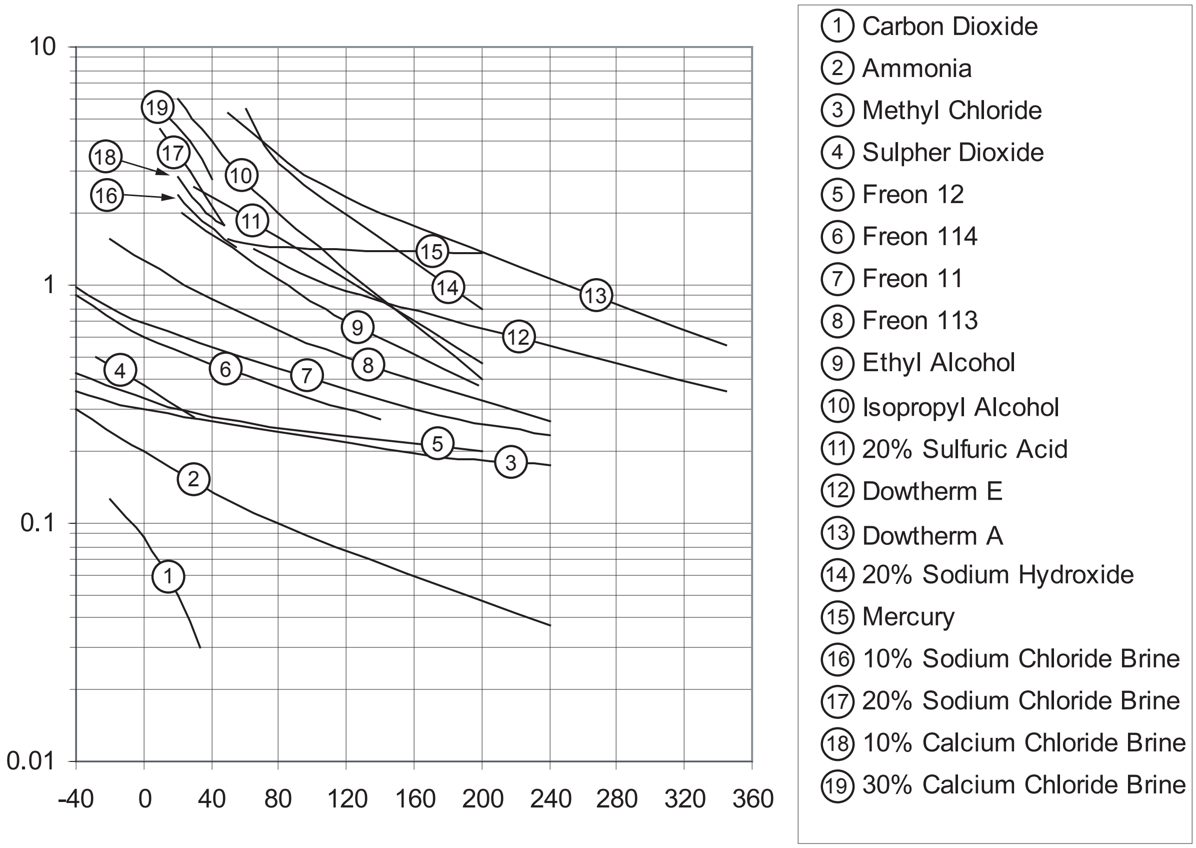
Example

The viscosity of water at 125 °F is 0.52 Centipoise (curve number 6).

NOTE
Consult factory whenever viscosity of fluid exceeds 300 centipoise.

(From Crane, Technical Paper 1410. Used by permission)

Figure A-2. Viscosity of Various Liquids



Example

The viscosity of water at 125 °F is 0.52 Centipoise (curve number 6).

(From Crane, Technical Paper 1410. Used by permission)

Figure A-3. Specific Gravity – Temperature Relationship for Petroleum Oils
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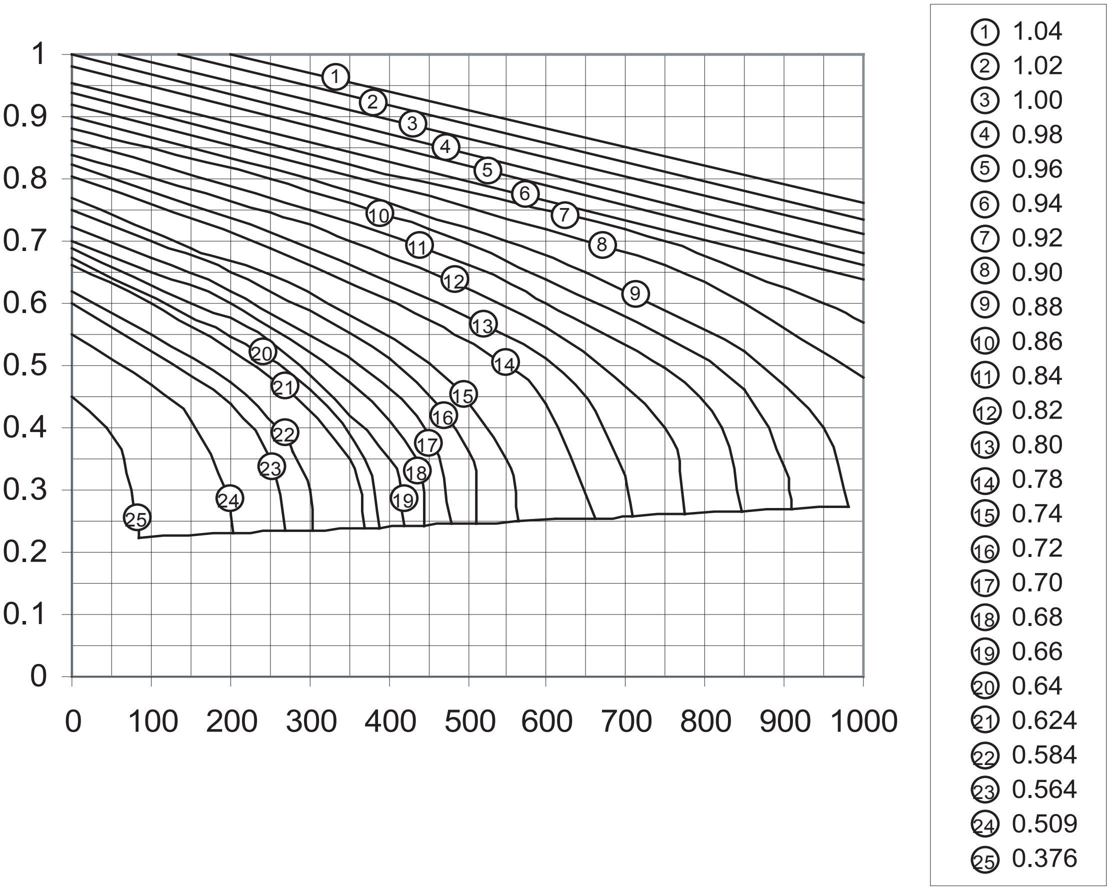

To find the weight density of a petroleum oil at its flowing temperature when the specific gravity at 60 x F is knows, multiply the specific gravity of the oil at flowing temperature (see Figure A-3) by 62.4, the density of water at 60 x F.

Figure A-4. Chart for Specific Gravity vs. API Gravity – for Hydrocarbon-based Products and Water Gravity °A.P.I

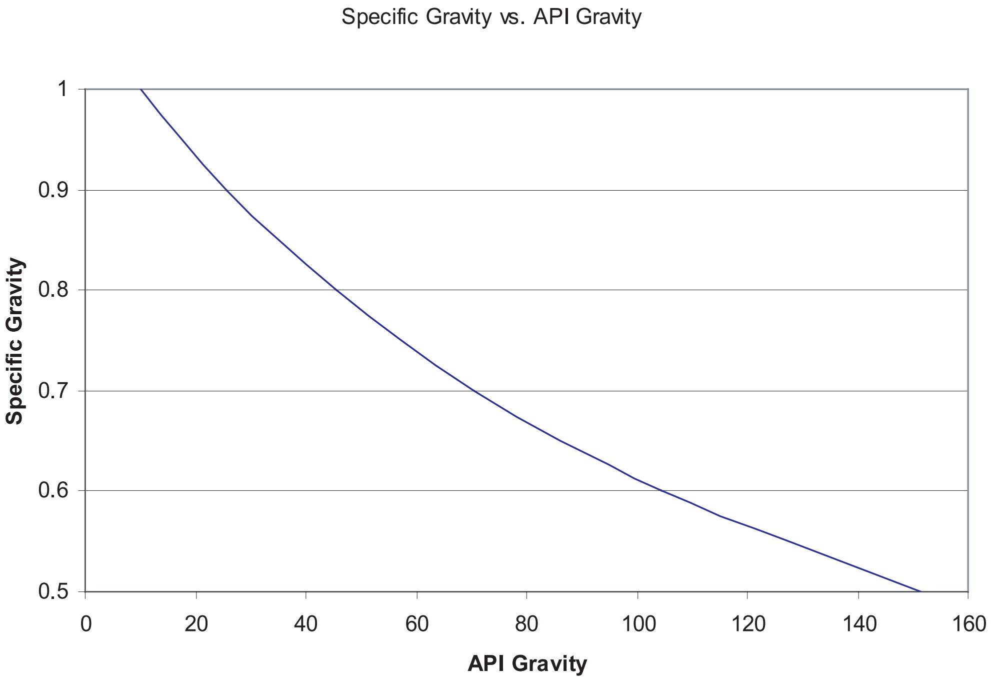

Table A-4. Properties of Selected Liquids

Liquid	Temp	Density(1)	Specific Gravity(2)
	°F	lb/ft^3	psia
Acetaldehyde	64	48.9	0.784
Acetone	60	49.4	0.792
Acetic Anhydride	68	67.5	1.083
Acid Benzoic	59	79.0	1.267
Acid, Acetic Conc.	68	65.5	1.050
Acid, Butyric, Conc.	68	60.2	0.965
Acid, Hydrochloric, 42.5%	64	92.3	1.400
Acid, Hydrochloric	64	43.5	0.697
Acid, Nitric, Conc. Boil	64	93.7	1.502
Acid, Ortho-phosphoric	65	114.4	1.834
Ammonia, Saturated	10	40.9	0.656
Aniline	68	63.8	1.023
Benzene	32	56.1	0.899
Brine, 10% CaCl	32	68.1	1.091
Brine, 10% NaCl	32	67.2	1.078
Bunker C Fuel Max	60	63.3	1.014
Carbon Disulphide	32	80.6	1.292
Carbon Tetrchloride	68	99.6	1.597
Chlororobenzene	68	69.1	1.108
Cresol, Meta	68	64.5	1.035
Diphenyl	163	61.9	0.993
Distillate	60	53.0	0.850
Fuel 3 Max	60	56.0	0.898
Fuel 3 Min	60	60.2	0.966
Fuel 5 Max	60	61.9	0.993
Fuel 6 Min	60	61.9	0.993
Furfural	68	72.3	1.160
Gasoline	60	46.8	0.751
Gasoline, Natural	60	42.4	0.680
Glycerol	122	78.6	1.261
Heptane	68	42.7	0.685
Kerosene	60	50.8	0.815
M. C. Residuum	60	58.3	0.935
Mercury	20	849.7	13.623
Mercury	40	848.0	13.596
Mercury	60	846.3	13.568
Mercury	80	844.6	13.541
Mercury	100	842.9	13.514
Methylene Chloride	68	83.4	1.337
Milk	--	64.2 - 64.6	--
Oil, Olive	59	57.3	0.919
Pentane	59	38.9	0.624
Phenol	77	66.8	1.072
Pyridine	68	61.3	0.983
SAE 10 Lube	60	54.6	0.876
SAE 30 Lube	60	56.0	0.898
SAE 70 Lube	60	57.1	0.916
Salt Creek Crude	60	52.6	0.843
32.6° API Crude	60	53.8	0.862
35.2° API Crude	60	52.8	0.847
40° API	60	51.4	0.825
48° API	60	49.2	0.788
Toulene (Toluol)	68	54.1	0.867
Trichloroethylene	68	91.5	1.468
Water	60	62.3707	1.000
Xylol (Xylene)	68	55.0	0.882

(1) Density is shown for the temperature listed.
(2) Specific gravity uses water at 60 °F as base conditions.

Table A-5. Air Density, lbm/ft^3

Temp	14.73	100	200	300	400	500	600	700	800	900	1000	1100
°F	psia	psia	psia	psia	psia	psia	psia	psia	psia	psia	psia	psia
– 40	0.0949	0.6488	1.3087	1.9796	2.661	3.3525	4.0533	4.7628	5.4798	6.2031	6.9315	7.6632
– 20	0.0905	0.6182	1.245	1.8799	2.5227	3.1728	3.8295	4.492	5.1594	5.8308	6.5051	7.1811
0	0.0866	0.5905	1.1875	1.7906	2.3995	3.0135	3.6321	4.2547	4.8805	5.5086	6.1382	6.7684
20	0.0830	0.5652	1.1353	1.71	2.2887	2.8711	3.4567	4.0447	4.6347	5.2258	5.8175	6.409
40	0.0797	0.5421	1.0878	1.6368	2.1886	2.7429	3.2992	3.857	4.4157	4.9748	5.5338	6.092
60	0.0765	0.5208	1.0442	1.5699	2.0974	2.6266	3.1569	3.6879	4.2191	4.7502	5.2805	5.8098
80	0.0737	0.5012	1.0041	1.5085	2.0141	2.5205	3.0275	3.5347	4.0416	4.5478	5.0529	5.5567
100	0.0711	0.4829	0.9670	1.4519	1.9375	2.4234	2.9093	3.3949	3.8798	4.3637	4.8464	5.3274
120	0.0687	0.4660	0.9327	1.3997	1.8668	2.3339	2.8006	3.2666	3.7316	4.1954	4.6577	5.1184
140	0.0644	0.4503	0.9007	1.3511	1.8013	2.2511	2.7001	3.1482	3.5951	4.0406	4.4845	4.9265
160	0.0641	0.4356	0.871	1.3061	1.7406	2.1744	2.6073	3.0391	3.4695	3.8985	4.3257	4.7509
180	0.0621	0.4218	0.8432	1.264	1.684	2.103	2.521	2.938	3.3529	3.7665	4.1783	4.5882
200	0.0602	0.4089	0.8171	1.2246	1.6311	2.0364	2.4405	2.8432	3.2444	3.6439	4.0417	4.4375
220	0.0585	0.3967	0.7927	1.1877	1.5815	1.9741	2.3654	2.7551	3.1432	3.5296	3.9144	4.2972
240	0.0568	0.3853	0.7697	1.1529	1.5349	1.9156	2.2948	2.6725	3.0485	3.4228	3.7953	4.1658
260	0.0552	0.3745	0.7480	1.1202	1.4911	1.8606	2.2288	2.5956	2.9608	3.3239	3.6846	4.0424
280	0.0537	0.3644	0.7275	1.0893	1.4497	1.8088	2.1666	2.5231	2.8779	3.2306	3.5803	3.9264
300	0.0523	0.3547	0.7081	1.0601	1.4107	1.7599	2.1078	2.4546	2.7997	3.1424	3.4819	3.8174
320	0.0510	0.3456	0.6898	1.0325	1.3737	1.7136	2.0523	2.3897	2.7356	3.059	3.389	3.7147
340	0.0497	0.3369	0.6724	1.0063	1.3388	1.6698	1.9997	2.3283	2.7553	2.98	3.3013	3.6184

Table A-6. Properties of Selected Gases

Gas	Chemical Formula	Molecular Weight	Density(1)	Specific Gravity(2)	Individual gas Constant R	Ration of Specific head = C_p/C_v
Acetylene	C_2H_2	26.0382	.06858	.897	59.348	1.28
Air	---	28.9644	.07649	.897	59.348	1.40
Ammonia	NH_3	17.0306	.04488	.587	90.738	1.29
Argon	A	39.9480	.10553	1.379	38.683	1.67
Butane-N	C_4H_{10}	58.1243	.15873	2.075	26.586	1.09
Carbon Dioxide	CO_2	44.0100	.11684	1.528	35.113	1.28
Carbon Monoxide	CO	28.0106	.07397	0.967	55.169	1.41
Chlorine	C_{12}	70.9060	.19046 0 °C	2.490 0 °C	21.794	1.36
Ethane	C_2H_6	30.0701	.08005	1.047	51.391	1.19
Ethylene	C_2H_4	28.0542	.07392	.967	55.083	1.22
Helium	He	4.00260	.01056	.138	368.07	1.66
Heptane, Average	C_7H_{16}	100.2060	.26451	3.458	15.421	---
Hexane, Average	C_6H_{14}	86.1785	.22748	2.974	17.932	1.08
Hydrochloric acid	HCl	36.4610	.09606	1.256	42.383	1.40
Hydrogen	H_2	2.01594	.00532	.070	766.55	1.40
Hydrogen Sulfide	H_2S	34.0799	.09024	1.177	45.344	1.32
Methane	CH_4	16.0430	.04243	.555	96.324	1.31
Methyl Chloride	CH_3Cl	50.4881	.13292	1.738	30.606	1.20
Neon	Ne	20.1830	.05155	.674	76.565	1.64
Nitric Oxide	NO	30.0061	.07908	1.034	51.500	1.40
Nitrogen	N_2	28.0130	.07397	.967	55.164	1.40
Nitrous Oxide	N_2O	44.0128	.11606	1.518	35.111	1.26
Octane Average	C_8H_{18}	114.2330	.30153	3.942	13.528	---
Oxygen	O_2	31.9988	.08453	1.105	48.293	1.40
Penatane, ISO	C_5H_{12}	72.1514	.19045	2.490	21.418	1.06
Propane	C_3H_8	44.0972	.11854	1.550	35.044	1.33
Propylene	C_3H_6	42.081	.04842 –47 °C	.634 –47 °C	36.722	1.14
Sulphur Dioxide	SO_2	64.0630	.16886	2.208	24.122	1.25

(1) Density is given for gas at 14.73 psia and 60 °F unless noted.
(2) Specific gravity used air at 14.73 psia and 60 °F as base conditions.

Figure A-5. Viscosity of Various Gases

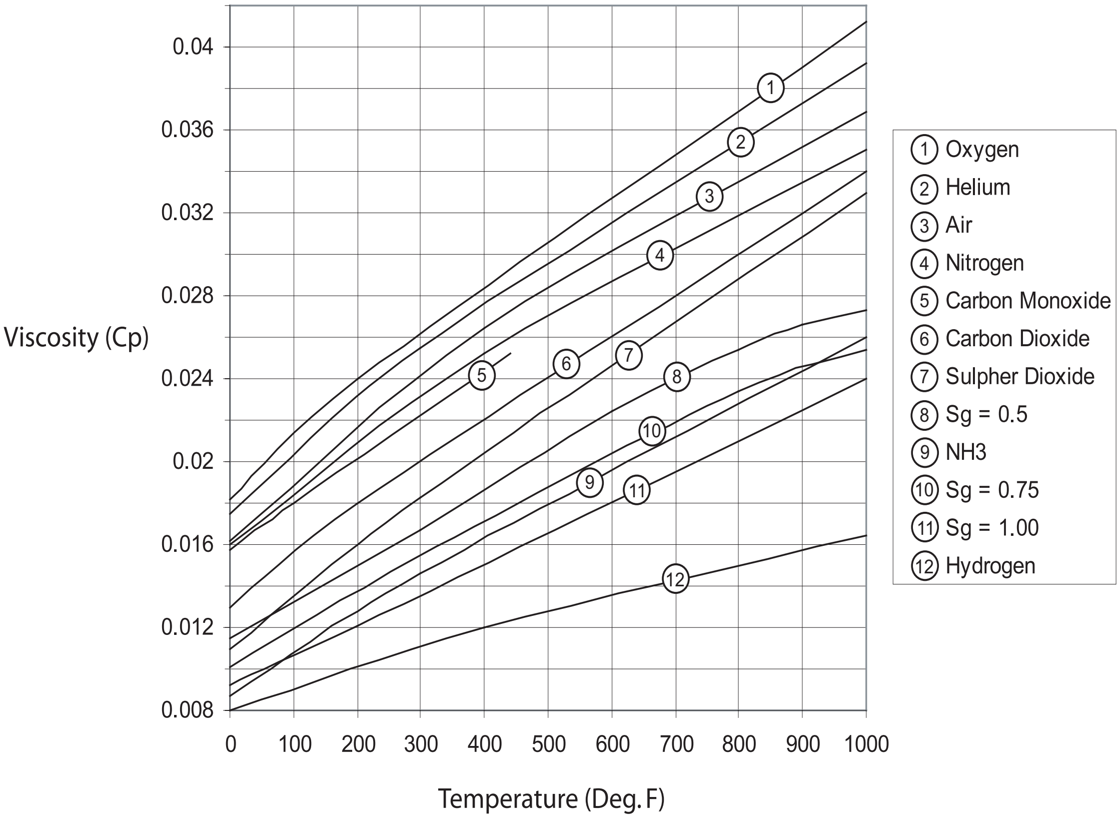

Figure A-5 Example: The viscosity of sulphur dioxide gas (SO_2) at 200 °F is 0.016 centipoise.

The curves for hydrocarbon vapors and natural gases in Figure A-5 are taken from Maxwell. The curves for all other gases (except helium) in the chart are based upon Sutherland's formula, as follows:

$$\mu = \mu_0\left(\frac{T_0 + C}{T + C}\right)\left(\frac{T}{T_0}\right)^{\frac{3}{2}}$$

where:
μ = viscosity, in centipoise at temperature T
μ_o = viscosity, in centipoise at temperature To
T = absolute temperature, in °Rankine, for which viscosity is desired
T_o = absolute temperature, in °Rankine, for which viscosity is known
C = Sutherland's constant

NOTE
The variation of viscosity with pressure is small for most gases. For the gases in Figure A-5 and Figure A-6, the correction of viscosity for pressure is less than 10% for pressures up to 500 lb/in.^{2} (3447 kPa).

Figure A-6. Viscosity of Refrigerant Vapors (saturated and superheated vapors)

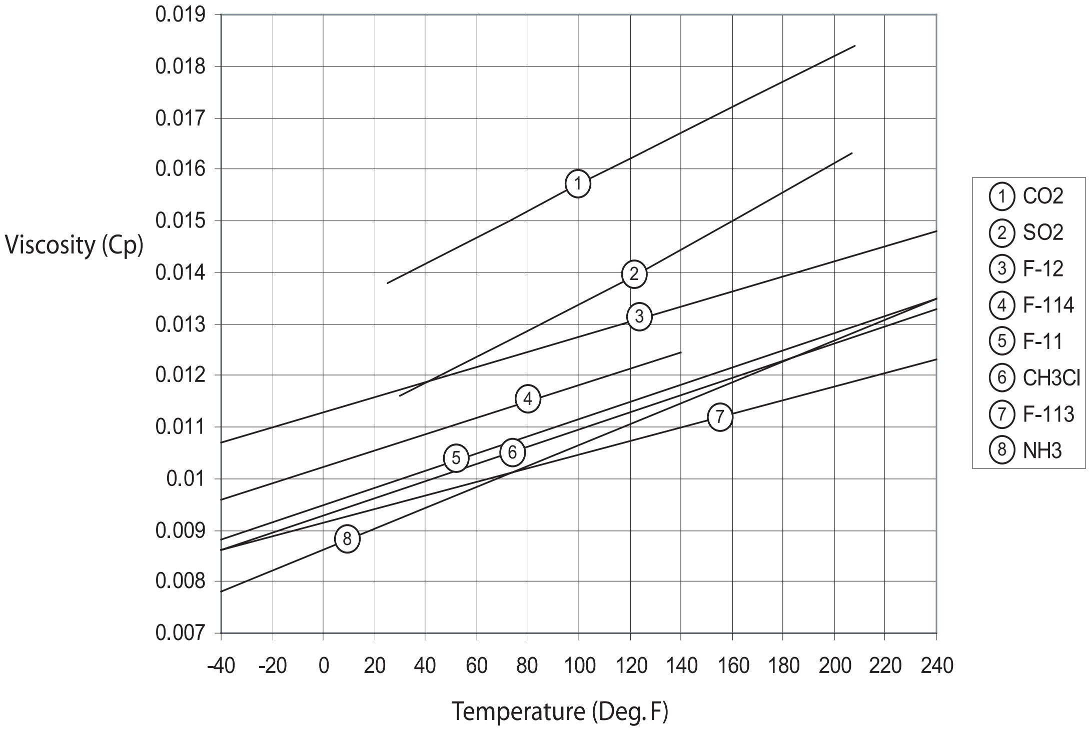

Figure A-6 Example: The viscosity of carbon dioxide gas (CO_2) at 80 °F is 0.016 centipoise.

Table A-7. Factors to Change from a Temperature Base of 60 °F to Other Temperature Bases

Temperature (°F)	F_{tb}	Temperature (°F)	F_{tb}	Temperature (°F)	F_{tb}	Temperature (°F)	F_{tb}	Temperature (°F)	F_{tb}
40	0.9615	50	0.9808	60	1.0000	70	1.0192	80	1.0385
41	0.9635	51	0.9827	61	1.0019	71	1.0212	81	1.0404
42	0.9654	52	0.9846	62	1.0038	72	1.0231	82	1.0462
43	0.9673	53	0.9865	63	1.0058	73	1.0250	83	1.0442
44	0.9692	54	0.9885	64	1.0077	74	1.0269	84	1.0462
45	0.9712	55	0.9904	65	1.0096	75	1.0288	85	1.0481
46	0.9731	56	0.9923	66	1.0115	76	1.0308	86	1.0500
47	0.9750	57	0.9942	67	1.0135	77	1.0327	87	1.0519
48	0.9769	58	0.9962	68	1.0154	78	1.0246	88	1.0538
49	0.9788	59	0.9981	69	1.0173	79	1.0365	89	1.0558
								90	1.0577

Table A-8. Flowing Temperature Factors - F_{tf}

Temperature (°F)	Factor
1	1.0621
2	1.0609
3	1.0598
4	1.0586
5	1.0575
6	1.0564
7	1.0552
8	1.0541
9	1.0530
10	1.0518
11	1.0507
12	1.0496
13	1.0485
14	1.0474
15	1.0463
16	1.0452
17	1.0441
18	1.0430
19	1.0419
20	1.0408
21	1.0392
22	1.0387
23	1.0376
24	1.0365
25	1.0355
26	1.0344
27	1.0333
28	1.0323
29	1.0312
30	1.0302
31	1.0291
32	1.0281
33	1.0270
34	1.0260
35	1.0249
36	1.0239
37	1.0229
38	1.0219
39	1.0208
40	1.0198
41	1.0188
42	1.0178
43	1.0168
44	1.0157
45	1.0147
46	1.0137
47	1.0127
48	1.0117
49	1.0107
50	1.0098
51	1.0089
52	1.0078
53	1.0068
54	1.0058
55	1.0048
56	1.0039
57	1.0029
58	1.0019
59	1.0010
60	1.000
61	0.9990
62	0.9981
63	0.9971
64	0.9962
65	0.9952
66	0.9943
67	0.9933
68	0.9924
69	0.9915
70	0.9905
71	0.9896
72	0.9887
73	0.9877
74	0.9868
75	0.9856
76	0.9850
77	0.9840
78	0.9831
79	0.9822
80	0.9813
81	0.9804
82	0.9795
83	0.9786
84	0.9777
85	0.9768
86	0.9759
87	0.9750
88	0.9741
89	0.9732
90	0.9723
91	0.9715
92	0.9706
93	0.9697
94	0.9688
95	0.9680
96	0.9671
97	0.9662
98	0.9653
99	0.9645
100	0.9636
110	0.9551
120	0.9469
130	0.9388
140	0.9309
150	0.9233
160	0.9158
170	0.9085
180	0.9014
190	0.8944
200	0.8876
210	0.8810
220	0.8745
230	0.8681
240	0.8619
250	0.8558
260	0.8498
270	0.8440
280	0.8383
290	0.8327
300	0.8275

Table A-9. Supercompressibility Factor – Fpv, Air Flowing Temperature

Pressure psia	**Temperature**													
	–40 °F	**–20 °F**	**0 °F**	**20 °F**	**40 °F**	**60 °F**	**80 °F**	**100 °F**	**120 °F**	**140 °F**	**160 °F**	**180 °F**	**200 °F**	**220 °F**
14.7	1.0092	1.0077	1.0065	1.0056	1.0048	1.0041	1.0035	1.0031	1.0027	1.0024	1.0021	1.0019	1.0016	1.0015
100	1.0613	1.0516	1.0437	1.0372	1.0319	1.0275	1.0239	1.0208	1.0182	1.0160	1.0141	1.0125	1.0112	1.0100
200	1.1193	1.1007	1.0856	1.0732	1.0629	1.0544	1.0472	1.0412	1.0361	1.0318	1.0281	1.0249	1.0222	1.0198
300	1.1744	1.1477	1.1259	1.1079	1.0930	1.0805	1.0700	1.0612	1.0537	1.0473	1.0419	1.0372	1.0331	1.0296
400	1.2270	1.1929	1.1649	1.1416	1.1223	1.1060	1.0924	1.0808	1.0710	1.0626	1.0554	1.0493	1.0439	1.0392
500	1.2774	1.2365	1.2026	1.1744	1.1508	1.1310	1.1143	1.1001	1.0880	1.0777	1.0689	1.0612	1.0546	1.0488
600	1.3260	1.2785	1.2391	1.2062	1.1786	1.1554	1.1358	1.1191	1.1048	1.0926	1.0821	1.0730	1.0652	1.0583
700	1.3728	1.3192	1.2746	1.2373	1.2058	1.1793	1.1568	1.1377	1.1213	1.1073	1.0952	1.0847	1.0756	1.0677
800	1.4181	1.3587	1.3091	1.2675	1.2324	1.2028	1.1775	1.1560	1.1376	1.1218	1.1081	1.0963	1.0860	1.0771
900	1.4620	1.3971	1.3428	1.2971	1.2585	1.2258	1.1979	1.1741	1.1537	1.1361	1.1209	1.1077	1.0963	1.0863
1000	1.5046	1.4345	1.3756	1.3260	1.2840	1.2483	1.2179	1.1918	1.1695	1.1502	1.1335	1.1191	1.1065	1.0955
1100	1.5460	1.4709	1.4077	1.3543	1.3090	1.2705	1.2376	1.2094	1.1851	1.1642	1.1460	1.1303	1.1166	1.1046
1200	1.5863	1.5064	1.4390	1.3820	1.3336	1.2923	1.2569	1.2266	1.2005	1.1779	1.1584	1.1414	1.1266	1.1136
1300	1.6257	1.5411	1.4697	1.4092	1.3577	1.3137	1.2760	1.2436	1.2157	1.1916	1.1706	1.1524	1.1365	1.1226
1400	1.6641	1.5751	1.4998	1.4358	1.3814	1.3348	1.2948	1.2604	1.2308	1.2051	1.1827	1.1633	1.1463	1.1314
1470	1.6905	1.5984	1.5204	1.4542	1.3977	1.3493	1.3078	1.2721	1.2412	1.2144	1.1911	1.1709	1.1531	1.1376

Appendix B Pipe Data

Table B-1. Pipe Data

Cast iron Pipe – ASA Standard

Pipe Size	Pipe O.D.	Class 50 50 psig		Class 100 100 psig		Class 150 150 psig		Class 200 200 psig		Class 250 250 psig		Class 300 300 psig		Class 350 350 psig	
		Wall	I.D.	Wall	I.D.	Wall	I.D.	Wall	I.D.	Wall	I.D.	Wall	I.D.	Wall	I.D.
2	3.96	0.32	3.32	0.32	3.32	0.32	3.32	0.32	3.32	0.32	3.32	0.32	3.32	0.32	3.32
3	4.80	0.35	4.10	0.35	4.10	0.35	4.10	0.35	4.10	0.35	4.10	0.35	4.10	0.35	4.10
4	6.90	0.38	6.14	0.38	6.14	0.38	6.14	0.38	6.14	0.38	6.14	0.38	6.14	0.38	6.14
5	9.05	0.41	8.23	0.41	8.23	0.41	8.23	0.41	8.23	0.41	8.23	0.41	8.23	0.41	8.23
10	11.10	0.44	10.22	0.44	10.22	0.44	10.22	0.44	10.22	0.44	10.22	0.48	10.14	0.52	10.06
12	13.20	0.48	12.24	0.48	12.24	0.48	12.24	0.48	12.24	0.52	12.16	0.52	12.16	0.56	12.08
14	15.30	0.48	14.34	0.51	14.28	0.51	14.28	0.55	14.20	0.59	14.12	0.59	14.12	0.64	14.02
16	17.40	0.54	16.32	0.54	16.32	0.54	16.32	0.58	16.24	0.63	16.14	0.68	16.04	0.68	16.04
18	19.50	0.54	18.42	0.58	18.34	0.58	18.34	0.63	18.24	0.68	18.14	0.73	18.04	0.79	17.92
20	21.60	0.57	20.46	0.62	21.36	0.62	20.36	0.67	20.26	0.72	20.16	0.78	20.04	0.84	19.92
24	25.80	0.63	24.54	0.68	24.44	0.73	24.34	0.79	24.22	0.79	24.22	0.85	24.10	0.92	23.96

Cast iron Pipe – AWWA Standard

Pipe Size	Class A 100 ft. 43 psig			Class B			Class C			Class D			Class E			Class F			Class G			Class H		
	O.D.	Wall	I.D.	O.D.	Wall	I.D.	O.D.	Wall	I.D.	O.D.	Wall	I.D.	O.D.	Wall	I.D.	O.D.	Wall	I.D.	O.D.	Wall	I.D.	O.D.	Wall	I.D.
2	3.80	0.39	3.02	3.95	0.42	3.12	3.96	0.45	3.06	3.96	0.48	3.00	---	---	---	---	---	---	---	---	---	---	---	---
3	4.80	0.42	3.96	5.00	0.45	4.10	5.00	0.48	4.04	5.00	0.52	3.96	---	---	---	---	---	---	---	---	---	---	---	---
4	6.90	0.44	6.02	7.10	0.48	6.14	7.10	0.51	6.08	7.10	0.55	6.00	7.22	0.58	6.06	7.22	0.61	6.00	7.38	0.65	6.08	7.38	0.69	6.00
5	9.05	0.46	8.13	9.05	0.51	8.03	9.30	0.56	8.18	9.30	0.60	8.10	9.42	0.66	8.10	9.42	0.71	8.00	9.60	0.75	8.10	9.60	0.80	8.00
10	11.10	0.50	10.10	11.10	0.57	9.96	11.40	0.62	10.16	11.40	0.68	10.04	11.60	0.74	10.12	11.60	0.80	10.00	11.84	0.86	10.12	11.84	0.92	10.00
12	13.20	0.54	12.12	13.20	0.62	11.96	13.50	0.68	12.14	13.50	0.75	12.00	13.78	0.82	12.14	13.78	0.89	12.00	14.08	0.97	12.14	14.08	1.04	12.00
14	15.30	0.57	14.16	15.30	0.66	13.98	15.65	0.74	14.17	15.65	0.82	14.01	15.98	0.90	14.18	15.98	0.99	14.00	16.32	1.07	14.18	16.32	1.16	14.00
16	17.40	0.60	16.20	17.40	0.70	16.00	17.80	0.80	16.20	17.80	0.89	16.02	18.16	0.98	16.20	18.16	1.08	16.00	18.54	1.18	16.18	18.54	1.27	16.00
18	19.50	0.64	18.22	19.50	0.75	18.00	19.92	0.87	18.18	19.92	0.96	18.00	20.34	1.07	18.20	20.34	1.17	18.00	20.78	1.28	18.22	20.78	1.39	18.00
20	21.60	0.67	20.26	21.60	0.80	21.00	22.06	0.92	20.22	22.06	1.03	21.00	22.54	1.15	20.24	22.54	1.27	20.00	23.02	1.39	20.24	23.02	1.51	20.00
24	25.80	0.76	24.28	25.80	0.89	24.02	26.32	1.04	24.22	26.32	1.16	24.00	26.90	1.31	24.28	26.90	1.45	24.00	27.76	1.75	24.26	27.76	1.88	24.00
30	31.74	0.88	29.98	32.00	1.03	29.94	32.40	1.20	30.00	32.74	1.37	30.00	33.10	1.55	30.00	33.46	1.73	30.00						
36	37.96	0.99	35.98	38.30	1.15	36.00	38.70	1.36	39.98	39.16	1.58	36.00	39.60	1.80	36.00	40.04	2.02	36.00						
42	44.20	1.10	42.00	44.50	1.28	41.94	45.10	1.54	42.02	45.58	1.78	42.02												
48	50.50	1.26	47.98	50.80	1.42	47.96	51.40	1.71	47.98	51.98	1.96	48.06												
54	56.66	1.35	53.96	57.10	1.55	54.00	57.80	1.90	54.00	58.40	2.23	53.94												
60	62.80	1.39	60.02	63.40	1.67	60.06	64.20	2.00	60.20	64.82	2.38	60.06												
72	75.34	1.62	72.10	76.00	1.95	72.10	76.88	2.39	72.10															
84	87.54	1.72	84.10	88.54	2.22	84.10																		

Stainless Steel, Hastelloy® C and Titanium Pipe(1)

Pipe	Size	1/2	3/4	1	1 1/4	1 1/2	2	2 1/2	3	3 1/2	4	5	6	8	10	12	14	16	18	20	22	24
Sched	Out. Dia.	.840	1.050	1.315	1.660	1.900	2.375	2.875	3.500	4.000	4.500	5.563	6.625	8.625	10.750	12.750	14.000	16.000	18.000	20.000	22.000	24.000
5S(2)	I.D.	.710	.920	1.185	1.530	1.770	2.245	2.709	3.334	3.834	4.334	5.345	6.407	8.407	10.482	12.438	13.668	15.670	17.670	19.634	21.624	23.563
	Wall	.065	.065	.065	.065	.065	.065	.083	.083	.083	.083	.109	.109	.109	.134	.156	.156	.165	.165	.188	.188	.218
10S	I.D.	.674	.884	1.097	1.442	1.682	2.157	2.635	3.260	3.760	4.260	5.295	6.357	8.329	10.420	12.390	13.624	15.624	17.624	19.564	21.564	23.50
	Wall	.083	.083	.109	.109	.109	.109	.120	.120	.120	.120	.134	.134	.148	.165	.180	.188	.188	.188	.218	.218	.250
40S	I.D.	.622	.824	1.049	1.380	1.610	2.067	2.469	3.068	3.548	4.026	5.047	6.065	7.981	1.020	12.00						
	Wall	★.109	★.113	★.133	★.140	★.145	★.154	★.203	★.216	★.226	★.237	★.258	★.280	★.322	★.365	■.375						
80S	I.D.	.546	.742	.957	1.278	1.500	1.939	2.323	2.900	3.364	3.826	4.813	5.761	7.625	9.750	11.75						
	Wall	▲.147	▲.154	▲.179	▲.191	▲.200	▲.218	▲.276	▲.300	▲.318	▲.337	▲.375	▲.432	▲.500	▲.500	▲.500						

(1) *These materials are generally available in schedules 40 and 80 only.*
(2) *Wall thickness of Schedule 5S and 10S does not permit threading in accordance with the American Standard for Pipe Threads (ASA No. B2.1).*

Carbon Steel and PVC[1] Pipe

Pipe	Size	1/2	3/4	1	1 1/4	1 1/2	2	2 1/2	3	3 1/2	4	5
	Out. Dia.	.840	1.050	1.315	1.660	1.900	2.375	2.875	3.500	4.000	4.500	5.563
Std	I.D.	.622	.824	1.049	1.380	1.610	2.067	2.469	3.068	3.548	4.026	5.047
	Wall	.109	.113	.133	.140	.145	.154	.203	.216	.226	.237	.258
Extra Heavy	I.D.	.546	.742	.957	1.278	1.500	1.939	2.323	2.900	3.364	3.826	4.813
	Wall	.147	.154	.179	.191	.200	.218	.276	.300	.318	.377	.375
Double Extra Heavy	I.D.	.252	.434	.599	.895	1.100	1.503	1.771	2.300	2.728	3.152	4.063
	Wall	.294	.308	.358	.382	.400	.436	.552	.600	.636	.674	.750
Sched 10	I.D.	---	---	---	---	---	---	---	---	---	---	---
	Wall	---	---	---	---	---	---	---	---	---	---	---
Sched 20	I.D.		---	---	---	---	---	---	---	---	---	---
	Wall		---	---	---	---	---	---	---	---	---	---
Sched 30	I.D.	---	---	---	---	---	---	---	---	---	---	---
	Wall	---	---	---	---	---	---	---	---	---	---	---
Sched 40	I.D.	.622	.824	1.049	1.380	1.610	2.067	2.469	3.068	3.548	4.026	5.047
	Wall	★.109	★.133	★.133	★.140	★.145	★.154	★.203	★.216	★.226	★.237	★.258
Sched 60	I.D.	---	---	---	---	---	---	---	---	---	---	---
	Wall	---	---	---	---	---	---	---	---	---	---	---
Sched 80	I.D.	.546	.742	.957	1.278	1.500	1.939	2.323	2.900	3.364	3.826	4.813
	Wall	.147	▲.154	▲.179	▲.191	▲.200	▲.218	▲.276	▲.300	▲.318	▲.337	▲.375
Sched 100	I.D.	---	---	---	---	---	---	---	---	---	---	---
	Wall	---	---	---	---	---	---	---	---	---	---	---
Sched 120	I.D.	---	---	---	---	---	---	---	---	---	3.624	4.563
	Wall	---	---	---	---	---	---	---	---	---	.438	.500
Sched 140	I.D.	---	---	---	---	---	---	---	---	---	---	---
	Wall	---	---	---	---	---	---	---	---	---	---	---
Sched 160	I.D.	.466	.614	.815	1.160	1.338	1.689	2.125	2.624	---	3.438	4.313
	Wall	.187	.218	.250	.250	.281	.343	.375	.438	---	.531	.625

Pipe	Size	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	42
	Out. Dia.	6.625	8.625	10.750	12.750	14.000	16.000	18.000	20.000	22.000	24.000	26.000	28.000	30.000	32.000	34.000	36.000	42.000
Std	I.D.	6.065	7.981	10.20	12.000	13.250	15.250	17.250	19.250	21.250	23.250	25.250	27.250	29.250	31.250	33.250	35.250	41.250
	Wall	.280	.322	.365	.375	.375	.375	.375	.375	.375	.375	.375	.375	.375	.375	.375	.375	■.375
Extra Heavy	I.D.	5.761	7.625	9.750	11.750	13.000	15.000	17.000	19.000	21.000	23.000	25.000	27.000	29.000	31.000	33.000	35.000	41.000
	Wall	.432	.500	.500	.500	.500	.500	.500	.500	.500	.500	.500	.500	.500	.500	.500	.500	■.500
Double Extra Heavy	I.D.	6.065	7.981	1.020	12.00	---	---	---	---	---	---	---	---	---	---	---	---	---
	Wall	★.280	★.322	★.365	■.375	---	---	---	---	---	---	---	---	---	---	---	---	---
Sched 10	I.D.	---	---	---	---	13.500	15.500	17.500	19.500	21.500	23.500	25.376	27.376	29.376	31.376	33.376	35.376	---
	Wall	---	---	---	---	.250	.250	.250	.250	.250	.250	.312	.312	.312	.312	.312	.312	---
Sched 20	I.D.	---	8.125	10.250	12.250	13.376	15.376	17.376	19.250	21.250	23.250	25.000	27.000	29.000	31.000	33.000	35.000	41.000
	Wall	---	.250	.250	.250	.312	.312	.312	★.375	★.375	★.375	▲.500	▲.500	▲.500	▲.500	▲.500	▲.500	▲.500
Sched 30	I.D.	---	8.071	10.136	12.090	13.250	15.250	17.124	19.000	21.000	22.876	---	26.750	28.750	30.750	32.750	34.750	40.750
	Wall	---	.277	.307	.330	★.375	★.375	.438	▲.500	▲.500	.562	---	.625	.625	.625	.625	.625	■.625
Sched 40	I.D.	6.065	7.981	10.020	11.938	13.124	15.000	16.976	18.814	---	22.626							
	Wall	★.280	★.322	★.365	.406	.438	▲.500	.562	.593	---	.687							
Sched 60	I.D.	---	7.813	9.750	11.626	12.814	14.688	16.500	18.376	20.250	22.064							
	Wall	---	.406	s.500	.562	.593	.656	.750	.812	.875	.968							
Sched 80	I.D.	5.761	7.625	9.564	11.376	12.500	14.314	16.126	17.938	19.750	21.564							
	Wall	▲.432	▲.500	.593	.687	.750	.843	.937	1.031	1.125	1.218							
Sched 100	I.D.	---	7.439	9.314	11.064	12.126	13.938	15.688	17.438	19.250	20.938							
	Wall	---	.593	.718	.843	.937	1.031	1.156	1.281	1.375	1.531							
Sched 120	I.D.	5.501	7.189	9.064	10.750	11.814	13.564	15.250	17.000	18.750	20.376							
	Wall	.562	.718	8.43	1.000	1.093	1.218	1.375	1.500	1.625	1.812							
Sched 140	I.D.	---	7.001	8.750	10.500	11.500	13.124	14.876	16.500	18.250	19.876							
	Wall	---	.812	1.000	1.125	1.250	1.438	1.562	1.750	1.875	2.062							
Sched 160	I.D.	5.189	6.813	8.500	10.126	11.188	12.814	14.438	16.064	17.750	19.314							
	Wall	.718	.906	1.125	1.312	1.406	1.593	1.781	1.968	2.125	2.343							

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(1) *These materials are generally available in schedules 40 and 80 only.*

Character Description

▲ = Wall thicknes is identical with the thickness of “Extra Heavy” pipe.

★ = Wall thicknes is identical with the thickness of “Standard Weight” pipe.

■ = These do not conform to the American Standard B36.10.

Pipe Weight Formula for Steel Pipe (pounds per foot):

$10.68 (D-t)t$

where:

D = Outside Diameter
t = Wall Thickness

Table B-2. F_{aa} Thermal Expansion Factor

Temperature (°F) of Piping Material								
Aluminum	**Copper**	**Type 430**	**2% CRMO**	**5% CRMO**	**Bronze**	**Carbon Steel**	**Type 316 Type 304**	**Correction Factor, F_{aa}**
– 264					– 317			0.993
– 204	– 322				– 245			0.994
– 155	– 230				– 190		– 276	0.995
– 108	– 163				– 137		– 189	0.996
– 63	– 102				– 86		– 119	0.997
– 19	– 44				– 34		– 55	0.998
25	19	44	– 13	– 14	17	– 6	7	0.999
68	68	68	68	68	68	68	68	1.000
113	127	157	146	151	122	144	130	1.001
		246	222	232	175	218	186	1.002
		332	296	312	225	289	240	1.003
		415	366	389	273	358	292	1.004
		494	434	460	321	425	343	1.005
		568	501	527	369	489	391	1.006
		641	566	594	417	551	439	1.007
		713	629	662		613	488	1.008
		783	690	730		675	536	1.009
		851	750	795		735	584	1.010
		918	811	858		794	631	1.011
		956	871	918		851	674	1.012
		1054	928	979		907	727	1.013
		1121	984	1040		961	777	1.014
		1189	1038	1102		1015	799	1.015

Appendix C Unit and Conversion Factors

Table C-1. Equivalents of Absolute Viscosity

Absolute or Dynamic Viscosity	Centipoise (μ)	Poise gram/cm-sec dyne-sec/cm^3 (100 μ)	slugs/ft-sec pound$_f$sec/ft^2 (μ'_ε)	pounds/ft-sec pounds-sec/ft^2 (μ_ε)
Centipoise (m)	1	0.01	2.09 (10^{-3})	6.72 (10^{-3})
Poise gram/cm-sec dyne-second/cm^3 (100 μ)	100	1	2.09 (10^{-3})	0.0672
slugs/ft-second pound$_f$second/ft^2 (μ'_ε)	47900	479	1	g or 32.3
pounds/ft-second pounds-second/ft^2 (μ_ε)	1487	14.87	1/g or .0311	1

Pound^f = Pound of Force
Pound^m = Pound of Mass

To convert absolute or dynamic viscosity from one set of units to another using Table C-1, locate the given set of units in the left hand column and multiply the numerical value by the factor shown horizontally to the right under the set of units desired.

As an example, suppose a given absolute viscosity of 2 poise is to be converted to slugs/foot-second. By referring to Table C-1, we find the conversion factor to be 2.09 (10-3). Then, 2 (poise) times 2.09 (10-3) = 4.18 (10-3) = 0.00418 slugs/foot-second.

Table C-2. Equivalents of Kinematic Viscosity

Kinematic Viscosity	Centipoise (υ)	Strokes cm^2/second (100 υ)	fm^2/second (υ')
Centipoise (υ)	1	0.01	1.076 (10^{-3})
Strokes cm^2/second (100 υ)	100	1	2.09 (10^{-3})
fm^2/second (υ')	92900	929	1

To convert kinematic viscosity from one set of units to another using Table C-2, locate the given set of units in the left hand column and multiply the numerical value by the factor shown horizontally to the right under the set of units desired.

As an example, suppose a given kinematic viscosity of 0.5 ft^2/second is to be converted to centistokes. By referring to Table C-2, we find the conversion factor to be 92900. Then, 0.5 ft^2/second times 92900 = 46450 centistokes.

Table C-3. Equivalents of Kinematic Viscosity and Saybolt Universal Viscosity

Kinematic Viscosity	Equivalent Saybolt Universal Viscosity, sec.	
Centistokes (υ)	At 100 °F Basic Values	at 210 °F
1.83	32.01	32.23
2.0	32.62	32.85
4.0	39.14	39.41
6.0	45.56	45.88
8.0	52.09	52.45
10.0	58.91	59.32
15.0	77.39	77.93
20.0	97.77	98.45
25.0	119.3	120.1
30.0	141.3	142.3
35.5	163.7	164.9
40.0	186.3	187.6
45.0	209.1	210.5
50.0	232.1	233.8
55.0	255.2	257.0
60.0	278.3	280.2
65.0	301.4	303.5
70.0	324.4	326.7
75.0	347.6	350.0
80.0	370.8	373.4
85.0	393.9	396.7
90.0	417.1	420.0
95.0	440.3	443.4
100.0	463.5	466.7
120.0	556.2	560.1
140.0	648.9	653.4
160.0	741.6	---
180.0	834.2	---
200.0	926.9	---
220.0	1019.6	---
240.0	1112.3	---
260.0	1205.0	---
280.0	1297.7	---
300.0	1390.4	---
320.0	1483.1	---
340.0	1575.8	---
360.0	1668.5	---
380.0	1761.2	---
400.0	1853.9	---
420.0	1946.6	---
440.0	2039.3	---
460.0	2132.0	---
480.0	2224.7	---
500.0	2317.4	---
Over 500	Saybolt seconds = Centistokes x 4.6347	Saybolt seconds = Centistokes x 4.6673

NOTE:
To obtain the Saybolt Universal viscosity equivalent to a kinematic viscosity determined at *t*, multiply the equivalent Saybolt Universal viscosity at 100 °F by 1+(*t* - 100) 0.000 064.

Example: 10υ at 210 °F are equivalent to 58.91 multiplied by 1.0070 or 59.32 seconds Saybolt Universal at 210 °F.

Table C-4. Equivalents of Kinematic Viscosity and Saybolt Furol Viscosity

Kinematic Viscosity	Equivalent Saybolt Furol Viscosity, sec.	
Centistokes (υ)	At 122 °F	at 210 °F
48	25.3	---
50	26.1	25.2
60	30.6	29.8
70	35.1	34.4
80	39.6	39.0
90	44.1	43.7
100	48.6	48.3
125	60.1	60.1
150	71.7	71.8
175	83.8	83.7
200	95.0	95.6
225	106.7	107.5
250	118.4	119.4
275	130.1	131.4
300	141.8	143.5
325	153.6	155.5
350	165.3	167.6
375	177.0	179.7
400	188.8	191.8
425	200.6	204.0
450	212.4	216.1
475	224.1	228.3
500	235.9	240.5
525	247.7	252.8
550	259.5	265.0
575	271.3	277.2
600	283.1	289.5
625	294.9	301.8
650	306.7	314.1
675	318.4	326.4
700	330.2	338.7
725	342.0	351.0
750	353.8	363.4
775	365.5	375.7
800	377.4	388.1
825	389.2	400.5
850	400.9	412.9
875	412.7	425.3
900	424.5	437.7
925	483.5	450.1
950	488.1	462.5
975	459.9	474.9
1000	471.7	487.4
1025	483.5	499.8
1050	495.2	512.3
1075	507.0	524.8
1100	518.8	537.2
1125	530.6	549.7
1150	542.4	562.2
1175	554.2	574.7
1200	566.0	587.2
1225	577.8	599.7
1250	589.5	612.2
1275	601.3	624.8
1300	613.1	637.3
Over 1300	Saybolt fluid seconds = Centistokes x 0.4717	Log (Saybolt Furol seconds - 2.87) = 0.4717 [Log (Centistokes)] - 0.3975

Tables C-3 (abstracted from Table 1, D2161-63T) and C-4 (abstracted from Table 3, D2161-63T) are reprinted with their permission of the America Society for Testing Materials (ASTM).

Table C-5. Equivalents of Degrees API, Degrees Baume, Specific Gravity, Weight Density, and Pounds per Gallon at 60 °F/60 °F.

Degrees on API or Baume Scale	Values for API Scale			Values for Baume Scale					
	Oil			Liquids lighter than water			Liquids heavier than water		
	Specific gravity (S)	Weight Density lb/ft^3 (ρ)	Pounds per Gallon	Specific gravity (S)	Weight Density lb/ft^3 (ρ)	Pounds per Gallon	Specific gravity (S)	Weight Density lb/ft^3 (ρ)	Pounds per Gallon
0	---	---	---	---	---	---	1.0000	62.36	8.337
2	---	---	---	---	---	---	1.0140	63.24	8.454
4	---	---	---	---	---	---	1.0284	64.14	8.574
6	---	---	---	---	---	---	1.0432	65.06	8.697
8	---	---	---	---	---	---	1.0584	66.01	8.824
10	1.0000	62.36	8.337	1.0000	62.36	8.337	1.0741	66.99	8.955
12	0.9861	61.50	8.221	0.9859	61.49	8.219	1.0902	67.99	9.089
14	0.9725	60.65	8.108	0.9722	60.63	8.105	1.1069	69.03	9.228
16	0.9593	59.83	7.998	0.9589	59.80	7.994	1.1240	70.10	9.371
18	0.9465	59.03	7.891	0.9459	58.99	7.886	1.1417	71.20	9.518
20	0.9340	58.25	7.787	0.9333	58.20	7.781	1.1600	72.34	9.671
22	0.9218	57.87	7.736	0.9211	57.44	7.679	1.1789	73.52	9.828
24	0.9100	56.75	7.587	0.9091	56.70	7.579	1.1983	74.73	9.990
26	0.8984	56.03	7.490	0.8974	55.97	7.482	1.2185	75.99	10.159
28	0.8871	55.32	7.396	0.8861	55.26	7.387	1.2393	77.29	10.332
30	0.8762	54.64	7.305	0.8750	54.57	7.295	1.2609	78.64	10.512
32	0.8654	53.97	7.215	0.8642	53.90	7.205	1.2832	80.03	10.698
34	0.8550	53.32	7.128	0.8537	53.24	7.117	1.3063	81.47	10.891
36	0.8448	52.69	7.043	0.8434	52.60	7.031	1.3303	82.96	11.091
38	0.8348	52.06	6.960	0.8333	51.97	6.497	1.3551	84.51	11.297
40	0.8251	51.46	6.879	0.8235	51.36	6.865	1.3810	86.13	11.513
42	0.8155	50.86	6.799	0.8140	50.76	6.786	1.4078	87.80	11.737
44	0.8063	50.28	6.722	0.8046	50.18	6.708	1.4356	89.53	11.969
46	0.7972	49.72	6.646	0.7955	49.61	6.632	1.4646	91.34	12.210
48	0.7883	49.16	6.572	0.7865	49.05	6.557	1.4948	93.22	12.462
50	0.7796	48.62	6.499	0.7778	48.51	6.484	1.5263	95.19	12.725
52	0.7711	48.09	6.429	0.7692	47.97	6.413	1.5591	97.23	12.998
54	0.7628	47.57	6.359	0.7609	47.45	6.344	1.5934	99.37	13.284
56	0.7547	47.07	6.292	0.7527	46.94	6.275	1.6292	101.60	13.583
58	0.7467	46.57	6.225	0.7447	46.44	6.209	1.6667	103.94	13.895
60	0.7389	46.08	6.160	0.7368	45.95	6.143	1.7059	106.39	14.222
62	0.7313	45.61	6.097	0.7292	45.48	6.079	1.7470	108.95	14.565
64	0.7238	45.14	6.034	0.7216	45.00	6.016	1.7901	111.64	14.924
66	0.7165	44.68	5.973	0.7143	44.55	5.955	1.8354	114.46	15.302
68	0.7093	44.23	5.913	0.7071	44.10	5.895	11.8831	117.44	15.699
70	0.7022	43.79	5.854	0.7000	43.66	5.836	1.9333	120.57	16.118
72	0.6953	43.36	5.797	0.6931	43.22	5.778	---	---	---
74	0.6886	42.94	5.741	0.6863	42.80	5.722	---	---	---
76	0.6819	42.53	5.685	0.6796	42.38	5.666	---	---	---
78	0.6754	42.12	5.631	0.6731	41.98	5.612	---	---	---
80	0.6690	41.72	5.577	0.6667	41.58	5.558	---	---	---
82	0.6628	41.33	5.526	0.6604	41.19	5.506	---	---	---
84	0.6566	40.95	5.474	0.6542	40.80	5.454	---	---	---
86	0.6506	40.57	5.424	0.6482	40.42	5.404	---	---	---
88	0.6446	40.20	5.374	0.6422	40.05	5.354	---	---	---
90	0.6388	39.84	5.326	0.6364	39.69	5.306	---	---	---
92	0.6331	39.48	5.278	0.6306	39.33	5.257	---	---	---
94	0.6275	39.13	5.231	0.6250	38.98	5.211	---	---	---
96	0.6220	38.79	5.186	0.6195	38.63	5.165	---	---	---
98	0.6166	38.45	5.141	0.6140	38.29	5.119	---	---	---
100	0.6112	38.12	5.096	0.6087	37.96	5.075	---	---	---

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Table C-6. Equivalents

Weight
1 kg = 2.205 lb
1 cubic inch of water (60 °F) = 0.073551 cubic inch of mercury (32 °F)
1 cubic inch of mercury (32 °F) = 13.596 cubic inch of water (60 °F)
1 cubic inch of mercury (32 °F) = 0.4905 lb

Velocity
1 foot per second = 0.3048 meter per second
1 meter per second = 3.208 foot per second

Density
1 pound per cubic inch = 27.68 gram per cubic centimeter
1 gram per cubic centimeter = 0.03613 pound per cubic inch
1 pound per cubic foot = 16.0184 kg per cubic meter
1 kilogram per cubic meter = 0.06243 pound per cubic foot

Physical Constants
Base of natural logarithms (*e*) = 2.7182818285
Acceleration of gravity (g) = 32.174 foot/second^2 = (980.665 centimeter/second^2)
Pi (π) = 3.1415926536

Measure	
1-in. = 25.4 millimeter	1 ft = 304.8 millimeter
1-in. = 2.54 centimeter	1 ft = 30.48 centimeter
1 millimeter = 0.03937-inch	1-in.^{2} = 6.4516 centimeter^2
1 millimeter = 0.00328 foot	1centimeter^2 = 0.0008 foot^2
1 micron = 0.000001 meter	1 foot^2 = 929.03 centimeter^2
1 torr = 1 millimeter mercury	Circumference of a circle = $2\pi r = \pi d$
10^2 = 1 atom mercury	Area of a circle = $\pi r^{2} = \pi d^{2}/4$

	° Kelvin	° Rankine	° Celsius(1)	° Fahrenheit(2)
Absolute Zero	0	0	–273.15	–459.67
Water Freezing Point (14.696 psia)	273.15	491.67	0	32
Water Boiling Point (14.696 psia)	373.15	671.67	100	212

(1) *To convert degree Celsius (t_c) to degrees Fahrenheit: $t = 1.8t_c = 32$*
(2) *To convert degree Fahrenheit to degree Celsius (t_c): $t_c = (t - 32)/1.8$.*

Prefixes
atto (a) = one-quintillionth = 0.000 000 000 000 000 001 = 10^{-18}
femto (f) = one-quadrilliointh = 0.000 000 000 000 001 = 10^{-15}
pico (p) = one-trillionth = 0.000 000 000 001 = 10^{-12}
nano (n) = one-billionth = 0.000 000 001 = 10^{-9}
micro (m) = one-millionth = 0.000 001 = $^{-6}$
milli (m) = one-thousandth = 0.001= 10^{-3}
centi (c) = one-hundredth = 0.01 = $^{-2}$
deci (d) = one-tenth = 0.1 = $^{-1}$
uni (one) = 1.0 = 10^{-0}
deka (da) = ten = 10.0 = 10^{1}
hecto (h) = one-hundred = 100.0 = 10^{2}
kilo (k) = one-thousand = 1 000.0 = 10^{3}
mega (M) = one-million = 1 000 000.0 = 10^{6}
giga (G) = one-billion = 1 000 000 000.0 = 10^{9}
teta (T) = one-trillion = 1 000 000 000 000.0 = 10^{12}

Table C-7. Equivalents of Liquid Measures and Weights

To Obtain Multiply Column X Row	U.S. Gallon	Imperial Gallon	U.S. Pint	U.S. Pound Water	U.S. Cubic Foot	U.S. Cubic Inch	Liter	Cubic Meter
U.S. Gallon	1	0.833	8	8.337	0.13368	231	3.78533	0.003785
Imperial Gallon	1.2009	1	9.60752	10	0.16054	277.42	4.54596	0.004546
U.S. Pint	0.125	0.1041	1	1.042	0.01671	28.875	0.473166	0.000473
U.S. Pound Water	0.11995	0.1	0.9596	1	0.016035	27.708	0.45405	0.000454
U.S. Cubic Foot	7.48052	6.22888	59.8442	62.365	1	1728	28.31702	0.028317
U.S. Cubic Inch	0.004329	0.00361	0.034632	0.03609	0.0005787	1	0.016387	0.0000164
Liter	0.2641779	0.2199756	2.113423	2.202	0.0353154	61.02509	1	0.001000
Cubic Meter	264.170	219.969	2113.34	2202	35.31446	61023.38	999.972	1

Water at 60 °F (15.6 °C) 1 Barrel = 42 gallons (petroleum measure).

Example:

Suppose a given absolute viscosity of 2 pose is to be converted to slugs/foot-second. By referring to Table C-7, we find the conversion factor to be 2.09 (10-3). Then, 2 (poise) times 2.09 (10-3) = 4.18 (10-3) = 0.00418 slugs/foot-second.

Table C-8. Equivalents of Liquid Measures and Weights

To Obtain Multiply Column X Row	lb/in^2	lb/ft^2	atmospheres	kg/cm^2	kg/m^2	inch water(1)	foot water(1)	inch mercury (1)	mm mercury (1)	bars	MPa	KPa	mm water(1)
lb/in^2	1	.144	0.068046	0.070307	703.070	27.7300	2.3108	2.03602	51.7149	0.068948	0.0068948	6.8948	704.342
lb/ft^2	0.006944	1	0.000473	0.0004888	4.88243	0.19257	0.016048	0.014139	0.35913	0.004788	0.0000479	0.04788	4.89127
atmospheres	14.696	2116.22	1	1.0332	1.0332	407.520	33.9600	29.921	760.00	1.01325	0.101325	101.325	10351.0
kg/cm^2	14.2233	2048.16	.096784	1	1000	394.41	32.868	28.959	735.558	0.98066	0.098066	98.066	10018.1
kg/m^2	0.001422	0.204816	0.0000968	0.001	1	0.3944	0.003287	0.002896	0.073556	0.000098	0.0000098	0.0098	1.00181
inch water (1)	0.036062	5.1929	0.002454	0.00253	29.354	1	0.08333	0.073423	1.8649	0.002486	0.000249	0.24864	25.24
foot water(1)	0.432744	62.315	0.29446	0.030425	304.249	12	1	0.88108	22.3793	0.029837	0.0029837	2.9837	304.800
inch mercury(1)	0.491154	70.7262	0.033420	0.03453	345.319	13.6197	1.1350	1	25.4	0.033864	0.0033864	3.3864	345.94
mm mercury(1)	0.0193368	2.78450	0.0013158	0.0013595	13.595	0.53621	0.044684	0.03937	1	0.001333	0.0001333	0.13332	13.6197
bars	14.5038	2088.54	0.98692	1.01972	10197.2	402.190	33.5158	29.5300	750.061	1	0.10	100	10215.6
MPa	145.038	20885.4	9.8692	10.1972	101972.0	4021.90	335.158	295.300	7500.61	10.0	1	1000	102156
KPa	0.145038	20.8854	0.0098692	0.0101972	101.972	4.02190	0.33516	0.2953	7.50061	0.01	0.001	1	102.156
mm water (1)	.0014198	.20445	.0000966	.0000998	.99819	.039370	.003281	.002891	.073423	.0000979	.0000098	.0097889	1

Water at 60 °F (15.6 °C) 1 Barrel = 42 gallons (petroleum measure).

(1) 68 °F (20 °C)

Example:

(8 Imperial gallons)(4.454596) = 36.36768 liters

To convert from one set of units to another, locate the given units in the left column and multiply the numerical value by the factor shown horizontally to the right under the set of units desired.

Table C-9. Temperature Conversion(1)

–459.4 ° to 0°			1 ° to 60 °			61 ° to 290 °			300 ° to 890 °			900 ° to 3000 °		
C	**F/C**	**F**	**C**	**F/C**	**F**	**C**	**F.C**	**F**	**C**	**F/C**	**F**	**C**	**F/C**	**F**
–273	–459.4	---	–17.2	1	33.8	16.1	61	141.8	149	300	572	482	900	1652
–268	–450	---	–16.7	2	35.6	16.7	62	143.6	154	310	590	488	910	1670
–262	–440	---	–16.1	3	37.4	17.2	63	145.4	160	620	608	493	920	1688
–257	–430	---	–15.6	4	39.2	17.8	64	147.2	166	330	626	499	930	1706
–251	–420	---	–15.0	5	41.0	18.3	65	149.0	171	340	644	504	940	1724
–246	–410	---	–14.4	6	42.8	18.9	66	150.8	177	350	662	510	950	1742
–240	–400	---	–13.9	7	44.6	19.4	67	152.6	182	360	680	516	960	1760
–234	–390	---	–13.3	8	46.4	20.0	68	154.4	188	370	698	521	970	1778
–229	–380	---	–12.8	9	48.2	20.6	69	156.2	193	380	716	527	980	1796
–223	–370	---	–12.2	10	50.0	21.1	70	158.0	199	390	734	532	990	1814
–218	–360	---	–11.7	11	51.8	21.7	71	159.8	204	400	752	538	1000	1832
–212	–350	---	–11.1	12	53.6	22.2	72	161.6	210	410	770	549	1020	1868
–207	–340	---	–10.6	13	55.4	22.8	73	163.4	216	420	788	560	1040	1904
–201	–330	---	–10.0	14	57.2	23.3	74	165.2	221	430	806	571	1060	1940
–196	–320	---	–9.4	15	59.0	23.9	75	167.0	227	440	824	582	1080	1976
–190	–310	---	–8.9	16	60.8	24.4	76	168.8	232	450	842	593	1100	2012
–184	–300	---	–8.3	17	62.6	25.0	77	170.6	238	460	860	604	1120	2048
–173	–280	---	–7.2	19	66.2	26.1	79	174.2	249	480	896	627	1160	2120
–169	–273	–459.4	–6.7	20	68.0	26.7	80	176.0	254	490	914	638	1180	2156
–168	–270	–454	–6.1	21	69.8	27.2	81	177.8	260	500	932	649	1200	2192
–162	–260	–436	–5.6	22	71.6	27.8	82	179.6	266	510	950	660	1220	2228
–157	–250	–418	–5.0	23	73.4	28.3	83	181.4	271	520	968	671	1240	2264
–151	–240	–400	–4.4	24	75.2	28.9	84	183.2	277	530	986	682	1260	2300
–146	–230	–382	–3.9	25	77.0	29.4	85	185.0	282	540	1004	693	1260	2300
–140	–220	–364	–3.3	26	78.8	30.0	86	186.8	288	550	1022	693	1280	2336
–134	–210	–346	–2.8	27	80.6	30.6	87	188.6	288	550	1022	704	1300	2372
–129	–200	–328	–2.2	28	82.4	31.1	88	190.4	293	560	1040	732	1350	2462
–123	–190	–310	–1.7	29	84.2	31.7	89	192.2	299	570	1058	760	1400	2552
–118	–180	–292	–1.1	30	86.0	32.2	90	194.0	304	580	1076	788	1450	2642
–112	–170	–274	–0.6	31	87.8	32.8	91	195.8	310	590	1094	816	1500	2732
–107	–160	–256	0.0	32	89.6	33.3	92	197.6	316	600	1112	843	1550	2822
–101	–150	–238	0.6	33	91.4	33.9	93	199.4	321	610	1130	871	1600	2912
–96	–140	–220	1.1	34	93.2	34.4	94	201.2	327	620	1148	899	1650	3002
–90	–130	–202	1.7	35	95.0	35.0	95	203.0	332	630	1166	927	1700	3092
–84	–120	–184	2.2	36	96.8	35.6	96	204.8	338	640	1184	954	1750	3182
–79	–110	–166	2.8	37	98.6	36.1	97	206.6	343	650	1202	982	1800	3272
–73	–100	–148	3.3	38	100.4	36.7	98	208.4	349	660	1220	1010	1850	3362
–68	–90	–130	3.9	39	102.2	37.2	99	210.2	354	670	1238	1038	1900	3452
–62	–80	–112	4.4	40	104.0	37.8	100	212.0	360	680	1256	1066	1950	3542
–57	–70	–94	5.0	41	105.8	43	110	230	366	690	1274	1093	2000	3632
–51	–60	–76	5.6	42	107.6	49	120	248	371	700	1292	1121	2050	3722
–46	–50	–58	6.1	43	109.4	54	130	266	377	710	1310	1177	2150	3902
–40	–40	–40	6.7	44	111.2	60	140	284	388	730	1346	1204	2200	3992
–34	–30	–22	7.2	45	113.0	66	150	302	393	740	1364	1232	2250	4082
–29	–20	–4	7.8	46	114.8	71	160	320	399	750	1682	1260	2300	4172
–23	–10	14	8.3	47	116.6	77	170	338	404	760	1400	1288	2350	4262
–17.8	0	32	8.9	48	118.4	82	180	356	410	770	1418	1316	2400	4352
–	–	–	9.4	49	120.2	88	190	374	416	780	1436	1343	2450	4442
–	–	–	10.0	50	122.0	93	200	392	421	790	1454	1371	2500	4532
–	–	–	10.6	51	123.8	99	210	410	427	800	1472	1399	2550	4622
–	–	–	11.1	52	125.6	100	212	413.6	432	810	1490	1427	2600	4712
–	–	–	11.7	53	127.4	104	220	428	438	820	1508	1454	2650	4802
–	–	–	12.2	54	129.2	110	230	446	443	830	1526	1482	2700	4892
–	–	–	12.8	55	131.0	116	240	464	449	840	1544	1510	2750	4982
–	–	–	13.3	56	132.8	121	250	482	454	850	1562	1538	2800	5072
–	–	–	13.9	57	134.6	127	260	500	460	860	1580	1566	2850	5162
–	–	–	14.4	58	136.4	132	270	518	466	870	1598	1593	2900	5252
–	–	–	15.0	59	138.2	138	280	536	471	880	1616	1621	2950	5342
–	–	–	15.6	60	140.0	143	290	554	477	890	1634	1649	3000	5432

(1) *Locate temperature in the middle column. If in degree Celsius, read degree Fahrenheit equivalent in right hand column. Of in degree Fahrenheit, read degree Celsius equivalent in left hand column.*

Appendix D Related Calculations

IDEAL AND REAL SPECIFIC GRAVITY

The real specific gravity of a gas is defined as the ratio of the density of the gas to the density of air while both gas and air are the same pressure and temperature. The fact that the temperature and pressure are not stated results in small variances in specific gravity determination. It has been common practice to determine the specific gravity at near atmospheric pressure and temperature and assume that this specific gravity holds true for all other pressure and temperatures. This assumption neglects compressibility effects.

Compressibility effects lead to defining the term “ideal specific gravity,” which is the ratio of the molecular weight of the gas to the molecular weight of air. As long as no chemical reactions occur which would change the composition (molecular weight) of the gas, the ideal specific gravity remains constant regardless of the pressure and temperature. The molecular weight of air is 28.9644.

The relationship between ideal specific gravity and real specific gravity is established as follows:

$PV = MZRT$

or

Equation D-1. $$PV = \frac{g_c \cdot W \cdot Z \cdot R \cdot T}{g}$$

where $M = \frac{g_c W}{g}$ or $P = \frac{g_c}{g} \cdot \frac{W \cdot Z \cdot R \cdot T}{V}$

Equation D-2. $$P = \Upsilon \cdot \frac{g_c \cdot Z \cdot R \cdot T}{g}$$

where $\Upsilon = \frac{W}{V}$

Since $g = \frac{\rho g}{g_c}$ then Equation D-2 can be written:

Equation D-3. $$P = \frac{\rho g}{g_c} \cdot \frac{Z \cdot R \cdot T}{g} = \rho \cdot Z \cdot R \cdot T$$

Equation D-4. $$\rho = \frac{P}{Z \cdot R \cdot T}$$

Now since the real specific gravity is defined as: $G = \frac{\rho_s}{\rho_a}$

It can be written as $G = \dfrac{\dfrac{\rho_g}{Z_g \cdot R_g \cdot T_g}}{\dfrac{\rho_a}{Z_a \cdot R_a \cdot T_a}}$

or

Equation D-5. $G = \frac{P_g \cdot Z_a \cdot R_a \cdot T_a}{P_a \cdot Z_g \cdot R_g \cdot T_g}$

The gas constant R is defined as the Universal Gas Constant divided by the molecular weight

$$R = \frac{1545.32}{\text{Mol. Wt.}}$$

Equation D-5 can be written as $G = \dfrac{P_g Z_a \dfrac{1545.32}{\text{Molecular Weight of Air}} \cdot T_a}{P_a Z_g \dfrac{1545.32}{\text{Molecular Weight of Gas}} \cdot T_g}$

or

Equation D-6. $G = \frac{P_g \cdot Z_a \cdot T_a}{P_a \cdot Z_g \cdot T_g} \times \frac{\text{Molecular Weight of Gas}}{\text{Molecular Weight of Air}}$

Now since the ideal specific gravity is $G_f = \frac{\text{Molecular Weight of Gas}}{\text{Molecular Weight of Air}}$

Equation D-6 can be written as:

Equation D-7. $G = \frac{P_g \cdot Z_a \cdot T_a}{P_a \cdot Z_g \cdot T_g} \cdot G_f$

Equation D-7 gives the relationship between real specific gravity and ideal specific gravity. As can be seen, if both the gas and air are at the same pressure and temperature, the difference between real and ideal specific gravities depends upon the respective compressibility factors.

The following nomenclature applies to the above equations:

P = Pressure in psia
V = Volume in cubic feet
M = Mass
R = Universal gas Constant = $G = \frac{1545.32}{\text{MolecularWeight}}$
T = temperature in degree Rankine
Z = Compressibility factor (deviation from Boyle's Law)
W = Weight
g_c = Standard gravitational constant, 32.1740 ft/second^2
g = Actual gravitational constant for location
γ = Specific Weight
ρ = Density
G = Real specific gravity
G_f = Ideal specific gravity

DERIVATION OF ANNUBAR PRIMARY ELEMENT FLOW EQUATIONS

The Annubar primary element flow equations listed in Section 2: Annubar Primary Element Flow Calculations are all derived from the hydraulic equation. The hydraulic equation for volumetric flow and mass flow is given on page 1-11. The following shows how the Annubar primary element flow equations are developed from the hydraulic equations.

Problem

Derive the volumetric flow rate in GPM for liquids where the differential pressure is measured in inches of water at 68 °F, the pipe diameter is measured in inches.

Solution

1 Gallon = 231-in.^{3} = 0.13368 ft^3

1 ft^3 = 7.48052 gallons

1-in. water at 68 °F (h_w) at standard gravity = 0.036065 lbf/in.^{2} (psi)

g = local gravity constant

g_c = standard gravity constant, 32.1740 ft/sec^2

ρ = Density lbm/ft^3

dP = $P_1 - P_2$ = differential pressure, lbf/ft^2

D = Diameter of pipe, inch

A = Area of pipe, ft^2

K = Annubar Flow Coefficient

Q = Volumetric Flow, GPM

Beginning with Equation D-8

Equation D-8.

$$Q = K \cdot A\sqrt{\frac{2g(P_1 - P_2)}{\rho}} = K \cdot A\sqrt{2g\frac{dP}{\rho}}$$

The units can be checked as follows:

$$Q = Ft^2\sqrt{\frac{ft\left(\frac{lbf}{ft^2}\right)}{s^2\left(\frac{lbm}{ft^3}\right)}} = \frac{ft^3}{s}$$

NOTE
In the above units conversion, lbf is set equal to lbm. This is only true at standard gravity. The gage location factor described later corrects for locations where the local gravity does not equal the standard gravity.

Substituting units leads to:

$$Q = K\left[\frac{60Sec}{Min}\right]\left[\frac{7.48052Gal}{Ft^3}\right]\left[\frac{Ft^3}{144inch^2}\right]\frac{\pi D^2 in^2}{4}$$

$$\sqrt{\frac{2\left[32.1740\frac{ft}{second^2}\right]h_w\left[0.036065\frac{lbf}{inch^2}\right]144\frac{inch^2}{ft^2}}{\rho\frac{lbm}{ft^3}}}$$

Equation D-9. $$G = GPM = 44.751KD^2\sqrt{\frac{h_w}{\rho}}$$

We can now define the density of any fluid by referencing that fluid to water at 60 °F.

$$\rho = \rho_{60} \cdot G_f$$

where:

ρ_{60} = density of water at 60 °F = 62.3707 lbm/ft^3
g_f = flowing specific gravity of the fluid

$$G = GPM = 44.751 \cdot K \cdot D^2 \cdot \sqrt{\frac{h_w}{62.3707G_f}}$$

Equation D-10. $$GPM = 5.6664 \cdot K \cdot D^2 \cdot \sqrt{\frac{h_w}{G_f}}$$

If the pipe temperature is different from the temperature at which the internal diameter (D) was measured, a factor (F_{AA}) must be applied to account for the area change. With these four factors applied, Equation D-10 becomes:

Equation D-11. $$GPM = 5.6664 \cdot K \cdot D^2 \cdot F_{AA} \cdot \sqrt{\frac{h_w}{G_f}}$$

This equation is identical to the first Annubar primary element flow equation for volume rate of flow in liquids.

Appendix E Flow Turndown and Differential Pressure Requirements

The Annubar primary element is the latest in averaging pitot tube technology and provides the highest accuracy over the widest range or turndown of any flow sensor of its kind. Like any measurement device, it must be applied properly to obtain the performance it is capable of. The definition and application of turndown to a flow system is often misunderstood, but plays a major role in the determination of proper flow system specification.

The concept of turndown and how it applies to an Annubar primary element and DP transmitter will be covered in this appendix.

FLOW TURNDOWN

The ability to measure the flowrate accurately over a wide range is dependent on several factors any of which can impose a limitation that may restrict the operation of a flow measurement system. The flow turndown is the ratio of the highest flowrate expected to be accurately measured by the flow measurement system to the lowest accurate flowrate. This quantity is expressed typically on one line with a colon. For example, if a turndown ratio is 10, the turndown is written “10:1” and is read as ten-to-one. The flow turndown is abbreviated “TD.”

It is important that the actual operating flowrates be estimated as closely as possible prior to buying a flow measurement system. To some flow measurement system users, this seems like a contradiction because they are buying the flow measurement system to tell them exactly that. However, a good estimate of the flowrate can be made by using simple devices and methods. Some problems can be avoided by doing this before buying a flow measurement system.

In many actual field service cases, the flow measurement system was apparently not functioning. The user realized, after a lot of time and effort was expended, that the flow in the pipe was so small relative to the capacity of the measurement system, that the flow could not be measured.

DIFFERENTIAL PRESSURE (DP TURNDOWN)

Because the DP transmitter or secondary meter must cover the range of signals from the flow measurement primary sensor, a “DP turndown”, or TD_h can be defined as the ratio of the highest DP to be measured to the lowest. Due to the square root relationship, the DP turndown will be equal to the square of the flow turndown, or TD:

Equation E-1. $TD_h = [TD]^2$ or $TD = \sqrt{TD_h}$

It is this relationship that restricts the ability of the DP-type flow measurement system to measure wide ranges. For example, for a 10:1 flow turndown, the DP turndown is 100:1. This means that a high flowrate that generates 50-in. water column (50-in. WC) will have a DP of approximately 0.50-in. WC at the minimum flowrate for a 10:1 flow turndown.

ACCURACY AND FLOW TURNDOWN

Before turndown can be determined, the accuracy of the flow system over the range of operation must be determined. In order to extend the turndown capability of this measurement, the accuracy (error) statement must be increased. This is true for most simple types of flow measurement systems.

Another method of improving the accuracy over a higher turndown is to calibrate the actual meter and incorporate this calibration information into the computation of the measured value.

FLOW MEASUREMENT SYSTEM TURNDOWN

Each flow measurement component should be examined for suitability to the application. Although some flow measurement systems can have up to six components, turndown most greatly affects the Annubar sensor and the DP transmitters or meters that read the DP signal. This section will focus on the Annubar and DP transmitters. To calculate true system accuracy and turndown, the performance of all components must be included.

PERCENT OF VALUE AND PERCENT OF FULL SCALE ACCURACY

When determining accuracy of measuring devices, the performance statements must be carefully read. There are two methods of expressing accuracy which are very different and affect the performance of the device over its operating range. It is important to note that error statements and representative curves actually represent the probability that the true error is somewhere within the indicated limit.

A “percent of value” accuracy is the error at a specific value, but in measuring devices typically implies that the device has a consistent error statement over the entire operating range. A “percent of full scale” accuracy relates the error of the device when it is measuring a quantity that represents 100% of the output signal. The actual or value error for a device with this type of accuracy statement is calculated using the following equation.

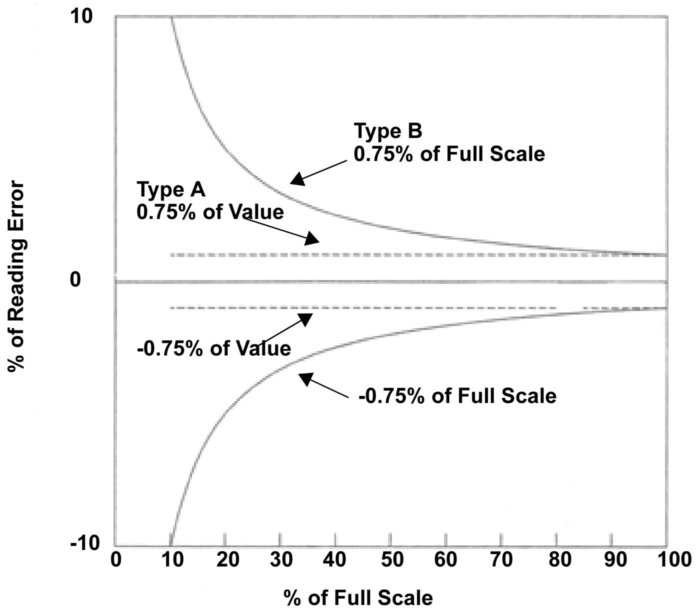
Equation E-2.

$$\%\text{ Value Error} = \frac{\%\text{ Full Scale Error}}{\%\text{ of Scale}} \cdot 100\%$$

The difference between these two methods is not obvious until they are plotted. Figure E-1 shows the two methods for expressing value error. Type “A” shows a 1% of value error, and type “B” a 1% of full scale error statement. Both are plotted over a 10:1 turndown.

DP transmitters and meters are typically “B” devices. Annubars and other primary flow sensor devices are typically “A” type.

Figure E-1. Percent of Value and Full Scale Error



ANNUBAR TURNDOWN LIMITATIONS

The design of the Annubar provides a consistent, linear calibration characteristic over a wide turndown range (see Figure E-1). The limitation at “high end” flows is structural and not functional. The low end limitations are due to practical limitations of the flow lab calibration facilities, the limit of turbulent flow, or the limitation of measuring the low differential pressures.

Turbulent flow exists above pipe Reynolds numbers from 4000 to 13000. Turbulent flow characterizes the velocity profile and exists in nearly all industrial pipe and ducting. Annubar sensors are calibrated for turbulent flows only.

The functional limitations for low flows are summarized in Table E-1. All calibration data for each sensor was used to determine a minimum “rod” Reynolds number, Rd. These limitations may be above or below the minimum practical differential pressure signal.

Other types of DP flow sensors such as orifice plates and venturi tubes have similar limitations, but are slightly more Reynolds number dependent which reduces their turndown at the lower ranges of their calibrations.

Table E-1. Annubar Minimum Functional Velocity and DP for Typical Process Fluids

		Minimum DP, in. H_2O (mm H_2O)		
Sensor	Minimum Rd	Water	Gas	Steam
1	6000	0.5 (12.7)	0.25 (6.35)	1 (25.4)
2	12500	0.5 (12.7)	0.25 (6.35)	1.5 (38.1)
3	25000	0.5 (12.7)	0.25 (6.35)	2 (50.8)

MINIMUM MEASURABLE DIFFERENTIAL PRESSURE

The low end limitations, due to the Annubar primary element calibration, may also be due to the ability to measure the differential pressure. This limit may be reached before the functional limit explained above and typically occurs in gas and low pressure stream flows.

The minimum measurable DP for the Annubar is based on the type of fluid measured and for liquids and gases is due to the level of DP fluctuations or noise in the signal.

For steam flows, the minimum DP is due to the method of DP transmitter to Annubar sensor hookup. The DP signal is conveyed through two water (condensate) legs. An additional error in measurement will occur if these water legs are not equal in height. Because of this inherent error, the minimum recommended DP must be higher.

PUTTING IT ALL TOGETHER: THE FLOW SYSTEM TURNDOWN

The flow system (flow primary or Annubar primary and secondary transmitter or meter) performance is determined over the selected operating range. Because the DP transmitter or meter is a type “B” accuracy device, the system accuracy will be type “B” or the error will increase at the lower scale. The combined error over the selected operating range is determined by using the “square root of the sum of the squares” rule, or

Equation E-3.

$$\%\text{ System Error} = \sqrt{E_p^2 + E_s^2}$$

where:

E_p = percent error in flow due to primary
E_s = percent error in flow due to secondary

At this point, things get a little complicated because each device contributes errors to the calculated flowrate through its relationship in the flow equation. An Annubar or other flow primary sensor will contribute directly to the error in flow, whereas a secondary device (DP transmitter or meter) contributes to the error in DP which is the square of the error in flow. For a DP transmitter or meter, the contribution to the flow calculation error is:

Equation E-4.

$$\%E_f(DP) = \pm\left[\sqrt{1 + \frac{\%E_{DP}}{100}} - 1\right] \cdot 100\,\%$$

where:

$\%E_f(DP)$ = percent error in flowrate due to DP
$\%E_{DP}$ = percent error in DP

The percent error in DP will depend on the percent scale, so that:

Equation E-5.

$$\%E_f(DP) = \pm\left[\sqrt{1+\frac{\%E_{DP}}{\%DP}}-1\right]\cdot 100\,\%$$

where:

$\%E_{FS}$ = percent of full scale error (accuracy) of the DP transmitter
%DP = percent of scale at which the DP transmitter is operating

Since the largest contributor to system error is due to the DP transmitter at the minimum scale, the turndown that is possible for the system will be determined by how large of an error statement can be tolerated at the minimum flowrate. This relationship can be turned around so that the error at minimum scale is calculated for the desired flow turndown. From Equation E-1

$$TD = \sqrt{TD_h} = \sqrt{\frac{100}{\%DP_{min}}} \qquad \text{or}$$

$$\%\,DP_{min} = \frac{100}{TD^2}$$

EquationE-6.

When Equation E-6 is combined with Equation E-5, the percent error in flow due to the DP transmitter or meter at minimum scale is determined

Equation E-7.

$$\%\ E_f(DP) = \pm\left[\sqrt{1+\frac{\%E_{DP}}{100}(TD)^2}-1\right]\cdot 100\ \%$$

Equation E-7 must be put into Equation E-3 to determine the error in flow at the minimum scale for the desired flow turndown. This relationship should be the deciding factor when determining the available flow turndown for any DP type flow measurement system.

Example

A Sensor Size 2 485 Annubar primary element and a DP transmitter are to be used to measure water flow (μ = 1 cP) between 3000 and 1000 GPM in a 10-in. sch 40 (10.02-in. I.D. line). The DP at maximum flow is approximately 84.02-in.H_2O. If the transmitter has an reference accuracy of 0.04% at that span, determine the error in flowrate due to the Annubar flow sensor and DP transmitter at 1000 GPM.

Solution

Calculate DP at minimum flowrate

$$TD_h = TD^2 \qquad \textit{(from Equation E-1)}$$

$$TD = \frac{3000}{1000} = 3$$

$$TD_h = 9(3)$$

$$h_{min} = \frac{h_{max}}{TD_h} = \frac{84.02}{9} = 9.34\text{ -in.}H_2O$$

Now, the minimum Reynolds number is this application must be checked against the minimum allowable Reynolds number per Table E-1.

$$R_D = \frac{3160\cdot GPM\cdot G}{D\cdot\mu_{cp}} = \frac{3160\cdot 1000\cdot 1}{10.02\cdot 1} = 315369$$

This value exceeds the minimum Reynolds number of 12500 from Table E-1 so the discharge coefficient uncertainty of the Annubar will be the published 0.75%.

Calculated Percent System Error:

$$\%\mathrm{SystemError} = \sqrt{E_p{}^2 + E_s{}^2} \qquad \textit{(from Equation E-5)}$$

where:

$E_p = 0.75\%$

$$E_s = \%\ E_f(DP) = \left(\sqrt{1 + \frac{\%\ E_{fs}}{100}TD^2} - 1\right) \cdot 100 = \left(\sqrt{1 + \frac{0.04\,\%}{100}3^2} - 1\right) \cdot 100 = 0.36\ \ \%$$

so:

$$\%\mathrm{SystemError} = \sqrt{0.75^2 + 0.36^2} = 0.832\,\%$$

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Appendix G Variable List

Variable	Description	Unit
V	Velocity	ft/sec
W	Mass flow rate	lbm/sec
R_D	Pipe Reynolds #	Dimensionless
R_d	Rod Reynolds #	Dimensionless
D	Pipe diameter	in.
d	Probe width	in.
ρ	Density	lb/ft3
μ	Absolute viscosity	cP
Q	Volumetric flow rate	ft3/sec
G_f	Specific gravity of flowing fluid	Dimensionless
P_f	Pressure, flowing	psia
A	Area	in2
G	Specific gravity	Dimensionless
h_w	Head or differential pressure	in H2O at 60 °F
h	Head	ft. of flowing fluid
B	Blockage	Dimensionless
Y_A	Gas Expansion Factor	Dimensionless
F_{pb}	Base pressure factor	Dimensionless
F_{tb}	Base temperature factor	Dimensionless
F_{tf}	Flowing temperature factor	Dimensionless
F_g	Specific gravity factor	Dimensionless
F_{pv}	Supercompressability factor	
F_m	Manometer factors	
F_{AA}	Thermal expansion factor	
F_L	Gage location factor	Dimensionless
Υ	Ratio of Specific Heats	Dimensionless
P	Pressure	psia
g	Local gravitational constant	ft/s2
g_c	Standard gravitational constant	ft/s2
υ	Kinematic viscosity	ft/s2
υ_{cs}	Kinematic viscosity	centistokes
D_{ft}	Pipe diameter	ft
	Flowing density	lbm.ft3
Q_s	Volumetric flowrate at standard conditions	SCFM
Q_A	Volumetric flowrate at actual conditions	ACFM
G_s	Specific gravity at standard conditions	Dimensionless
F_{NA}	Units conversion factor	Dimensionless
F_{RA}	Reynolds number factor	
T	Temperature	°F
T_f	Flowing temperature	°F
K	Flow coefficient	Dimensionless
C^1	Calculations constant	Dimensionless
μ_{cP}	Absolute viscosity	centiPoise

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