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Annubar® Flow Handbook

Fluid Flow Measurement Using

Annubar Flow Sensors

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INTRODUCTION

The Engineering Department of Dieterich Standard has prepared this book in order to bring together all the information necessary to accurately measure fluid flow using the Annubar Flow Sensor.

Fluid flow measurement involves many variables. Fluid properties which 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 our 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 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, you may wish to contact Dieterich Standard, Customer Service Department, for assistance.

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Chapter 1

Fluid Flow Theory

NOTES

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 descpriptions of the most common properties are given below.

Pressure

The pressure is the force exerted by a fluid per unit area. In the English system of units, the most common unit of pressure measurement is pounds force per square inch (lbf/in^2 or psi).

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). 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 show graphically in Fig. 1.1

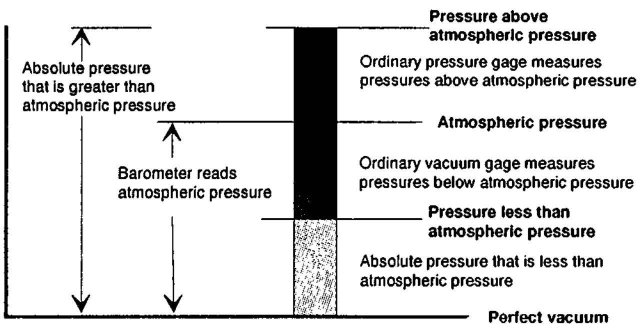


Figure 1.1

Absolute zero pressure, or a perfect vacuum, would be obtained 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 is 14.696 psia, or 760 millimeters of mercury at 0°C. 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

Altitude in Feet	Atmospheric Pressure in psia
0	14.696
500	14.433
1,000	14.173
1,500	13.917
2,000	13.664
2,500	13.416
3,000	13.171
3,500	12.930
4,000	12.692
4,500	12.458
5,000	12.227
6,000	11.777
7,000	11.340
8,000	10.916
9,000	10.505
10,000	10.106
15,000	8.293
20,000	6.753

Gage pressure is always measured above atmospheric pressure. To obtain absolute pressure, the atmospheric pressure must be added to the gage pressure.

Vacuum pressure is usually expressed in inches of mercury below atmospheric pressure. To obtain absolute pressure, the vacuum pressure must be subtracted from the atmospheric perssure.

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, 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)
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 manometer which contains water, mercury, alcohol, oil, or other fluids. A simple manometer is shown in Fig. 1.2. The differential pressure can be calculated by the relation:

$\Delta P = \rho h \, g/g_c$ ......

..... 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
g/g_c = the ratio of the local to standard gravitational acceleration constants.

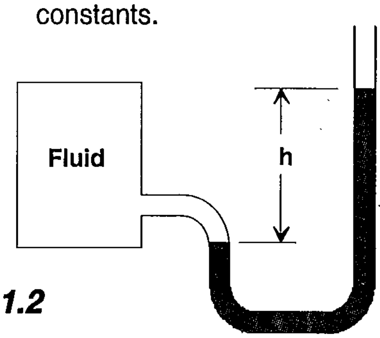


Figure 1.2

For most applications, the ratio g/g_c can be assumed to be unity. For precise calculaations, the ration g/g_c can be found in Table 2.11. (Page 2-22)

Commercial instuments used for indicating or recording the differential pressure operate using various principles; such as "dry" or bellows-type manometer, variable reluctance, capacitance, or strain-gage. These types of instruments generally give the true differential pressure without the need for additional corrections. However, liquid filled manometers are subject to additional corrections. For a complete discussion of these corrections, see Appendix C.

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. The most common temperature scale used in this country is the Fahrenheit. This temperature scale is defined such that boiling water at standard atmospheric pressure is 212°F and the freezing temperature of water is 32°F.

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 temperature". According to the kinetic theory, all molecular activity ceases at absolute zero temperature.

Absolute zero temperature is -459.69°F.

Thus: °R = °F + 459.69
where, °R = degrees Rankine
°F = degrees Fahrenheit

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. In the English System of units, density is usually expressed in pounds-mass-per cubic foot (lbm/ft^3). With this system of units, the density of a substance does not depend on the location of the substance.

Specific Weight is defined as the weight, due to the gravitational pull of the earth, of a substance per unit volume. In the English System of units, specific weight is expressed in pounds-force per cubic foot (lbm/ft^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/sec^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 60°F is used as the reference substance. The density of distilled water at 60°F is 62.3707 lbm/ft^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 weighings 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 is specific gravities, in degrees Baume or in degrees API (American Petroleum Institute). The relations between specific gravity and degrees Baume are given by the following formulas:

1. For liquids heavier than water:

$$DegB = 145 - \left(\frac{145}{Sp.Gr.60\,/\,60°F} \right)$$

2. For liquids lighter than water:

$$DegB = \left(\frac{140}{Sp.Gr.60\,/\,60°F} \right) - 130$$

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

$$DegAPI = \left(\frac{141.5}{Sp.Gr.60\,/\,60°F} \right) - 131.5$$

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 of real and ideal specific gravities, see Appendix C.

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 another particle. It is the resistance to a change of velocity between adjacent particles. Molasses is generally known as a viscous liquid. Its viscosity is greater than that of water. The viscosity of gasoline is less than that of water. 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 should have units of lbm/ft-sec. However, it has become common practice, in this country, 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} (mu).

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

Annubar is a head-type meter and requires fluid to convey the D.P. 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.

$$\nu = \mu/\rho$$

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 which are cm²/sec.

$$1 \text{ (stoke)} = 100 \text{ (centistokes)} \quad \frac{cm^2}{sec}$$

$$\nu \text{ (centistoke)} = \frac{\nu \text{ (centipoise)}}{\rho(gm/cm^3)} =$$

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

$$[\nu\,(centistoke)] \times [0.00001076] = \nu\left(\frac{ft^2}{sec}\right)$$

NATURE OF FLUID FLOW IN PIPES

FLOW PATTERNS

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.

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.

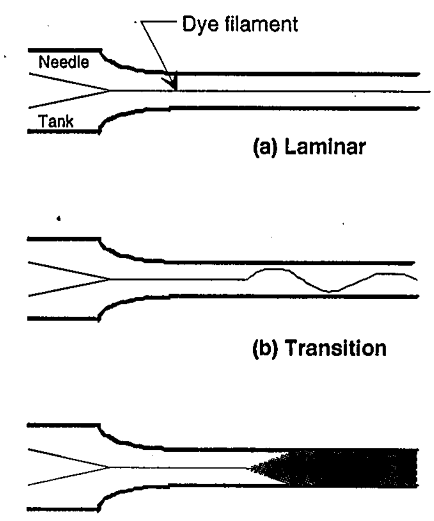


Figure 1.3

Laminar flow occurs when the velocity is small and the dye remains in a straight line as shown in Figure 1.3(a).

Transition flow occurs at a slightly higher velocity than laminar flow. The dye does not remain in a straight line, but then it does not spread throughout the pipe as is shown in Figure 1.3(b).

Turbulent flow occurs at velocities above transition flow. The dye spreads throughout the pipe as shown in Figure 1.3(c). 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.

$$w = \rho A V$$

$$\left(\frac{lbm}{sec}\right) = \left(\frac{lbm}{ft^3}\right)\left(ft^2\right)\left(\frac{ft}{sec}\right)$$

This equation states that for steady state flow, the mass rate of flow (lbm/sec) at any point in the pipeline can be calculated from the product of the density (lbm/ft³), the cross-sectional area of the pipe (ft²), and the average velocity (ft/sec).

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 in feet (D), the density in lbm/cu-ft (ρ), the viscosity in lbm/ft-sec (μ), and the velocity in ft/sec (v) of the fluid.

$$R_D = \frac{Dv_\rho}{\mu} \quad \frac{(ft)\,(ft/sec)\left(lbm/ft^3\right)}{lbm/ft-sec}$$

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.

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, for this reason, 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 $1/\nu$ giving:

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

Also, the volume rate of flow (ft³/sec) is $Q = \pi(D^2/4)V$, thus another alternate combination for Reynolds Number is:

$$R_D = \frac{4Q\rho}{\pi D\mu}$$

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

$$R_D = \frac{4W}{\pi D\mu}$$

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

$$R_D = \frac{1895W}{D\mu_{cp}}$$

From common usage and for purposes of this handbook, the pipe diameter (D) will be given in inches and the viscosity (μ_{cp}) will be given in centipoise. Using these values, the pipe Reynolds Number (R_D) can be calculated by any of the following equations:

Liquid:

$$R_D = \frac{3160 \times GPM \times G_f}{D \times \mu_{cp}}$$

Gas:

$$R_D = \frac{0.4831 \times SCFH \times G}{D \times \mu_{cp}}$$

Liquid, Gas and Steam:

$$R_D = \frac{6.316 \times lbm/hr}{D \times \mu_{cp}}$$

where,

- ACFH = flowrate of fluid in actual cubic feet per hour
- G = specific gravity of flowing gas, air = 1.0
- G_f = specific gravity of flowing liquid. Ratio of the density of flowing liquid to the density of water at 60°F which is 62.3703 lbm/cu-ft.
- GPM = U.S. gallons per minute
- lbm/hr = flowrate of fluid in pounds mass per hour
- SCFH = flowrate of gas in standard cubic feet per hour at 14.73 psia and 60°F
- ρ_f = density of flowing fluid in lbm/cubic foot

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.

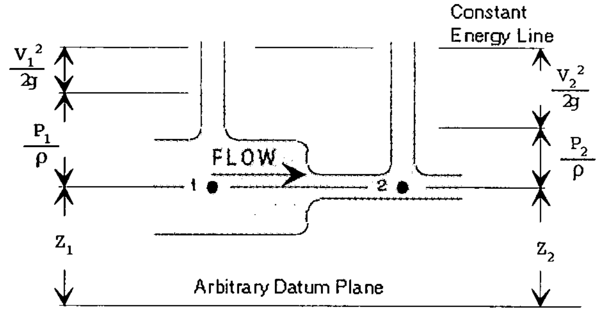


Figure 1.4

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:

$$\frac{V_1^2}{2g} + \frac{P_1}{\rho} = \frac{V_2^2}{2g} + \frac{P_2}{\rho} \tag{1.1}$$

where,

- V = velocity, ft/sec
- g = gravitation constant, ft/sec²
- P = pressure, lb^f/ft^2
- lbm/hr = flowrate of fluid in pounds mass per hour
- ρ = density, lbm/ft³

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.

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2 \tag{1.2}$$

... since the flow is incompressible ($\rho_1 = \rho_2$), equation (1.2) reduces to:

$$A_1 V_1 = A_2 V_2 \tag{1.3}$$

... solving for V_1 in equation (1.3):

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

... and substituting into equation (1.1):

$$\frac{1}{2g}\left(\frac{A_2V_2}{A_1}\right)^2+\frac{P_1}{\rho}=\frac{V_2^2}{2g}+\frac{P^2}{\rho}$$

$$\frac{V_2^2}{2g}-\frac{1}{2g}\left(\frac{A_2V_2}{A_1}\right)^2=\frac{P_1}{\rho}-\frac{P_2}{\rho}$$

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

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

$$V_2=\sqrt{2g\frac{(P_1-P_2)}{\rho}}\sqrt{\frac{1}{1-\left(\frac{A_2}{A_1}\right)^2}} \qquad \textbf{(1.4)}$$

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

$$W_{theo}=\rho A_2V_2=A_2\sqrt{2g\rho(P_1-P_2)}\sqrt{\frac{1}{1-\left(\frac{A_2}{A_1}\right)^2}} \qquad \textbf{(1.5)}$$

The theoretical equation for volumetric flow is:

$$W_{theo}=A_2V_2=A_2\sqrt{\frac{2g(P_1-P_2)}{\rho}}\sqrt{\frac{1}{1-\left(\frac{A_2}{A_1}\right)^2}} \qquad \textbf{(1.6)}$$

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

$$C=\frac{W_{actual}}{W_{theoretical}}=\frac{Q_{actual}}{Q_{theoretical}} \qquad \textbf{(1.7)}$$

Therefore, the actual volumetric flow for liquids is:

$$Q_{actual}=Q=A_2C\sqrt{\frac{2g(P_1-P_2)}{\rho}}\sqrt{\frac{1}{1-\left(\frac{A_2}{A_1}\right)^2}} \qquad \textbf{(1.8)}$$

By defining the flow coefficient K of an Annubar as:

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

the volumetric flow (equation 1.8) reduces to:

$$Q=KA_2\sqrt{\frac{2g(P_1-P_2)}{\rho}} \qquad \textbf{(1.9)}$$

In a like manner, the mass rate of flow (equation 1.5) reduces to:

$$W=KA_2\sqrt{2g\rho(P_1-P_2)} \qquad \textbf{(1.10)}$$

By using consistent units, equation (1.9) can be checked as follows:

$$Q=ft^2\sqrt{\frac{ft\ (lbf/ft^2)}{\sec^2 (lbf/ft^3)}}=\frac{ft^3}{\sec}$$

Likewise, equation (1.10) is:

$$W=ft^2\sqrt{\frac{ft}{\sec^2}\frac{lbm}{ft^3}\frac{lbf}{ft^2}}=\frac{lbm}{\sec}$$

Note: In the above units conversion, lbf is set equal to lbm. This is only true at standard gravity (g_c = 32.174 ft/sec^2). 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 ammumption leads to the historical name "headtype meters".

By using the following:

$$h=\frac{lbf/ft^2}{lbm/ft^3}=ft$$

where h is feet (head) of flowing fluid, equation (1.9) can be written as:

$$Q=KA\sqrt{2g\frac{(lbf/ft^2)}{(lbm/ft^3)}}=KA\sqrt{2gh}$$

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

ACTUAL AND STANDARD VOLUMETRIC FLOWRATE FOR GASES

The most common unit of volumetic measurement in the United States is the cubic foot. To be sure, 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 above, the volumetric flow (Q) can be calculated in ft^3/sec. 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 1.9, and that the equation shows that flowrate is 5 ft^3/sec. 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 when it fills the cubic foot space. 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 20 psig and 40°F is flowing at 50 actual ft^3/sec; it is not obvious that the same amount of matter (mass) would flow through a pipeline at 750 psia and 102.5°F if the flowrate was 1.5 actual ft^3/sec.

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 flowrate measurement is of a gas that would be contained in a one cubic foot enclosure if the pressure was 14.73 psia and the temperature was 60°F.

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 in 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 $Q_1 = V_1/t$ and $Q_2 = V_2/t$ 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 (14.73 psia and 60°F), the flowrate Q_1 is the standard volumetric flowrate Q_s.

$$\frac{14.73 Q_s}{(460+60)} = \frac{P_2 Q_2}{T_2}$$

This equation allows the standard volumetric flowrate (Q_s) to be calculated from any actual volumetric flowrate (Q_2) where the pressure and temparature are known.

$$Q_s = \frac{P_2}{14.73} \times \frac{(460+60)}{T_2} \times Q_2$$

In an example above, 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=50 ft.^{3}/sec
P=20psia
T=40°F

$$Q_s = \frac{20}{14.73} \times \frac{(460+60)}{(460+40)} \times 50$$

$$Q_s = 70.6 \text{ standard } ft.^3/\text{sec}$$

Flowrate #2: Q=1.5 ft.3/sec
P=750psia
T=102.5°F

$$Q_s = \frac{750}{14.73} \times \frac{(460+60)}{(460+102.5)} \times 1.5$$

$$Q_s = 70.6 \text{ standard } ft.^3/\text{sec}$$

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:

$$\frac{P_1 V_1}{Z_1 T_1} = \frac{P_2 V_2}{Z_2 T_2}$$

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

$$Q_s = \frac{P_2}{14.73} \times \frac{(460+60)}{T_2} \times \frac{Z_b}{Z_2} \times Q_2$$

Where, Z_b = compressibility factor at base or standard conditions and is generally considered to be unity (Zb=1.000).
Z_2 = compressibility factor at P_2 and T_2.

More discussion on compressibility factors can be found in section C-4 under the ideal and real specific gravity heading.

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. The liquid volumetric flow equation (Eq 2.1) of Section 2 of this handbook gives the flowrate 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 flow, 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 accomlished simply by multiplying by 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 water at 60°F, both of the above conversions are identical.

Chapter 2

Annubar Flow Calculations

NOTES

ANNUBAR FLOW EQUATIONS

The Annubar flow equations are all derived from the hydraulic equations which are shown in equations 1.9 and 1.10 of Chapter 1. For a detailed example of a derivation of an Annubar equation, see Appendix C.

Equation No 2.1: Volume rate of flow - Liquids (Actual Conditions)

$$Q_A = C'\sqrt{h_w} \quad OR \quad h_w = \left[\frac{Q_A}{C'}\right]^2$$

Where, $C' = F_{NA}KD^2F_{RA}F_MF_{AA}F_1\sqrt{\frac{1}{G_f}}$

Note: For description of standard volumetric flow equations, see page 1-10.

Equation No 2.2: Mass rate of flow - Liquids

$$W = C'\sqrt{h_w} \quad OR \quad h_w = \left[\frac{W}{C'}\right]^2$$

Where, $C' = F_{NA}KD^2F_{RA}F_MF_{AA}F_1\sqrt{\rho_f}$

Equation No 2.3: Mass rate of flow - Gas and Steam

$$W = C'\sqrt{h_w} \quad OR \quad h_w = \left[\frac{W}{C'}\right]^2$$

Where, $C' = F_{NA}KD^2F_{RA}F_MF_{AA}F_1\sqrt{\rho_f}$

Equation No 2.4: Volume rate of flow - Gas (Standard Conditions)

$$Q_S = C'\sqrt{h_wP_f} \quad OR \quad h_w = \frac{1}{P_f}\left[\frac{Q_S}{C}\right]^2$$

Where, $C' = F_{NA}KD^2F_{RA}Y_AF_{pb}F_{tb}F_{tf}F_gF_{pv}F_mF_{AA}F_1$

Note: For Annubar flow equations for use with temperature integrators, see page C-6.

Equation No 2.5: Volume rate of flow - Gas (Actual Conditions)

$$Q_A = C'\sqrt{h_w} \quad OR \quad h_w = \left[\frac{Q_A}{C'}\right]^2$$

Where, $C' = F_{NA}KD^2F_{RA}Y_AF_MF_{AA}F_1\sqrt{\frac{1}{\rho_f}}$

For a detailed description of each term in the above equations, see nomenclature on pages 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 workpads. 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 on page 2-23.

Note: The Diamond II Annubar needs no correction for the Reynolds Number. For this reason, set the value of F_{RA} = 1.000, or remove this factor from the flow equation.

Equation Number 2.1 — **LIQUID ..... Volume Rate of Flow (Actual Conditions)**

Rate of Flow	Unit Conversion Factor	Annubar Flow Coefficient (Table 2.1)	Internal Pipe Diameter	Reynolds Number Factor*	Manometer Factor (Table 2.9)	Thermal Expansion Factor (Table 2.10)	Location Factor (Table 2.11)	Flowing Specific Gravity	Differential Pressure ("H_2O at 68°F)
	Annubar Flow Constant C'								
Q_A =	F_{NA} x	K x	D^2 x	F_{RA} x	F_M x	F_{AA} x	F_1 x	$\sqrt{1/G_f}$ x	$\sqrt{h_W}$
GPM	5.6664		$(in)^2$						
GPH	339.99		$(in)^2$						
GPD	8159.7		$(in)^2$						
BPH (42 gal)	8.0949		$(in)^2$						
BPD (42 gal)	194.28		$(in)^2$						
Ft^3/min	.75749		$(in)^2$						
Imp. GPM	4.7183		$(in)^2$						

To solve for differential pressure : $h_W = \left[\frac{Q_A}{C'}\right]^2$

Equation Number 2.2 — **LIQUID ..... Mass Rate of Flow**

Rate of Flow	Unit Conversion Factor	Annubar Flow Coefficient (Table 2.1)	Internal Pipe Diameter	Reynolds Number Factor*	Manometer Factor (Table 2.9)	Thermal Expansion Factor (Table 2.10)	Location Factor (Table 2.11)	Flowing Density (lbm/ft^3)	Differential Pressure ("H_2O at 68°F)
	Annubar Flow Constant C'								
W =	F_{NA} x	K x	D^2 x	F_{RA} x	F_M x	F_{AA} x	F_1 x	$\sqrt{\rho_f}$ x	$\sqrt{h_W}$
lbm/Hr	358.94		$(in)^2$						
lbm/Min	5.9823		$(in)^2$						
lbm/Sec	.09970		$(in)^2$						

To solve for differential pressure : $h_W = \left[\frac{W}{C'}\right]^2$

Equation Number 2.3 — Gas and Steam ..... Mass Rate of Flow

Rate of Flow	Unit Conversion Factor	Annubar Flow Coefficient (Table 2.1)	Internal Pipe Diameter	Reynolds Number Factor*	Annubar Expansion Factor (Table 2.3)	Manometer Factor (Table 2.9)	Thermal Expansion Factor (Table 2.10)	Location Factor (Table 2.11)	Flowing Density (lbm/Ft³)	Differential Pressure ("H_2O at 68°F)
	Annubar Flow Constant C'									
W =	F_{NA} x	K x	D^2 x	F_{RA} x	Y_A x	F_M x	F_{AA} x	F_1 x	$\sqrt{\rho_f}$ x	$\sqrt{h_W}$
lbm/Hr	358.94		$(in)^2$							
lbm/Min	5.9823		$(in)^2$							
lbm/Sec	.09970		$(in)^2$							

To solve for differential pressure : $h_W = \left[\frac{W}{C'}\right]^2$

Equation Number 2.4 — Gas ..... Volume Rate of Flow (Standard Conditions)

Rate of Flow	Unit Conversion Factor	Annubar Flow Coefficient (Table 2.1)	Internal Pipe Diameter	Reynolds Number Factor*	Annubar Expansion Factor (Table 2.3)	Pressure Base Factor (Table 2.4)	Temp Base Factor (Table 2.5)	Flowing Temp Factor (Table 2.6)	Specific Gravity Factor (Table 2.7)	Super-Compress Factor (Table 2.8)	Manometer Factor (Table 2.9)	Thermal Expansion Factor (Table 2.10)	Location Factor (Table 2.11)	Differential Pressure ("H^2O at 68°F)	Flowing Pressure (PSIA)	
	Annubar Flow Constant C'															
Q_S =	F_{NA} x	K x	D^2 x	F_{RA} x	Y_A x	F_{pb} x	F_{tb} x	F_{tf} x	F_g x	F_{pv} x	F_M x	F_{AA} x	F_1 x	$\sqrt{h_W}$ x	$\sqrt{P_f}$	
SCFM	5.6362		$(in)^2$													
SCFH	338.17		$(in)^2$													
SCFD	8116.1		$(in)^2$													

To solve for differential pressure : $h_W = \frac{1}{P_f}\left[\frac{Q_S}{C}\right]^2$

Equation Number 2.5 — Gas and Steam ..... Mass Rate of Flow

Rate of Flow	Unit Conversion Factor	Annubar Flow Coefficient (Table 2.1)	Internal Pipe Diameter	Reynolds Number Factor*	Annubar Expansion Factor (Table 2.3)	Manometer Factor (Table 2.9)	Thermal Expansion Factor (Table 2.10)	Location Factor (Table 2.11)	Flowing Density (lbm/Ft³)	Differential Pressure ("H_2O at 68°F)
	Annubar Flow Constant C'									
Q_A =	F_{NA} x	K x	D^2 x	F_{RA} x	Y_A x	F_M x	F_{AA} x	F_1 x	$\sqrt{\frac{1}{\rho_f}}$ x	$\sqrt{h_W}$
ACFM	5.9823		$(in)^2$							
ACFH	358.94		$(in)^2$							
ACFD	8614.5		$(in)^2$							

* Not required for Diamond Annubar

To solve for differential pressure : $h_W = \left[\frac{Q_A}{C'}\right]^2$

Nomenclature For Flow Equations

D = Internal diameter of pipe, inches

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 Annubars mounted in carbon steel pipe, F_{AA} = 1.0000 for temperatures between 31° and 106°F. See Table 2.10

F_g = Specific Gravity Factor. This factor corrects the flow equation whenever the gas is not air. The factor can be found in Table 2.7 or 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 page 1.4 and Appendix C.

F_l = Gage Location Factor. The gage location factor is included in order to adjust for locations other than 45° latitude and sea level. This adjustment accounts for the effect of changes in the acceleration of gravity from the value of 32.174 ft/sec^2 assumed in the basic equations. See Table 2.11.

F_m = Manometer Factor. The manometer factor is used only with liquid filled manometers to correct for the weight of the unbalanced column of fluid above the reference fluid in the manometer. For mercury filled manometers measuring gaseous fluids, use Table 2.9.

Historically, this correction has been known as the "wet-leg" or "air-leg" correction. The magnitude of the correction factor depends upon the densities of the fluids involved. For a complete description of this factor, see Appendix C.

For "dry-bellows" type differential pressure instrumentation, F_m = 1.000.

F_{NA} = Units Conversion Factor. This factor is used to convert the flow rate to the desired or wanted set of units. Appendix C 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.

If a different pressure base is required, the pressure base factor can be found in Table 2.4 or calculated as follows:

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

P_{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 2.8 (a) 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}. Table 2.8 (b) of this handbook gives an abbreviated listing of the supercompressibility factors for natural gas.

F_{RA} = Reynolds Number Factor. The Reynolds Number Factor takes into account the changes in the flow coefficient over the operating range. For some types of meters, this factor is significant, and must be applied for the meter to operate within its accuracy tolerance.

The Diamond II Annubar exhibits little or no variation of the flow coefficient with Reynolds Number, and does not require an adjustment.

Set the value of F_{RA} = 1.000 for all flow calculations for Diamond II Annubars.

F_{tb} = Temperature Base Factor. The temperature base factors are calculated to give gas volumes at a base temperature of 60°F (520°R).

If a different temperature base is required, Table 2.5 can be used or the factor can be calculated as:

$$F_{tb} = \frac{\text{temperature base } (^\circ\text{F}) + 460}{520}$$

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 is 60°F (520°R). If measurement is made at any other flowing temperature, then the flowing temperature factor must be applied. The factor can be found in Table 2.6 or calculated as:

$$F_{tf} = \sqrt{\frac{520}{\text{flowing temperature } (^\circ\text{F}) + 460}}$$

G_v = Specific Gravity of Flowing Liquid. Ratio of the density of the flowing fluid to the density of water at 60°F which is 62.3707 lbm/ft³. See Appendix A for specific gravities of various liquids.

h_w = Differential pressure as measured by the Annubar. 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/sec²).

$$h_w = \text{inches of water @ 68°F}$$

K = Flow Coefficient. Table 2.1 lists the flow coefficient for various type Annubars as it is related to the internal pipe diameter. The flow coeffients that are listed are the coefficients that exist at the base Reynolds Number. The base Reynolds number is equivalent to 60°F water flowing at a velocity of 10 feet/second. The base Reynolds Number can be calculated as:

$$R_B = 68869\ (D)$$

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.

Q_A = Actual Volumetric Flow Rate. This term is the flow rate of the fluid passing the Annubar in actual volume units per unit of time. Examples are actual cubic feet per hour (ACFH), GPM, etc.

Q_S = Standard Volumetric Flow Rate. This term is the flow rate of the fluid passing the Annubar 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 when it fills a cubic foot. 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 if the flowing pressure and temperature were equal to the base pressure and temperature. For this handbook, the base pressure is 14.73 psia and the base temperature is 60°F (520°R).

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

Y_A = Expansion Factor. When a gas flows around an Annubar, 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 temparature difference between the upstream and downstream pressure ports of the Annubar. 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.

For gases with a specific heat ratio of 1.4, Table 2.3 (a) should be used. Examples of gases with a specific heat ratio of 1.4 are air CO, H_2, NO, N_2, and O_2.

For gases with a specific heat ratio of 1.3, Table 2.3 (b) should be used. 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.

ρ_f = Flowing Density. For this handbook, the densities are expressed in lbm/ft^3. Appendix A gives densities of various fluids.

TABLE 2.1
Annubar Diamond II Flow Coefficient, K

This table shows the flow coefficients for various type Annubars with varying internal line or pipe diameter. Linear interpolation may be used for pipe sizes not listed.

Type 10

Nom. Pipe Size	Schedule	Pipe ID	K
1/2"	40	0.622	.4265
3/4"	40	0.824	.5067
1"	80	0.957	.5547
	40	1.049	
1-1/4"	80	1.278	.5870
	40	1.380	
1-1/2"	80	1.500	.6030
	40	1.610	
2"	80	1.939	.6197
	40	2.067	

Type 15/16

Nom. Pipe Size	Schedule	Pipe ID	K
2"	XX-STG	1.503	.5627
	160	1.689	.5746
	80	1.939	.5865
	-	2.000	.5888
	40	2.067	.5912
2-1/2"	XX-STG	1.771	.5789
	160	2.125	.5932
	80	2.323	.5990
	40	2.469	.6026
	-	2.500	.6033
3"	XX-STG	2.300	.5984
	160	2.624	.6059
	80	2.900	.6109
	-	3.000	.6124
	40	3.068	.6134
3-1/2"	XX-STG	2.728	.6079
	80	3.364	.6172
	-	3.500	.6187
	40	3.548	.6192
4"	XX-STG	3.152	.6146
	160	3.438	.6180
	80	3.826	.6218
	-	4.000	.6233
	40	4.026	.6235
5"	XX-STG	4.063	.6237
	160	4.313	.6255
	80	4.813	.6285
	-	5.000	.6295
	40	5.047	.6297

Type 25/26

Nom. Pipe Size	Schedule	Pipe ID	K
4"	XX-STG	3.152	.5480
	80	3.826	.5704
	-	4.000	.5747
	40	4.026	.5753
5"	XX-STG	4.063	.5762
	160	4.313	.5814
	80	4.813	.5901
	-	5.000	.5928
	40	5.047	.5934
6"	XX-STG	4.987	.5926
	160	5.189	.5953
	80	5.761	.6018
	-	6.000	.6041
	40	6.065	.6047
8"	160	6.813	.6105
	XX-STG	6.875	.6110
	80	7.625	.6155
	40	7.981	.6173
	-	8.000	.6174
10"	160	8.500	.6196
	80	9.564	.6236
	X-STG	9.750	.6242
	-	10.000	.6249
	40	10.020	.6250
12"	160	10.126	.6253
	80	11.376	.6285
	X-STG	11.750	.6293
	40	11.938	.6297
	STD	12.000	.6298
14"	80	12.500	.6308
	X-STG	13.000	.6317
	40	13.124	.6319
	STD	13.250	.6319
	-	14.000	.6332
16"	80	14.314	.6337
	40	15.000	.6346
	STD	15.250	.6349
	-	16.000	.6357
18"	80	16.126	.6359
	X-STG	17.000	.6368
	STD	17.250	.6370
	-	18.000	.6377
20"	80	17.398	.6371
	X-STG	19.000	.6385
	STD	19.250	.6387
	-	20.000	.6392
24"	XSTG	23.000	.6410
	STD	23.250	.6411
	-	24.000	.6415
30"	X-STG	29.000	.6434
	STD	29.250	.6435
	-	30.000	.6437
36"	X-STG	35.000	.6450
	STD	32.250	.6450
	-	36.000	.6452
42"	X-STG	41.000	.6461
	STD	41.250	.6461
	-	42.000	.6462

Type 35/36

Nom. Pipe Size	Schedule	Pipe ID	K
12"	160	10.126	.6116
	80	11.376	.6165
	X-STG	11.750	.6178
	40	11.938	.6184
	STD	12.000	.6186
14"	80	12.500	.6200
	X-STG	13.000	.6214
	40	13.124	.6217
	STD	13.250	.6220
	-	14.000	.6238
16"	80	14.314	.6245
	40	15.000	.6259
	STD	15.250	.6263
	-	16.000	.6276
18"	80	16.126	.6278
	X-STG	17.000	.6292
	STD	17.250	.6296
	-	18.000	.6306
20"	80	17.938	.6305
	X-STG	19.000	.6318
	STD	19.250	.6321
	-	20.000	.6329
24"	80	21.564	.6344
	S-STG	23.000	.6355
	STD	23.250	.6357
	-	24.000	.6363
30"	X-STG	29.000	.6392
	STD	29.250	.6393
	-	30.000	.6396
36"	X-STG	35.000	.6415
	STD	36.250	.6416
	-	36.000	.6418
42"	X-STG	41.000	.6431
	STD	41.250	.6432
	-	42.000	.6434
48"	-	48.000	.6445
60"	-	60.000	.6461
72"	-	72.000	.6472
84"	-	84.000	.6479
96"	-	96.000	.6485

Type 45/46

Nom. Pipe Size	Schedule	Pipe ID	K
24"	80	21.564	.6224
	X-STG	23.000	.6244
	STD	23.250	.6248
	-	24.000	.6257
30"	X-XTG	29.000	.6306
	STD	29.250	.6308
	-	30.000	.6314
36"	X-STG	35.000	.6345
	STD	35.250	.6347
	-	36.000	.6350
42"	X-STG	41.000	.6373
	STD	41.250	.6374
	-	42.000	.6376
48"	-	48.000	.6395
60"	-	60.000	.6422
72"	-	72.000	.6439
84"	-	84.000	.6452
96"	-	96.000	.6461

Diamond II Annubar Flow Coefficient Reynolds Number Dependency

When the Diamond II Annubar is usd within the acceptable Reynolds Number range defined by Dieterich Standard, the Annubar'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 plus or minus one percent of the published K-value.

Diamond II's K-factor independence of Reynold's Number is very beneficial. It allows the user to measure a large range of Reynolds Numbers without need of a correction factor for changing Reynolds Numbers. The Diamond II's K-factor independence can be attributed to a constant separation point along the edges of it's diamond shape and the probe's ability to take a proper average of its sensing holes.

The Diamond II Annubar's Flow Coefficient Theory

Dieterich Standard is 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 Diamond II K-factors than in flow meters that use only an empirical data base for determining their flow coefficients.

The Diamond II Annubar 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), and the differental pressure contribution due to the Annubar's blockage in the pipe (H_b).

The Differential Pressure due to the Shape of the Annubar (H_S).

An Annubar 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 Annubaar and is known as the stagnation pressure. The downstream, or low pressure is caused by the fluid traveling past the Annubar, creating a suction on the rear side. This suction phenomenon can be attributed to a boundary layer flow separation.

The Differential Pressure due to the Annubar's Pipe Blockage (H_b).

An Annubar is an obstruction in the pipe and therefore, reduces the cross-sectional area in 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 will be affected by the Annubar's blockage in the pipe.

Since an Annubar 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 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, and by dividing the differential pressure produced by Annubar into H_S and H_b, one can derive the relationship between the Annubar K-factor and the Annubar'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:

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

The constants C_1 and C_2 must be determined experimentally. Once C_1 and C_2 are determined, equation (1) becomes the theoretical link between the Annubar K-factor (K_A) and the Annubar's blockage in the pipe (B).

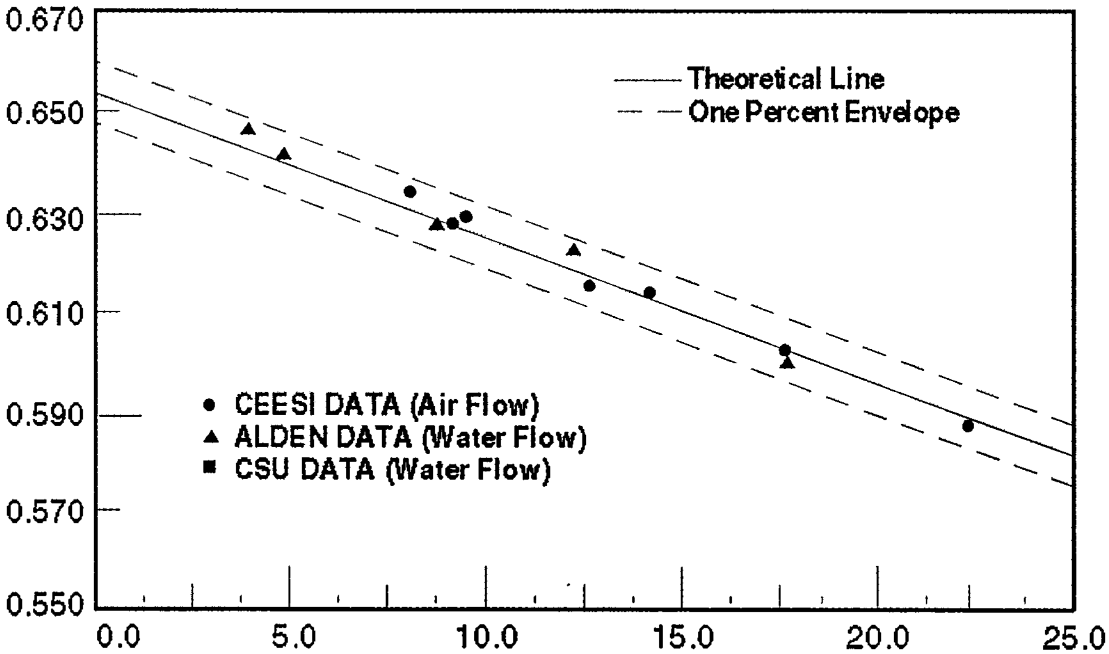
The Importance of the Flow Coefficient, or K vs. B Theory

As with any other meter, the Annubar's accuracy is only as good as its flow coefficient (K-factor). The most accurate way to determine a meter's flow coefficient is to test that meter in the application for which it was intended by reproducing the flowing conditions in a flow laboratory by matching piping conditions, Reynolds Numbers, fluid densities, temperatures, pressures, and installation. Although this method is accurate, it is impractical and expensive to empirically test every flow meter for every application. In lieu of testing every meter for the application for which it was intended, flow meter manufacturers will test a representative sample of their meters in a sampling of line sizes and Reynolds Numbers. This base line data and curve fitting technique is used to predict flow coefficients in untested line sizes and untested Reynolds Number ranges.

Another way to insure the accuracy of published flow coefficients for untested flow meters is to develop theoretical relationships that link the meter's flow coefficient to physical parameters in the pipe. For an orifice plate or a venturi, one such relationship is known as the "velocity of approach factor" and relates the meter's flow coefficient to its beta ratio. An Annubar also has a theoretical relationship between its flow coefficient and its blockage in the pipe. This relationship is qualified by the K vs. Blockage equation.

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.

K vs. BLOCKAGE
Test Data For Diamond II Annubars



Data No.	Annubar Model	Line Size	Blockage	K-Ave.	K-Predicted	Percent Error
1	25	6	17.77	0.60350	0.6046	0.19
2	25	12	9.05	0.63560	0.6296	0.95
3	35	12	13.20	0.62120	0.6181	0.50
4	25	16	7.04	0.62960	0.6349	0.84
5	35	16	10.27	0.62000	0.6263	1.01
6	35	24	6.73	0.63600	0.6357	0.04
7	25	12	9.05	0.63510	0.6296	0.87
8	35	12	13.20	0.61570	0.6181	0.39
9	25	10	10.75	0.62290	0.6250	0.34
10	25	6	17.77	0.61080	0.6046	1.02
11	15	4	11.21	0.62290	0.6237	0.13
12	15	3	14.64	0.61440	0.6140	0.07
13	15	2	21.85	0.58880	0.5918	0.51
14	35	36	4.44	0.64510	0.6416	0.55

Diamond II Annubar Operating Limitations

For an Annubar to operate accurately, the flowing fluid must be separate from the probe at the same location (along the edges of the diamond shape). 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 diamond shape. For Diamond II models 10 through 46, the minimum rod Reynolds Numbers are:

Model	Minimum Reynold's Number
10	2000
15/16	5000
25/26	10000
35/36	15000
45/46	25000

Above these rod Reynolds Numbers, Diamond II Annubars will operate accurately. To determine the rod Reynolds Number at any given flowrate, use the following relationship:

$$\mathrm{Re}_{rod} = \frac{DV_{\rho}}{\mu}$$

where: ρ = fluid density in lbs/ft^3
D = probe width in feet
V = velocity of fluid in feet per second
μ = fluid viscosity in lbm/ft-sec

For model 10	D = .0153
For models 15/16	D = .0298
For models 25/26	D = .0703
For models 35/36	D = .1025
For models 45/46	D = .1650

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

The upper operating limit for Diamond II Annubars 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 (for gases).
3. Severe cavitation occurs on the downstream side of the Annubar.

TABLE 2.3
Expansion Factor For Gases, Y_A

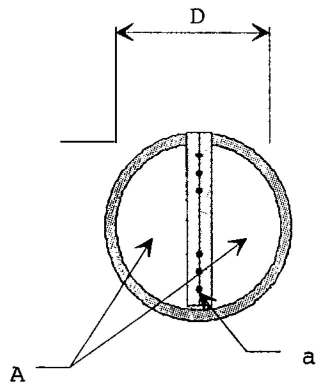
Use the algorithm and calculate, or the tables and interpolate Y_A. These algorithms adjust for density and internal energy effects of the gas as it flows around the Annubar.

For Types 15/16, 25/26, 35/36, 45/46

$$Y_A = 1-\left((1-B)^2 .011332 - .00342\right)\frac{h_w}{P_f\gamma}$$

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

B = Blockage
D = Internal Pipe Diameter (inches)
d = 0.183 for 10
= 0.3576 for 15/16
= 0.8460 for 25/26
= 1.230 for 35/36
= 1.980 for 45/46
h_W = Differential pressure in inches of water column
P_f = Flowing line pressure in psia
γ = Ratio of specific heats



a = Annubar projected area
= d x D
A = Pipe inside area
= $\pi D^2 / 4$
B = a / A = 4d / πD

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. An iteration is then necessary to determine its final value.

Table 2.3A - Gas Expansion Factor, Y_A (k = 1.4)

h_w / P_f	Area Ratio (1 - B)							
	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.2	.9998	.9997	.9996	.9995	.9993	.9992	.9990	.9989
0.4	.9996	.9994	.9992	.9989	.9986	.9984	.9981	.9977
0.6	.9994	.9991	.9987	..9984	.9980	.9975	.9971	.9966
0.8	.9992	.9988	.9983	.9978	.9973	.9967	.9961	.9955
1.0	.9990	.9985	.9979	.9973	.9966	.9959	.9951	.9943
1.2	.9988	.9982	.9975	.9967	.9959	.9951	.9942	.9932
1.4	.9986	.9979	.9970	.9962	.9952	.9942	.0032	.9921
1.6	.9984	.9976	.9966	.9956	.9946	.9934	.9922	.9910
1.8	.9982	.9973	.9962	.9951	.9939	.9926	.9912	.9898
2.0	.9980	.9970	.9958	.9945	.9932	.9918	.9903	.9887

Note: P_f must be in psia and
h_W must be in inches of water column @ 68°F

Examples of Gases with k = 1.4

Air	
Carbon monoxide	CO
Hydrogen	H_2
Hydrogen chloride	HCl
Nitric oxide	NO
Nitrogen	N_2
Oxyyen	O_2

Table 2.3B - Gas Expansion Factor, Y_A (k = 1.3)

h_w / P_f	Area Ratio (1 - B)							
	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.2	.9998	.9997	.9995	.9994	.9993	.9991	.9990	.9988
0.4	.9996	.9993	.9991	.9988	.9985	.9982	.9979	.9976
0.6	.9994	.9990	.9986	..9982	.9978	.9973	.9969	.9963
0.8	.9992	.9987	.9982	.9976	.9971	.9965	.9958	.9951
1.0	.9989	.9984	.9977	.9971	.9963	.9956	.9948	.9939
1.2	.9987	.9980	.9973	.9965	.9956	.9947	.9937	.9927
1.4	.9985	.9977	.9968	.9959	.9949	.9938	.0027	.9915
1.6	.9983	.9974	.9964	.9953	.9941	.9929	.9916	.9903
1.8	.9981	.9970	.9959	.9947	.9934	.9920	.9906	.9890
2.0	.9979	.9967	.9955	.9941	.9927	.9911	.9895	.9878

Note: P_f must be in psia and
h_W must be in inches of water column @ 68°F

Examples of Gases with k = 1.3

Natural gas	
Acetylene	C_2H_2
Ammonia	NH_3
Carbon dioxide	CO_2
Chlorine	Cl_2
Hydrogen sulfide	H_2S
Methane	CH_4
Nitrous oxide	N_2O
Sulphur dioxide	SO_2
Steam	

TABLE 2.4

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

Factors To Change From A Pressure Base of 14.73 PSIA To Other Pressure Bases

Pressure Base PSIA	F_{pb}
14.4	1.0229
14.525	1.0141
14.65	1.0055
14.696	1.0023
14.70	1.0020
14.725	1.0003
14.73	1.0000
14.375	0.9997
14.775	0.9970
14.90	0.9886
15.025	0.9804
15.15	0.9723
15.225	0.9675
15.275	0.9643
15.325	0.9612
15.40	0.9565
15.525	0.9488
15.65	0.9412
15.775	0.9338
15.90	0.9264
16.025	0.9192
16.15	0.9121
16.275	0.9051
16.40	0.8982
16.70	0.8820

TABLE 2.5

$$F_{tb} = \frac{\text{BASE °F} + 460}{60 + 460}$$

Factors To Change From A Temperature Base of 60°F To Other Temperature Bases

Temperature Degrees F	F_{tb}	Temperature Degrees F	F_{tb}
40	0.9615	65	1.0096
41	0.9635	66	1.0115
42	0.9654	67	1.0135
43	0.9673	68	1.0154
44	0.9692	69	1.0173
45	0.9712	70	1.0192
46	0.9731	71	1.0212
47	0.9750	72	1.0231
48	0.9769	73	1.0250
49	0.9788	74	1.0269
50	0.9808	75	1.0288
51	0.9827	76	1.0308
52	0.9846	77	1.0327
53	0/9865	78	1.0346
54	0.9885	79	1.0365
55	0.9904	80	1.0385
56	0.9923	81	1.0404
57	0.9942	82	1.0423
58	0.9962	83	1.0442
59	0.9981	84	1.0462
60	1.000	85	1.0481
61	1.0019	86	1.0500
62	1.0038	87	1.0519
63	1.0058	88	1.0538
64	1.0077	89	1.0558
		90	1.0577

TABLE 2.6

$$F_{tf} = \sqrt{\frac{520}{460 + \text{actual flowing temperature } (^\circ\text{F})}}$$

Flowing Temperature Factors - F_{tf}

°F	Factor	°F	Factor	°F	Factor	°F	Factor	°F	Factor	°F	Factor
1	1.0621	21	1.0392	41	1.0188	61	0.9990	81	0.9804	110	0.9551
2	1.0609	22	1.0387	42	1.0178	62	0.9981	82	0.9795	120	0.0469
3	1.0598	23	1.0376	43	1.0168	63	0.9971	83	0.9786	130	0.9388
4	1.0586	24	1.0365	44	1.0157	64	0.9962	84	0.9777	140	0.9309
5	1.0575	25	1.0355	45	1.0147	65	0.9952	85	0.9768	150	0.9233
6	1.0564	26	1.0344	46	1.0137	66	0.9943	86	0.9759	160	0.9158
7	1.0552	27	1.0333	47	1.0127	67	0.9933	87	0.9750	170	0.9085
8	1.0541	28	1.0323	48	1.0117	68	0.9924	88	0.9741	180	0.9014
9	1.0530	29	1.0312	49	1.0107	69	0.9915	89	0.9732	190	0.8944
10	1.0518	30	1.0302	50	1.0098	70	0.9905	90	0.9723	200	0.8876
11	1.0507	31	1.0291	51	1.0089	71	0.9896	91	0.9715	210	0.8810
12	1.0496	32	1.0281	52	1.0078	72	0.9887	92	0.9706	220	0.8745
13	1.0485	33	1.0270	53	1.0068	73	0.9877	93	0.9697	230	0.8681
14	1.0474	34	1.0260	54	1.0058	74	0.9868	94	0.9688	240	0.8619
15	1.0463	35	1.0249	55	1.0048	75	0.9859	95	0.9680	250	0.8558
16	1.0452	36	1.0239	56	1.0039	76	0.9850	96	0.9671	260	0.8498
17	1.0441	37	1.0229	57	1.0029	77	0.9840	97	0.9662	270	0.8440
18	1.0430	38	1.0219	58	1.0019	78	0.9831	98	0.9653	280	0.8383
19	1.0419	39	1.0208	59	1.0010	79	0.9822	99	0.9645	290	0.8327
20	1.0408	40	1.0198	60	1.0000	80	0.9813	100	0.9636	300	0.8272

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 is 60°F (520°R). If measurement is made at any other flowing temperature, then the flowing temperature factor must be applied. The factor can be calculated as:

$$F_{tf} = \sqrt{\frac{520}{460 + \text{actual flowing temperature } (^\circ\text{F})}}$$

TABLE 2.7

$$F_g = \sqrt{\frac{1.000}{G}} \quad G(\text{Air}) = 1.000$$

Specific Gravity Factors, F_g

Specific Gravity G	Factor F_g	Specific Gravity G	Factor F_g	Specific Gravity G	Factor F_g	Specific Gravity G	Factor F_g
0.500	1.4142	0.675	1.2172	0.850	1.0847	1.05	0.9759
0.505	1.4072	0.680	1.2127	0.855	1.0815	1.06	0.9713
0.510	1.4003	0.685	1.2082	0.860	1.0783	1.07	0.9667
0.515	1.3935	0,690	1.2039	0.865	1.0752	1.08	0.9623
0.520	1.3868	0,695	1.1995	0.870	1.0721	1.09	0.9578
0.525	1.3801	0,700	1.1952	0.875	1.0690	1.10	0.9535
0.530	1.3736	0.705	1.1910	0.880	1.0660	1.11	0.9492
0.535	1.3672	0.710	1.1868	0.885	1.0630	1.12	0.9449
0.540	1.3698	0.7151	1.1826	0.890	1.0600	1.13	0.9407
0.545	1.3546	0.720	1.1785	0.895	1.0570	1.14	0.9366
0.550	1.3484	0.725	1.1744	0.900	1.0541	1.15	0.9325
0.555	1.3423	0.730	1.1704	0.905	1.0512	1.16	0.9285
0.560	1.3363	0.735	1.1664	0.910	1.0483	1.17	0.9245
0.565	1.3304	0.740	1.1625	0.915	1.0454	1.18	0.9206
0.570	1.3245	0.745	1.1586	0.920	1.0426	1.19	0.9167
0.575	1.3188	0.750	1.1547	0.925	1.0398	1.20	0.9129
0.580	1.3131	0.755	1.1509	0.930	1.0370	1.21	0.9091
0.585	1.3074	0.760	1.1471	0.935	1.0342	1.22	0.9054
0.590	1.3019	0.765	1.1433	0.940	1.0314	1.23	0.9017
0.595	1.2964	0.770	1.1396	0.945	1.0287	1.24	0.8980
0.600	1.2910	0.775	1.1359	0.950	1.0260	1.25	0.8944
0.605	1.2856	0.780	1.1323	0.955	1.0233	1.26	0.8909
0.610	1.2804	0.785	1.1287	0.960	1.0206	1.27	0.8874
0.615	1.2752	0.790	1.1251	0.965	1.0180	1.38	0.8839
0.620	1.2700	0.795	1.1215	0.970	1.0153	1.29	0.8805
0.625	1.2649	0.800	1.1180	0.975	1.0127	1.30	0.8771
0.630	1.2599	0.805	1.1146	0.980	1.0102	1.31	0.8737
0.635	1.2549	0.810	1.1111	0.985	1.0076	1.32	0.8704
0.640	1.2500	0.815	1.1077	0.990	1.0050	1.33	0.8671
0.645	1.2451	0.820	1.1043	0.995	1.0025	1.34	0.8639
0.650	1.2403	0.825	1.1010	1.00	1.0000	1.35	0.8607
0.655	1.2356	0.830	1.0976	1.01	0.9950	1.36	0.8575
0.660	1.2309	0.835	1.0944	1.02	0.9901	1.37	0.8544
0.665	1.2263	0.840	1.0911	1.03	0.9853	1.38	0.8513
0.670	1.2217	0.845	1.0879	1.04	0.9806	1.39	0.8482

F_g = Specific Gravity Factor. This factor corrects the flow equation whenever the gas is not air. The factor can be calculated as:

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

TABLE 2.8 (a)

Supercompressibility Factor, F_{pv}

Air

Flowing Temperature, T_f = °F

P_f PSIA	-40	-20	0	20	40	60	80	100	120	140	160	180	200	220
14.7	1.0006	1.0005	1.0004	1.0003	1.0003	1.0002	1.0002	1.0001	1.0001	1.0000	1.0000	1.0000	1.0000	0.9999
100	1.0044	1.0035	1.0028	1.0023	1.0018	1.0014	1.0010	1.0007	1.0004	1.0002	1.0000	0.9998	0.9997	0.9995
200	1.0087	1.0070	1.0056	1.0044	1.0034	1.0026	1.0019	1.0013	1.0008	1.0003	0.9999	0.9996	0.9993	0.9990
300	1.0129	1.0103	1.0082	1.0065	1.0050	1.0037	1.0027	1.0018	1.0010	1.0003	0.9998	0.9993	0.9988	0.9985
400	1.0170	1.0136	1.0107	1.0084	1.0064	1.0048	1.0034	1.0022	1.0012	1.0003	0.9995	0.9989	0.9983	0.9978
500	1.0211	1.0167	1.0131	1.0102	1.0078	1.0057	1.0040	1.0025	1.0012	1.0001	0.9992	0.9984	0.9977	0.9971
600	1.0249	1.0197	1.0154	1.0119	1.0089	1.0065	1.0044	1.0027	1.0012	0.9999	0.9988	0.9979	0.9971	0.9964
700	1.0286	1.0224	1.0174	1.0134	1.0100	1.0072	1.0048	1.0028	1.0011	0.9996	0.9984	0.9973	0.9963	0.9955
800	1.0320	1.0250	1.0193	1.0147	1.0109	1.0077	1.0050	1.0028	1.0009	0.9992	0.9978	0.9966	0.9956	0.9947
900	1.0352	1.0273	1.0210	1.0158	1.0116	1.0081	1.0052	1.0027	1.0006	0.9987	0.9972	0.9959	0.9948	0.9938
1000	1.0382	1.0294	1.0224	1.0168	1.0122	1.0083	1.0051	1.0025	1.0002	0.9982	0.9965	0.9951	0.9939	0.9928
1100	1.0408	1.0312	1.0237	1.0176	1.0126	1.0084	1.0050	1.0021	0.9996	0.9975	0.9958	0.9943	0.9930	0.9918
1200	1.0431	1.0328	1.0247	1.0182	1.0128	1.0084	1.0047	1.0017	0.9991	0.9968	0.9950	0.9933	0.9920	0.9908
1300	1.0450	1.0341	1.0255	1.0185	1.0129	1.0082	1.0044	1.0011	0.9984	0.9961	0.9940	0.9923	0.9909	0.9897
1400	1.0465	1.0351	1.0260	1.0187	1.0128	1.0079	1.0039	1.0005	0.9976	0.9951	0.0031	0.9913	0.9898	0.9885
1470	1.0477	1.0359	1.0265	1.0190	1.0129	1.0079	1.0037	1.0002	0.9973	0.9947	0.9926	0.9908	0.9900	0.9879

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 deviates, 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: $F_{pv} = \sqrt{\frac{1}{Z}}$

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 Fpv. Table 2.8 (b) gives an abbreviated listing of the supercompressibility factors for natural gas.

TABLE 2.8 (b)

Supercompressibility Factor, F_{pv}

0.6 Specific Gravity Hydrocarbon Gas

Flowing Temperature, T_f = °F

P_f PSIA	-40	-20	0	20	40	60	80	100	120	140	160	180	200	220
14.7	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
100	1.0157	1.0137	1.0119	1.0104	1.0091	1.0079	1.0070	1.0061	1.0054	1.0047	1.0041	1.0036	1.0032	1.0028
200	1.0329	1.0284	1.0245	1.0212	1.0184	1.0160	1.0141	1.0123	1.0108	1.0094	1.0082	1.0072	1.0063	1.0055
300	1.0517	1.0441	1.0378	1.0325	1.0281	1.0243	1.0212	1.0185	1.0161	1.0141	1.0123	1.0108	1.0094	1.0082
400	1.0725	1.0610	1.0518	1.0442	1.0380	1.0327	1.0284	1.0247	1.0215	1.0187	1.0163	1.0142	1.0124	1.0108
500	1.0954	1.0792	1.0665	1.0564	1.0481	1.0413	1.0357	1.0309	1.0268	1.0233	1.0202	1.0176	1.0153	1.0132
600	1.1211	1.0988	1.0821	1.0690	1.0585	1.0499	1.0430	1.0370	1.0320	1.0277	1.0240	1.0208	1.0180	1.0156
700	1.1500	1.1202	1.0986	1.0820	1.0691	1.0587	1.0502	1.0432	1.0372	1.0321	1.0277	1.0240	1.0207	1.0178
800	1.1826	1.1431	1.1158	1.0955	1.0798	1.0674	1.0575	1.0492	1.0423	1.0364	1.0313	1.0270	1.0232	1.0199
900	1.2193	1.1678	1.1337	1.1092	1.0906	1.0761	1.0646	1.0551	1.0472	1.0405	1.0348	1.0299	1.0256	1.0219
1000	1.2597	1.1939	1.1522	1.1231	1.1014	1.0847	1.0716	1.0609	1.0520	1.0445	1.0381	1.0326	1.0279	1.0237
1100	1.3021	1.2211	1.1711	1.1370	1.1120	1.0931	1.0784	1.0665	1.0566	1.0483	1.0413	1.0352	1.0301	1.0255
1200	1.3421	1.2481	1.1898	1.1506	1.1224	1.1013	1.0850	1.0719	1.0610	1.0519	1.0443	1.0377	1.0321	1.0272
1300	1.3754	1.2735	1.2079	1.1639	1.1325	1.1091	1.0912	1.0770	1.0652	1.0554	1.0471	1.0400	1.0339	1.0287
1400	1.4007	1.2959	1.2246	1.1764	1.1421	1.1166	1.0971	1.0818	1.0691	1.0586	1.0497	1.0421	1.0356	1.0300
1500	1.4138	1.3132	1.2393	1.1879	1.1511	1.1235	1.1026	1.0863	1.0728	1.0615	1.0521	1.0440	1.0371	1.0312
1600	1.4175	1.3248	1.2512	1.1978	1.1589	1.1298	1.1076	1.0904	1.0762	1.0643	1.0543	1.0458	1.0385	1.0323
1700	1.4145	1.3311	1.2603	1.2062	1.1658	1.1353	1.1121	1.0941	1.0792	1.0667	1.0563	1.0474	1.0398	1.0333
1800	1.4068	1.3330	1.2663	1.2126	1.1715	1.1400	1.1160	1.0974	1.0819	1.0689	1.0580	1.0487	1.0409	1.0341
1900	1.3959	1.3312	1.2695	1.2173	1.1760	1.1439	1.1194	1.1002	1.0842	1.0708	1.0595	1.0499	1.0417	1.0347
2000	1.3827	1.3264	1.2704	1.2202	1.1793	1.1470	1.1221	1.1026	1.0861	1.0724	1.0607	1.0508	1.0424	1.0352
2100	1.3680	1.3186	1.2677	1.2207	1.1812	1.1493	1.1243	1.1044	1.0876	1.0734	1.0614	1.0513	1.0429	1.0355
2200	1.3527	1.3093	1.2635	1.2190	1.1820	1.1508	1.1258	1.1058	1.0887	1.0741	1.0619	1.0516	1.0431	1.0358
2300	1.3365	1.2988	1.2579	1.2175	1.1816	1.1513	1.1266	1.1066	1.0893	1.0745	1.0621	1.0517	1.0432	1.0359
2400	1.3205	1.2879	1.2511	1.2139	1.1800	1.1508	1.1266	1.1067	1.0894	1.0745	1.0619	1.0515	1.0431	1.0357
2500	1.3059	1.2763	1.2436	1.2095	1.1777	1.1496	1.1261	1.1065	1.0892	1.0741	1.0615	1.0511	1.0427	1.0355
2600	1.2906	1.2646	1.2352	1.2040	1.1742	1.1475	1.1248	1.1056	1.0885	1.0736	1.0610	1.0506	1.0422	1.0350
2700	1.2756	1.2527	1.2265	1.1980	1.1703	1.1450	1.1230	1.1043	1.0875	1.0728	1.0603	1.0499	1.0415	1.0343
2800	1.2608	1.2408	1.2174	1.1915	1.1657	1.1418	1.1208	1.1026	1.0862	1.0717	1.0593	1.0489	1.0407	1.0335
2900	1.2464	1.2289	1.2081	1.1845	1.1606	1.1381	1.1180	1.1005	1.0845	1.0703	1.0580	1.0478	1.0396	1.0324
3000	1.2324	1.2172	1.1987	1.1773	1.1552	1.1341	1.1150	1.0981	1.0825	1.0687	1.0566	1.0464	1.0383	1.0313

Note: For expanded tables of supercompressibility factors for natural gas, see A.G.A. Report No. 3 or A.G.A. Supercompressibility Tables (NX-19).

TABLE 2.9

F_m - Manometer Factors

Note: This table is for use with mercury-filled manometers that have gas in contact with the mercury surface, and installed at sea level elevation at 45° Latitude.

See Table 2.11 for elevation and latitude correction factors.

For manometers filled with fluids other than mertcury and gas, see Appendix C.

Specific Gravity	Ambient Temp	Static Pressure PSI 0	500	1000	1500	2000	2500	3000
.550	0°F	1.0030	1.0019	1.0006	.9990	.9973	.9960	.9951
.600	"	1.0030	1.0018	1.0002	.9982	.9962	.9949	.9940
.650	"	1.0030	1.0017	.9997	.9971	.9950	.9938	.9930
.700	"	1.0030	1.0015	.9991	.9957	.9937	.9926	.9920
.750	"	1.0030	1.0014	.9984	.9940	.9923	.9913	.9910
.550	20°F	1.0020	1.0010	.9997	.9983	.9969	.9956	.9947
.600	"	1.0020	1.0009	.9994	.9977	.9959	.9946	.9937
.650	"	1.0020	1.0008	.9990	.9968	.9949	.9936	.9927
.700	"	1.0020	1.0007	.9985	.9957	.9936	.9924	.9917
.750	"	1.0020	1.0005	.9980	.9944	.9924	.9912	.9907
.550	40°F	1.0010	1.0000	.9989	.9977	.9964	.9952	.9942
.600	"	1.0010	.9999	.9986	.9972	.9956	.9943	.9933
.650	"	1.0010	.9998	.9983	.9965	.9947	.9933	.9923
.700	"	1.0010	.9997	.9980	.9957	.9936	.9922	.9913
.750	"	1.0010	.9996	.9975	.9947	.9925	.9912	.9903
.550	60°F	1.0000	.9991	.9980	.9969	.9957	.9946	.9936
.600	"	1.0000	.9990	.9978	.9965	.9951	.9938	.9928
.650	"	1.0000	.9989	.9975	.9959	.9943	.9929	.9919
.700	"	1.0000	.9988	.9972	.9953	.9933	.9919	.9909
.750	"	1.0000	.9987	.9968	.9944	.9923	.9909	.9900
.550	80°F	.9990	.9981	.9971	.9961	.9950	.9940	.9931
.600	"	.9990	.9980	.9969	.9957	.9945	.9933	.9923
.650	"	.9990	.9979	.9967	.9953	.9938	.9925	.9915
.700	"	.9990	.9978	.9964	.9948	.9930	.9916	.9905
.750	"	.9990	.9977	.9961	.9941	.9921	.9906	.9896
.550	100°F	.9980	.9972	.9962	.9953	.9943	.9933	.9925
.600	"	.9980	.9971	.9960	.9949	.9938	.9926	.9917
.650	"	.9980	.9970	.9958	.9945	.9932	.9919	.9909
.700	"	.9980	.9969	.9956	.9941	.9925	.9912	.9901
.750	"	.9980	.9968	.9953	.9935	.9917	.9903	.9892
.550	120°F	.9970	.9962	.9953	.9944	.9935	.9926	.9918
.600	"	.9970	.9961	.9951	.9941	.9930	.9920	.9911
.650	"	.9970	.9960	.9949	.9937	.9925	.9914	.9904
.700	"	.9970	.9959	.9947	.9933	.9920	.9907	.9896
.750	"	.9970	.9958	.9945	.9929	.9913	.9899	.9888

TABLE 2.10

F_{AA} - Thermal Expansion Factor

Temperature, °F of Piping Material									
Alum	**Copper**	**Type 430**	**2% CRMO**	**5% CRMO**	**Bronze**	**Steel**	**Monel**	**Type 316 or Type 304**	**Corr Factor, F_{AA}**
									.992
-264					-317				.993
-204	-322				-245				.994
-155	-230				-190			-276	.995
-108	-163				-137		-236	-189	.996
-63	-102				-86		-150	-119	.997
-19	-44				-34		-71	-55	.998
+25	+19	+44	-13	-14	+17	-6	+2	+7	.999
+68	+68	+68	+68	+68	+68	+68	+68	+68	1.000
+113	+127	+157	+146	+151	+122	+144	+136	+130	1.001
		+246	+222	+232	+175	+218	+199	+186	1.002
		+332	+296	+312	+225	+289	+260	+240	1.003
		+415	+366	+389	+273	+358	+319	+292	1.004
		+494	+434	+460	+321	+425	+377	+343	1.005
		+568	+501	+527	+369	+489	+433	+391	1.006
		+641	+566	+594	+417	+551	+489	+439	1.007
		+713	+629	+662		+613	+544	+488	1.008
		+783	+690	+730		+675	+599	+536	1.009
		+851	+750	+795		+735	+653	+584	1.010
		+918	+811	+858		+794	+717	+631	1.011
		+986	+871	+918		+851	+759	+674	1.012
		+1054	+928	+979		+907	+810	+727	1.013
		+1121	+984	+1040		+961	+861	+777	1.014
		+1189	+1038	+1102		+1015	+911	+799	1.015

TABLE 2.11

F_l - Gage Location Factors

Gravitation correction factors for manometer factor adjustment. To be used for liquid filled manometers only.

Degrees Latitude	Gage Elevation Above Sea Level - Lineal Feet Sea Level	2000'	4000'	6000'	8000'	10000'
0 (Equator)	.9987	.9986	.9985	.9984	.9983	.9982
5	.9987	.9986	.9985	.9984	.9983	.9982
10	.9988	.9987	.9986	.9985	.9984	.9983
15	.9989	.9988	.9987	.9986	.9985	.9984
20	.9990	.9989	.9988	.9987	.9986	.9985
25	.9991	.9990	.9989	.9988	.9987	.9986
30	.9993	.9992	.9991	.9990	.9989	.9988
35	.9995	.9994	.9993	.9992	.9991	.9990
40	.9998	.9997	.9996	.9995	.9994	.9993
45	1.0000	.9999	.9998	.9997	.9996	.9995
50	1.0002	1.0001	1.0000	.9999	.9998	.9997
55	1.0004	1.0003	1.0002	1.0001	1.0000	.9999
60	1.0007	1.0006	1.0005	1.0004	1.0003	1.0002
65	1.0008	1.0007	1.0006	1.0005	1.0004	1.0003
70	1.0010	1.0009	1.0008	1.0007	1.0006	1.0005
75	1.0011	1.0010	1.0009	1.0008	1.0007	1.0006
80	1.0012	1.0011	1.0010	1.0009	1.0008	1.0007
85	1.0013	1.0012	1.0011	1.0010	1.0009	1.0008
90 (Pole)	1.0013	1.0012	1.0011	1.0010	1.0009	1.0008

Note: The F_l values given in this Table are to account for gages being operated under gravitational forces that depart from standard gravity of 32.1740 ft/sec^2 (sea level, 45° latitude). The values in this table are the square root of the ratio of local gravity to standard gravity.

$$F_l = \sqrt{\frac{g}{gc}}$$

Flow Calculation Examples:

Problem:

An oil with a specific gravity of 0.825 is flowing at a rate of 6000 GPM. The 20" standard wall (ID - 19.26") carbon steel pipeline has a pressure of 75 psig and a temperature of 100°F. What is the differential pressure (h_w) that a Type DCR-26 Diamond II Annubar would measure?

Solution:

From equation 2.1

$$h_w = \left[\frac{Q_A}{C'}\right]^2$$

Q_A = 6000GPM

$$C' = F_{NA} K D^2 F_{RA} F_M F_{AA} F_l \sqrt{\frac{1}{G_f}}$$

F_{NA}	=5.6664	[Eq. 2.1]
K =	.6387	[Table 2.1]
D^2 =	$(19.25)^2$	
F_M =	1.000	[Table 2.9]
F_{AA}=	1.000	[Table 2.10]
F_l =	1.000	[Table 2.11]

$$\sqrt{\frac{1}{G_f}} = \sqrt{\frac{1}{.825}} = 1.101$$

F_{RA} =1.000

C' =(5.6664)(.6387)(370.6)(1.101) = 1476.7

$$h_w = \left(\frac{6000}{1476.7}\right)^2 = 16.51'' H_2O@60F$$

Problem:

Steam at 500 psia and 620°F is flowing in a 24 inch ID carbon steel pipe. The measured differential pressure on a type DFF-35 Diamond II Annubar is 15" H_2O. What is the flowrate in lbm/hr?

Solution:

From equation 2.3

$$W = F_{NA} D^2 F_{RA} Y_A F_M F_{AA} F_l \sqrt{\rho_f}\sqrt{h_w}$$

F_{NA}	=358.94	
K =	.6363	[Table 2.1]
F_{RA}	=1.0000	
D^2 =	$(124)^2$ = 576	
F_M =	1.000	[Table 2.9]
F_{AA}=	1.008	[Table 2.10]
F_l =	1.000	[Table 2.11]

$$\sqrt{h_w} = \sqrt{15} = 3.873$$

The density of the steam can be found from page A-3.

ρ_f = 0.8413 lbm/FT^3

ρ_f = $\sqrt{.8413}$ =.9172

To calculate Y_A, Table 2.3(b) must be used. First, for a type 76 Annubar, (1-B) = .9347.

The value of h_w/P_f = 15/500 =.03

Interpolation of Table 2.3(b) gives:

Y_A = .9999

Using the above method, the flow equation becomes:

W = (358.94)(.6363)(576)(.9999)(1.0)(1.008)(1.01)(.9172)(3.873)

W = 471.015 lbm/hr

Problem:

Natural gas with a specific gravity of 0.63 is flowing in a 12" Schedule 80 carbon steel pipe. The operating pressure is 1264 psia and the operating temperature is 120°F. For a type DCR-25 Diamond II Annubar, determine the differential pressure (h_w) for a flowrate of 6MM SCFH at a base temperature of 60°F.

Solution:

From equation 2.4

$$h_w = \frac{1}{P_f}\left[\frac{Q_s}{C'}\right]^2$$

$$C' = F_{NA} K D^2 F_{RA} Y_A F_{pb} F_{tb} F_{tf} F_g F_{pv} F_m F_{AA} F_l$$

$F_{NA} =$	338.17	
$K =$	.6285	[Table 2.1]
$F_{RA} =$	1.0000	
$D^2 =$	$(11.376)^2 = 129.41$	[Table 2.1]
$F_{pb} =$	0.9084	[Table 2.4]
$F_{tb} =$	1.0000	Table [2.5]
$F_{tf} =$	0.9469	[Table 2.6]
$F_g =$	1.2599	Table 2.7]
$F_{pv} =$	1.0637	Taable 2.b(b)]
$F_M =$	1.000	[Table 2.9]
$F_{AA} =$	1.001	[Table 2.10]
$F_l =$	1.000	[Table 2.11]

The expansion factor, Y_A, can be found in Table 2.3(b). To determine Y_A, the differential pressure, h_w, must be known. However, it can be seen from this table that the value of Y_A approaches 1.00 as the line pressure P_f increases. For now, assume Y_A= 1.000

Y_A = 1.000 [Table 2.3(b)]

The value of C' can now be calculated

C' = (338.17)(.6285)(129.41)(1.000)(.9804)(1.0000)(.9469)(1.2599)(1.0637)(1.000)(1.001)(1.000)

C' = 34253

$$h_w = \frac{1}{P_f}\left[\frac{Q_s}{C'}\right]^2 = \frac{1}{1264}\left[\frac{6{,}000{,}000}{34253}\right]^2$$

h_w = 24.27" $H_2 0$ @ 60°F

For this differential pressure, the assumed value of 1.000 for Y_A can now be checked:

$$h_w = \frac{24.27}{27.73} = 0.88\,psi$$

$$h_w / P_f = \frac{0.88}{1264} = .0007$$

(1-B) = .9053

Y_A = 1.0000

As can be seen, the assumed value and the true value of Y_A are the same. Therefore, the value of h_w = 24.27" $H_2 0$ is the correct answer.

Chapter 3

Installation and Operational Considerations

NOTES

INSTALLATION AND OPERATIONAL CONSIDERATIONS

The Annubar flow sensor is designed to provide an accurate measurement of fluid flow over a wide range of flow rates. In all cases, the Annubar must be sized, specified and ordered according to the catalog. The flow calculation must be performed in accordance with Chapter 2 of this manual. Finally, the Annubar must be installed correctly following the instructions provided with each unit. As with all things, there is a possibility of having problems. This chapter is presented to provide a better understand of the effects of improper installation and application of Annubar primary flow elements, and to thereby emphasize the need for care in selection, installation and use.

ALIGNMENT ERROR

The Annubar probe senses a total pressure (impact and static pressure) through the velocity ports and a low pressure through the downstream ports. The impact pressure and the downstream low pressure are affected by the alignment of the sensing 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. Changes within the limits indicated in Figure 3.1 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 is not or cannot be installed within the limits, it may be necessary to do an in-line calibration. The Annubar output signal will be repeatable and stable but will be shifted by some unknown amount. After determining a new Flow Coefficient, the Annubar will perform within its normal accuracy tolerances.

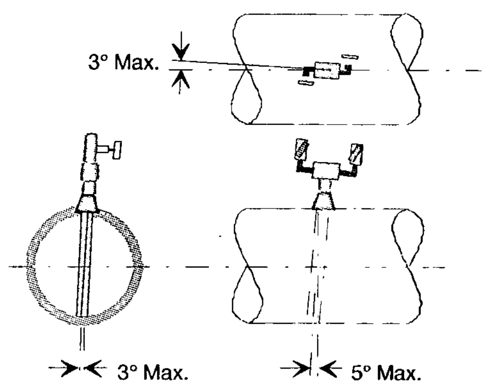


Figure 3.1
Permissable Misalignment

SIZING ERROR

For accurate measurement, the design of the Annubar probe requires that the flow sensing ports be located at specific points in the flow stream. When the Annubar is manufactured, the location of the ports is based on the inside diameter and wall thickness of the pipe. When the Annubar is installed in the line using the proper fittings, the sensing ports end up at the proper locations. If an Annubar 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 that is installed in an incorrect line size will give a repeatable signal. A calibration factor will have to be determined to make accurate flow measurements. Once this is done, the Annubar may be used normally.

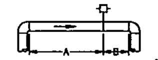
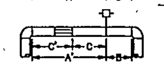
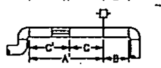
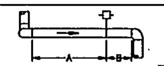
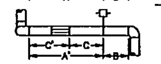
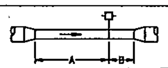
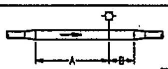
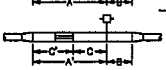
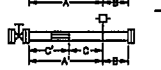
FLOW DISTURBANCE - UPSTREAM

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 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 lengths of straight run of pipe upstream of the Annubar 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 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

MINIMUM DIAMETERS OF STRAIGHT PIPE [1]	UPSTREAM DIMENSION: WITHOUT STRAIGHTENING VANES, IN PLANE A	UPSTREAM DIMENSION: WITHOUT STRAIGHTENING VANES, OUT OF PLANE A	UPSTREAM DIMENSION: WITH STRAIGHTENING VANES, A'	C	C'	DOWNSTREAM DIMENSION B
	7	9				3
			6	3	3	
	9	14				3
			8	4	4	
	19	24				4
			9	4	5	
	8	8				3
			8	4	4	
	8	8				3
			8	4	4	
	24	24				4
			9	4	5	

1. Values shown are the recommended spacing in terms of internal diameters for normal industial metering requirements. For laaboratory or high accuracy work, add 25% to above values.
2. Includes gate, globe, plug, and other throttling valves that are only paartially opened. If valve is to be fully open, use values shown for "Pipe size change". Control valves should be located after Annubar element.

Leakage of Instrument Lines and Connections

Flow measurement using an Annubar 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 D.P. The magnitude of this D.P. is small and quite often less than one (1) psi. Any leaks in the instrument lines or connections will change the D.P. output of the Annubar. If a leak occurs in the high pressure (impact) lines, a low D.P. will be seen by the secondary instrumentation. Any leak in the low pressure (downstream) lines will result in a high D.P. With the low D.P.'s involved, even a small leak can cause very large flow measurement error.

Flow Parameter Changes

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

A precise flow calculation is done as part of the application of an Annubar and secondary instrumentation. If any of the flowing 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. The new flow calculation will then provide necessary information for calibrating the secondary instrumentation.

Dirt Accumulation

One inherent advantage of an Annubar over devices such as an orifice plate is its ability to function in flows carrying dirt and grease. The shape of the Annubar 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 the performance unless, under extreme cases, some of the sensing ports are completely obstructed or the outside shape is drastically changed by buildup.

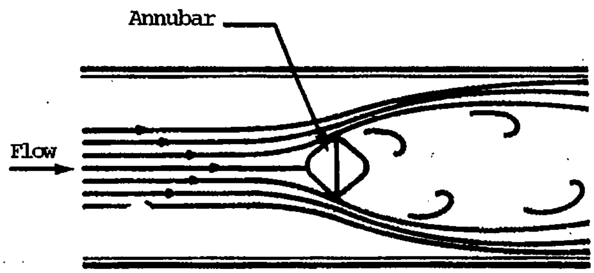


Figure 3.2
Flow Pattern

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

In flow where there is a large amount of foreign material, it may be necessary to perform a routine preventative maintenance removal of the Annubar for cleaning. The outer surfaces should be cleaned with a soft wire brush. The internal passages are cleaned a soft wire and compressed air and, if necessary, a solvent for dissolving the material. As a precaution, where the flow is extremely dirty, the Annubar may be ordered with clean out ports. These ports are located in the Annubar head directly in line with the inner tubes so that rodding out the tubes is possible.

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

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.

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

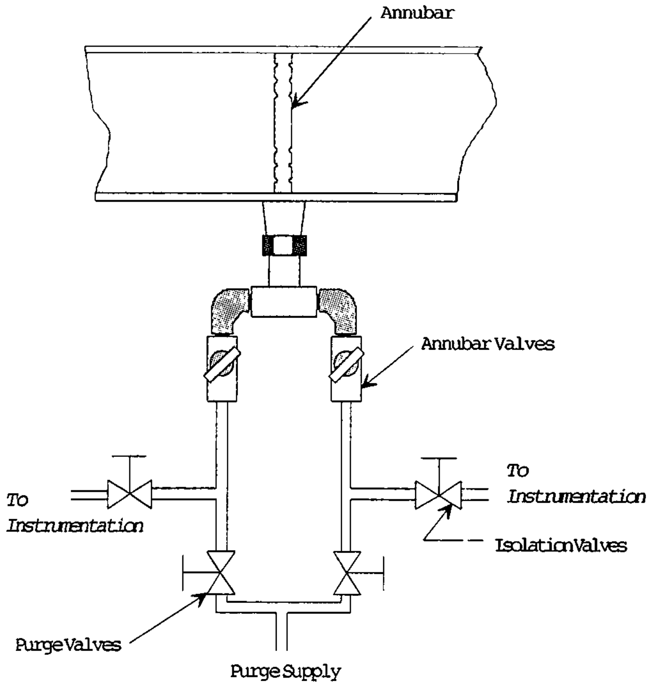


Figure 3.3
Annubar Purging

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. If the Annubar is ordered with cleanout ports the purge fluid connections may be made through them by removing the plugs.

Blow-down of the Annubar is a method of purging. This method uses process line pressure to clean the Annubar. Some means of opening the instrument lines, purge ports or the opposite end purge connection to a drain is required. The fluid then flows out carrying the debris with it.

Care must be taken to protect the secondary instrumentation from high pressures when purging an Annubar. Some means must be provided for valving off the lines to the secondary instrumentation when the purging is taking place.

Gas Entrapment

Flow measurement with an Annubar or any head type device involves measuring and comparing pressures of very low magnitude or very little differences. Problems caused 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 signal is a fluctuating pressure because of flow turbulence. The entrapped gas being compressible 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. It is important to follow the installation recommendations for placement of the Annubar and instrumentation to minimize gas entrapment. Periodic bleeding of the secondary instrumentation and lines may be necessary.

Flow Parameter Limitations

The Annubar will function in a wide variety of fluid flow situations. There are two specific situations in which the Annubar 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 the factory.

NOTES

APPENDIX A

FLUID PROPERTIES

NOTES

Density of Superheated Steam and Compressed Water

Density, ρ, lbm/ft^3

Temp °F	1 PSIA	2 PSIA	5 PSIA	10 PSIA	20 PSIA	50 PSIA	100 PSIA	200 PSIA	500 PSIA	750 PSIA	1000 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	60.61	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	57.97	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	.1076	.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	.01914	.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	.8019	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	.01355	.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	.2621	.6700	1.025	1.394
860	.001272	.002545	.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	.01151	.02302	.05764	.1155	.2321	.5885	.8933	1.206
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

Properties of Saturated Water

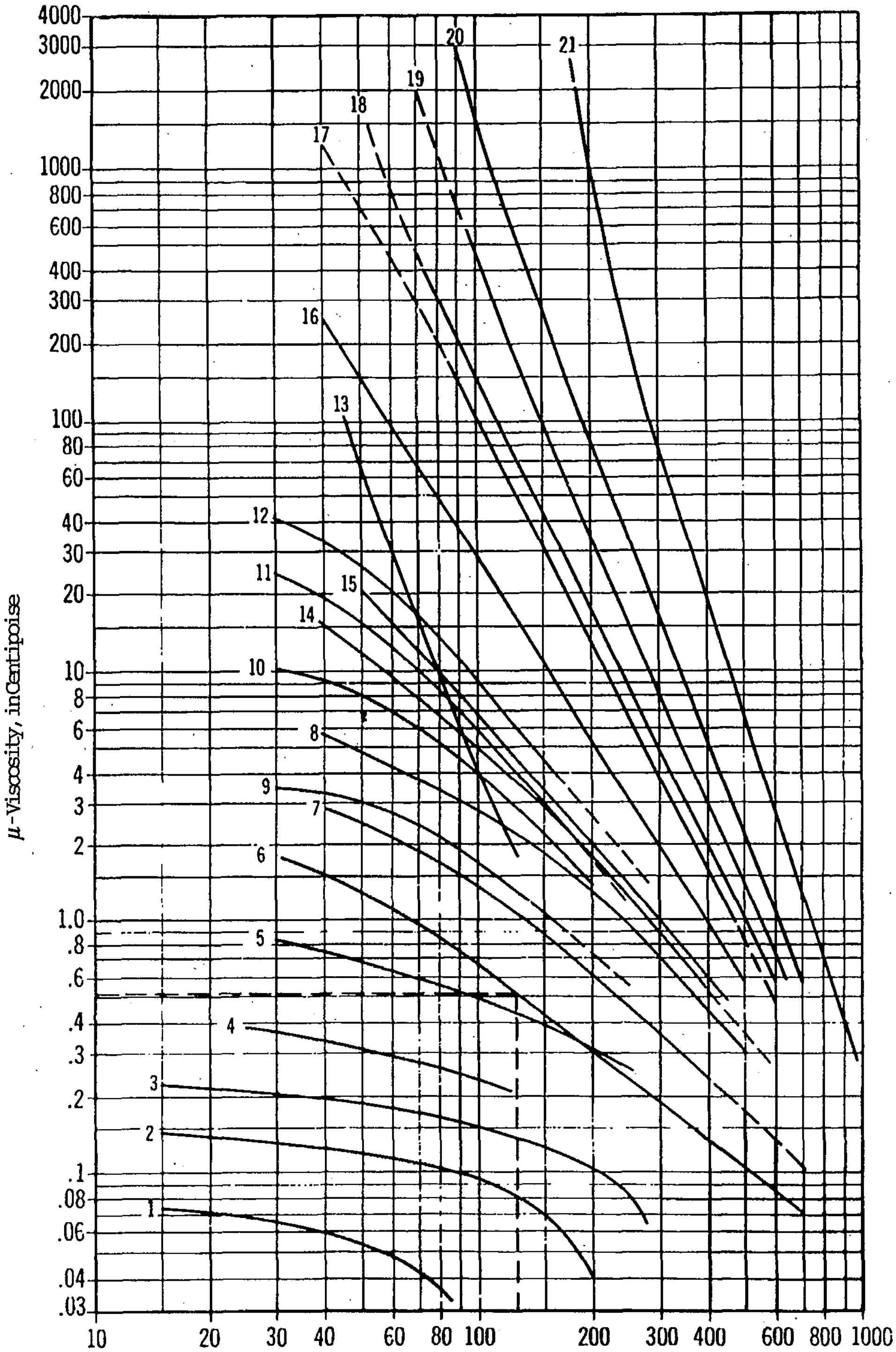
Temp. °F	Density lbm/ft³	Specific G_f	Viscosity Centipoise	Temp °F	Density lbm/ft³	Specific G_f	Viscosity Centipoise	Temp °F	Density lbm/ft³	Specific G_f	Viscosity Cenipoise	Temp. °F	Density lbm/ft³	Specific G_f	Viscosity Centipoise
				66	62.3344	.9994	1.03	165	60.8909	.9763	.380	340	55.9458	.8970	.157
32	62.4140	1.0007	1.75	67	62.3275	.9993	1.02	170	60.7862	.9746	.366	345	55.7674	.8941	.155
33	62.4167	1.0007	1.72	68	62.3205	.9992	1.00	175	60.6789	.9729	.353	350	55.5859	.8912	.152
34	62.4191	1.0008	1.69	69	62.3132	.9991	.988	180	60.5693	.9717	.341	355	55.4042	.8883	.150
35	62.4212	1.0008	1.66	70	62.3058	.9990	.975	185	60.4573	.9693	.330	360	55.2192	.8853	.147
36	62.4229	1.0008	1.63	71	62.2981	.9988	.962	190	60.3430	.9675	.319	365	55.0320	.8823	.145
37	62.4242	1.0009	1.61	72	62.2902	.9987	.950	195	60.2265	.9656	.309	370	54.8424	.8793	.143
38	62.4252	1.0009	1.58	73	62.2822	.9986	.937	200	60.1076	.9637	.300	375	54.6506	.8762	.141
39	62.4258	1.0009	1.55	74	62.2739	.9984	.925	205	59.9866	.9618	.291	380	54.4563	.8731	.139
40	62.4261	1.0009	1.53	75	62.2654	.9983	.913	210	59.8635	.9598	.282	385	54.2597	.8700	.137
41	62.4261	1.0009	1.50	76	62.2568	.9982	.902	215	59.7382	.9578	.274	390	54.0606	.8668	.135
42	62.4257	1.0009	1.48	77	62.2479	.9980	.890	220	59.6108	.9558	.267	395	53.8590	.8635	.133
43	62.4251	1.0009	1.45	78	62.2389	.9979	.879	225	59.4813	.9537	.259	400	53.6548	.8603	.131
44	62.4241	1.0009	1.43	79	62.2297	.9977	.868	230	59.3497	.9516	.252	405	53.4481	.8569	.129
45	62.4229	1.0008	1.41	80	62.2203	.9976	.857	235	59.2161	.9494	.246	410	53.2387	.8536	.127
46	62.4213	1.0008	1.38	81	62.2107	.9974	.847	240	59.0804	.9472	.239	415	53.0267	.8502	.126
47	62.4194	1.0008	1.36	82	62.2009	.9973	.837	245	58.9428	.9450	.233	420	52.8119	.8467	.124
48	62.4173	1.0007	1.34	83	62.1910	.9971	.826	250	58.8031	.9428	.228	425	52.5942	.8433	.122
49	62.4149	1.0007	1.32	84	62.1809	.9970	.816	255	58.6614	.9405	.222	430	52.3737	.8397	.121
50	62.4122	1.0007	1.30	85	62.1706	.9968	.807	260	58.5177	.9382	.217	435	52.1503	.8361	.119
51	62.4092	1.0006	1.28	90	62.1166	.9959	.761	265	58.3720	.9359	.212	440	51.9238	.8325	.118
52	62.4059	1.0006	1.26	95	62.0585	.9950	.718	270	58.2244	.9335	.207	445	51.6942	.8288	.116
53	62.4024	1.0005	1.24	100	61.9964	.9940	.680	275	58.0747	.9311	.203	450	51.4615	.8251	.115
54	62.3986	1.0004	1.22	105	61.9307	.9929	.645	280	57.9231	.9287	.198	455	51.2255	.8213	.114
55	62.3946	1.0004	1.20	110	61.8612	.9918	.612	285	57.7695	.9262	.194	460	50.9862	.8175	.112
56	62.3903	1.0003	1.19	115	61.7884	.9907	.582	290	57.6139	.9237	.190	465	50.7434	.8136	.111
57	62.3858	1.0002	1.17	120	61.7121	.9894	.555	295	57.4563	.9212	.186	470	50.4971	.8096	.110
58	62.3810	1.0002	1.15	125	61.6326	.9882	.529	300	57.2966	.9186	.183	475	50.2472	.8056	.109
59	62.3760	1.0001	1.14	130	61.5500	.9868	.505	305	57.1350	.9161	.179	480	49.9935	.8016	.108
60	62.3707	1.0000	1.12	135	61.4643	.9855	.483	310	56.9713	.9134	.176	485	49.7359	.7974	.106
61	62.3652	.9999	1.10	140	61.3757	.9840	.463	315	56.8056	.9108	.172	490	49.4744	.7932	.105
62	62.3595	.9998	1.09	145	61.2842	.9826	.444	320	56.6378	.9081	.169	495	49.2087	.7890	.104
63	62.3535	.9997	1.07	150	61.1899	.9811	.426	325	56.4680	.9054	.166				
64	62.3474	.9996	1.06	155	61.0928	.9795	.410	330	56.2960	.9026	.163				
65	62.3410	.9995	1.04	160	60.9932	.9779	.394	335	56.1220	.8998	.160				

Viscosity of Water and Steam

Temp °F	Viscosity of Water and Steam - In Centipoise (μ)									
	1 PSIA	**2 PSIA**	**5 PSIA**	**10 PSIA**	**20 PSIA**	**50 PSIA**	**100 PSIA**	**200 PSIA**	**500 PSIA**	**1000 PSIA**
Sat. Water	.667	.524	.368	.313	.255	.197	.164	.138	.111	.094
Sat. Steam	.010	.010	.011	.012	.012	.013	.014	.015	.017	.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	.028	.028
850	.026	.026	.026	.026	.026	.026	.027	.027	.027	.027
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	.103
450	.018	.018	.018	.018	.017	.017	.017	.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
250	.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

Values below the line are for water.

Viscosity of Water and Liquid Petroleum Products



1. Ethane (C_2H_6)
2. Propane (C_3H_6)
3. Butane (C_4H_{10})
4. Natural Gasoline
5. Water
7. Kerosene
8. Distillate
9. 48 Deg. API Crude
10. 40 Deg. API Crude
11. 35.6 Deg. API Crude
12. 32.6 Deg. API Crude
13. Salt Creek Crude
14. Fuel 3 (Max.)
15. Fuel 5 (Min.)
16. SAE 10 Lube (100 V.I.)
17. SAE 30 Lube (100 V.I.)
18. Fuel 5 (Max.) or Fuel 6 (Min.)
19. SAE 70 Lube (100V.I.)
20. Bunker C Fuel (Max.) and M.C. Residuum
21. Asphalt

Example: The viscosity of water at 125°F is 0.52 centipoise (Curve No. 6).
Note: Consult factory whenever viscosity of fluid exceeds 300 centipoise.