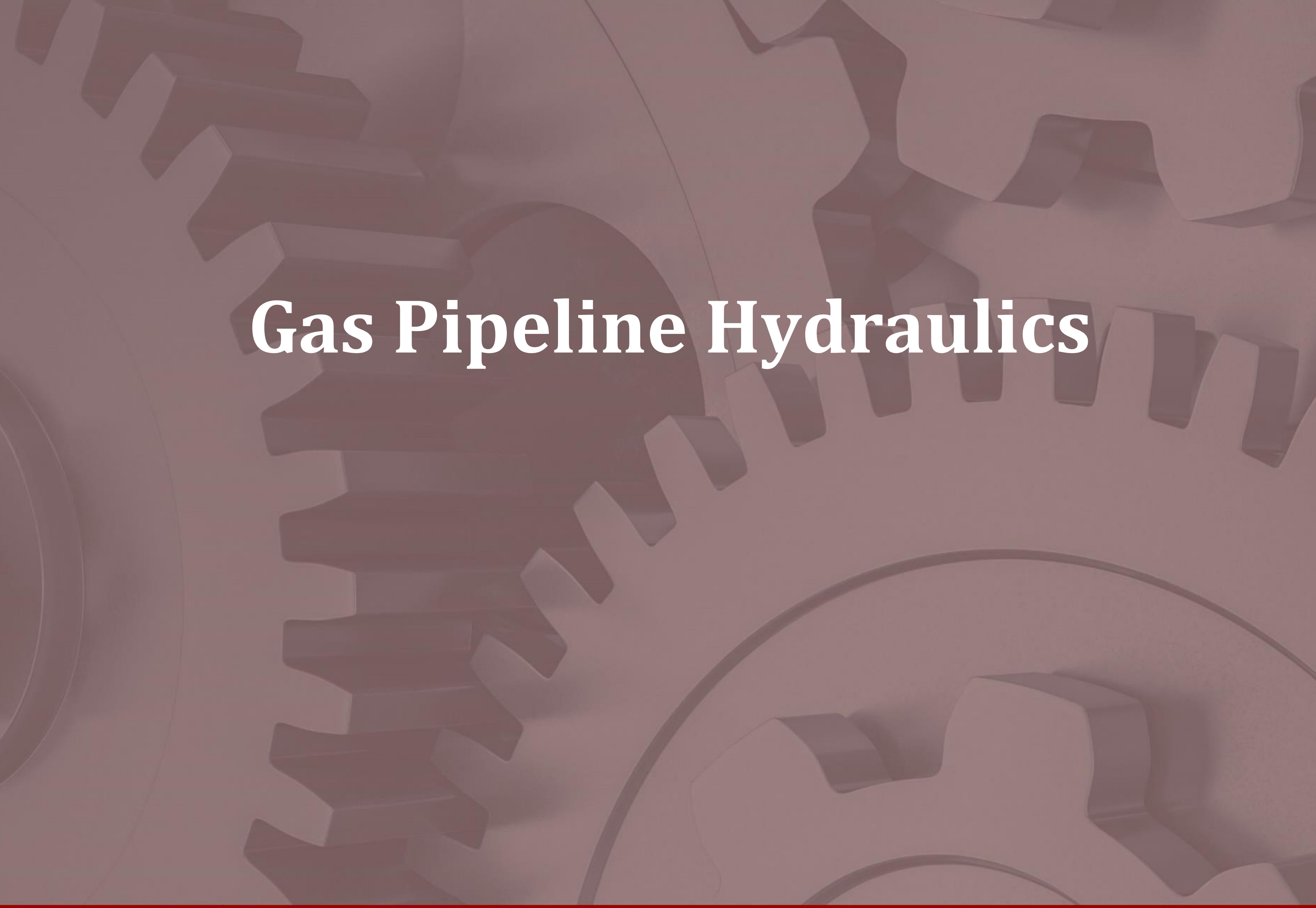

Gas Pipeline Hydraulics

An Online Continuing Education Course for Engineers

Course Number: O-5001

Credit: 5 Hours / 5 PDH / 5 CPD

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Gas Pipeline Hydraulics

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Introduction to gas pipeline hydraulics

This online course on gas pipeline hydraulics covers the steady state analysis of compressible fluid flow through pipelines. Mathematical derivations are reduced to a minimum, since the intent is to provide the practicing engineer a practical tool to understand and apply the concepts of gas flow in pipes. In particular, we will cover natural gas pipeline transportation including how pipelines are sized for a particular flow rate, the pressure required to transport a given volume of gas and the compression horsepower required. The properties of natural gas that affect pipe flow will be reviewed first followed by the concepts of laminar and turbulent flow and Reynolds number. Frictional pressure loss and the method of calculating the friction factor using the Moody diagram and the Colebrook and AGA methods will be illustrated with examples. Several other popular flow equations, such as the Weymouth and Panhandle formulas will be introduced and explained with example problems. Increasing pipeline throughput using intermediate compressor stations as well as pipe loops will be discussed. The strength requirement of pipes, allowable operating pressure and hydrostatic test pressure will be reviewed with reference to the DOT code requirements. Several fully solved example problems are used to illustrate the concepts introduced in the various sections of the course. A multiple-choice quiz is included at the end of the course.

1. Properties of Gas

Gases and liquids are generally referred to as fluids. Gases are classified as compressible fluids because unlike liquids, gases are subject to large variations in volume with changes in pressure and temperature. Liquids on the other hand are generally considered to be incompressible. Liquid density and volume change very little with pressure. However, liquids do show a variation in volume as the temperature changes. The mass of a gas is the quantity of matter and does not change with temperature or pressure.

Mass is measured in slugs or pound mass (lbm) in the U.S. Customary system of units (USCS). In the Systeme International (SI) units, mass is measured in kilograms (kg). Weight is a term that is sometimes used synonymously with mass. Strictly speaking, weight of a substance is a force (vector quantity), while mass is a scalar quantity. Weight depends upon the acceleration due to

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gravity and hence depends upon the geographical location. Weight is measured in pounds (lb) or more correctly in pound force (lbf) in the USCS units. In SI units weight is expressed in Newton (N). If the weight of a substance is 10 lbf, its mass is said to be 10 lbm. The relationship between weight W in lb and mass M in slugs is as follows

$$W = Mg \tag{1.1}$$

Where g is the acceleration due to gravity at the specific location. At sea level, it is equal to 32.2 ft/s^2 in USCS units and 9.81 m/s^2 in SI units.

Volume of a gas is the space occupied by the gas. Gases fill the container that houses the gas. The volume of a gas generally varies with temperature and pressure. However, if the gas occupies a fixed volume container, increasing the pressure will increase the gas temperature, and vice versa. This is called Charles Law for gases. If the gas is contained in a cylindrical vessel with a piston and a weight is placed on the piston, the pressure within the gas is constant equal to the weight on the piston, divided by the piston area. Any increase in temperature will also increase the gas volume by the movement of the piston, while the gas pressure remains constant. This is another form of the Charles Law for gases. Charles law will be discussed in more detail later in this section. Volume of a gas is measured in cubic feet (ft^3) in the USCS units and cubic meters (m^3) in SI units.

The density of a gas is defined as the mass per unit volume as follows

$$\text{Density} = \text{mass} / \text{volume} \tag{1.2}$$

Therefore, density is measured in $slug/ft^3$ or lbm/ft^3 in USCS units and in kg/m^3 in SI units. Similar to volume, gas density also varies with temperature and pressure. Since density is inversely proportional to the volume from Eq (1.2), we can conclude that density increases with pressure while the volume decreases. Similarly, increase in temperature decreases the density, while volume increases.

Specific weight of a gas refers to the weight per unit volume. It is referred to in lb/ft^3 in USCS units and N/m^3 in SI units.

$$\text{Specific weight} = \text{weight of gas} / \text{volume occupied} \tag{1.3}$$

The specific weight, like the volume of a gas, varies with the temperature and pressure.
If the weight of a certain quantity of gas is 10 lb and the volume occupied is 1000 ft^3, the specific weight is $\frac{10}{1000}$ or 0.01 lb/ft^3. On the other hand, the density of this gas can be stated as

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0.01 lbm/ft^3 or $\left(\frac{0.01}{32.2}\right)$ = 0.00031 slug/ft^3. Therefore, specific weight and density are closely related. Another term, called the specific volume is the inverse of the specific weight, expressed in ft^3/lb in the USCS units and m^3/N in SI units.

Specific volume = volume of gas / weight of gas
(1.4)

The specific gravity of a fluid is defined as a ratio of the density of the fluid to that of a standard fluid such as water or air at some standard temperature. For liquids, water is the standard of comparison, while for gases air is used as the basis.

Specific gravity of gas = density of gas / density of air (at the same temperature)
(1.5)

Being a ratio of similar properties, the specific gravity is dimensionless.

Thus, the specific gravity of a particular gas may be stated as 0.65 relative to air at 60 ^{O}F. Sometimes, specific gravity is abbreviated to gravity and may be stated as follows:
Gravity of gas = 0.65 (air = 1.00)

Using molecular weights, we can define the gas gravity as the ratio of the molecular weight of the gas to that of air. The molecular weight of air is usually considered to be 29.0 and therefore, the specific gravity of gas can be stated as follows:

$$G = \frac{Mw}{29.0} \tag{1.6}$$

Where
G = specific gravity of gas, dimensionless
Mw = molecular weight of gas
The specific gravity of a gas like its density varies with temperature and pressure.

Viscosity of a fluid relates to the resistance to flow of the fluid. Higher the viscosity, more difficult it is to flow. The viscosity of a gas is very small compared to that of a liquid. For example, a typical crude oil may have a viscosity of 10 centipoise (cP), whereas a sample of natural gas has a viscosity of 0.0019 cP. Viscosity may be referred to as absolute or dynamic viscosity measured in cP or kinematic viscosity measured in centistokes (cSt). Both these units are SI units, but commonly used even when working with USCS units. Other units of viscosity in USCS units are lb/ft-s for dynamic viscosity and ft^2/s for kinematic viscosity.

The specific heat of a gas is defined as the quantity of heat required to raise the temperature of one lb of gas by one ^{O}F. For gases, two specific heats are used: Cp, the specific heat at constant

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pressure and Cv, the specific heat at constant volume. The ratio of the specific heats $\frac{Cp}{Cv}$ is designated as γ and is an important parameter in flow of gases and in expansion and contraction of gases.

Pressure of a gas must be defined before we get on with the other important properties concerning gas flow.

Pressure is defined as the force per unit area acting at any point in the gas. Imagine a container of volume V occupied by a certain mass of gas M as shown in Fig. 1.1

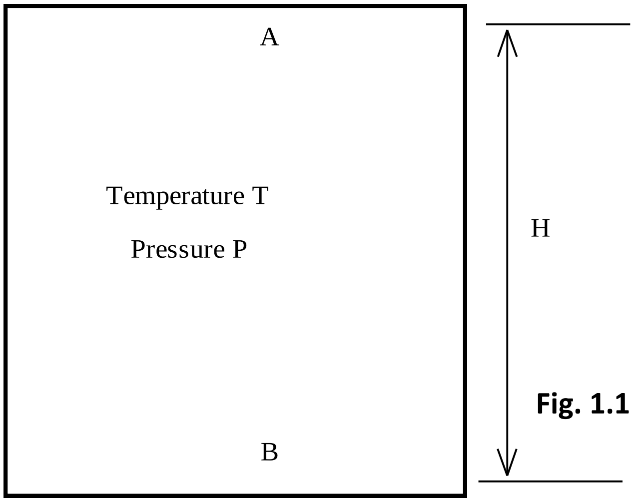

Fig. 1.1 Pressure in a gas

The gas is contained within this volume at some temperature T and pressure P and is in equilibrium. At every point within the container there is said to be a constant pressure P. Since the density of gas, compared to that of a liquid, is very small, the pressure of the gas at a point A near the top of the container will be the same as that at a point B near the bottom of the container. If the difference in elevations between the two points is H, theoretically, the pressure of gas at the bottom point will be higher than that at the top point by the additional weight of the column of gas of height H. However, since the gas density is very small, this additional pressure is negligible. Therefore, we say that the pressure of gas is constant at every point within the container. In USCS units, gas pressure is expressed in lb/in^2 or psi and sometimes in lb/ft^2 or psf. In SI units, pressure is stated as kilopascal (kPa), megapascal (MPa), bar or kg/cm^2. When dealing with gases it is very important to distinguish between gauge pressure and absolute pressure. The absolute pressure at any point within the gas is the actual pressure inclusive of the local atmospheric pressure (approximately 14.7 psi at sea level). Thus in the example above, if the local atmospheric pressure outside the gas container is P_{atm} and

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the gas pressure in the container as measured by a pressure gauge is P_g, the absolute or total gas pressure in the container is

$$P_{abs} = P_g + P_{atm} \qquad (1.7)$$

The adder to the gauge pressure is also called the base pressure. In USCS units, the gauge pressure is denoted by psig while the absolute pressure is stated as psia. Therefore, if the gauge pressure is 200 psig and the atmospheric pressure is 14.7 psi, the absolute pressure of the gas is 214.7 psia. In most equations involving flow of gases and the gas laws, absolute pressure is used. Similar to absolute pressure, we also refer to the absolute temperature of gas. The latter is obtained by adding a constant to the gas temperature. For example, in USCS units, the absolute temperature scale is the Rankin scale. In SI units, Kelvin is the absolute scale for temperature. The temperature in ^{O}F or ^{O}C can be converted to absolute units as follows:

$$^{O}R = {}^{O}F + 460 \qquad (1.8)$$

$$K = {}^{O}C + 273 \qquad (1.9)$$

Note that degrees Rankin is denoted by ^{O}R whereas for degrees Kelvin, the degree symbol is dropped. Thus it is common to refer to the absolute temperature of a gas at 80 ^{O}F as (80 + 460) = 540 ^{O}R and if the gas were at 20 ^{O}C, the corresponding absolute temperature will be (20 + 273) = 293 K. In most calculations involving gas properties and gas flow, the absolute temperature is used.

The **Compressibility factor**, Z is a dimensionless parameter less than 1.00 that represents the deviation of a real gas from an ideal gas. Hence it is also referred to as the gas deviation factor. At low pressures and temperatures Z is nearly equal to 1.00 whereas at higher pressures and temperatures it may range between 0.75 and 0.90. The actual value of Z at any temperature and pressure must be calculated taking into account the composition of the gas and its critical temperature and pressure. Several graphical and analytical methods are available to calculate Z. Among these, the Standing-Katz, AGA and CNGA methods are quite popular. The critical temperature and the critical pressure of a gas are important parameters that affect the compressibility factor and are defined as follows.

The *critical temperature* of a pure gas is that temperature above which the gas cannot be compressed into a liquid, however much the pressure. The *critical pressure* is the minimum pressure required at the critical temperature of the gas to compress it into a liquid.

As an example, consider pure methane gas with a critical temperature of 343 ^{O}R and critical pressure of 666 psia.

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The *reduced temperature* of a gas is defined as the ratio of the gas temperature to its critical temperature, both being expressed in absolute units (^{O}R or K). It is therefore a dimensionless number.

Similarly, the *reduced pressure* is a dimensionless number defined as the ratio of the absolute pressure of gas to its critical pressure.

Therefore, we can state the following:

$$T_r = \frac{T}{T_c} \tag{1.10}$$

$$P_r = \frac{P}{P_c} \tag{1.11}$$

Where
P = pressure of gas,
T = temperature of
T_r = reduced temper
P_r = reduced pressure
T_c = critical temperatu
P_c = critical pressure, p

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Using the preceding equatic … re of a sample of methane gas at 70^{O}F and 12

$$T_r = \frac{70+460}{343} = 1.5452$$

and

$$P_r = \frac{1200}{666} = 1.8018$$

For natural gas mixtures, the terms *pseudo-critical temperature* and *pseudo-critical pressure* are used. The calculation methodology will be explained shortly. Similarly, we can calculate the *pseudo-reduced* temperature and *pseudo-reduced pressure* of a natural gas mixture, knowing its *pseudo-critical temperature* and *pseudo-critical pressure*.

The Standing-Katz chart, Fig. 1.2 can be used to determine the compressibility factor of a gas at any temperature and pressure, once the reduced pressure and temperature are calculated knowing the critical properties.

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