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INTRODUCTION

Scope

The understanding of how gasses and fluids flow in equipment is the foundation of equipment design. All of the other Engineering Design Guidelines are based on these fundamentals; therefore it is critical that the principles of fluid flow are understood before designing equipment. The principles are not complex, but neither are they simple due to the interdependence of pressure drop and friction.

This design guideline covers the basic elements in the field of Piping Fluid Flow Material Selection and Line Sizing in sufficient detail to design a pipeline and / or other piping classes. This design guideline includes single phase liquid flow, single phase gas flow for hydrocarbon, water, steam and natural gases.

Proper pipe sizing is determined by the length of the pipe and the allowable pressure drop in the line. The allowable pressure drop may be influenced by factors, including process requirements, economics, safety, and noise or vibration limitations.

This guideline also covers other piping related equipment, such as valve, fittings and orifices. Pressure drop calculations in these fitting are discussed in detail to help the design of piping systems.

Fluid phases can be considered as pure liquid or pure gas phases. In this guideline, these differences phases were discussed in detail for the engineering design for the laminar and turbulence flow and for various substances of fluids, for example, water, steam and hydrocarbon. A second guideline discusses mixed phase fundementals.

The theory section covers the selection method of the piping material based on their application and engineering calculations for the sizing of the piping. In the application section of this guideline, four case studies are shown and discussed in detail, highlighting the way to apply the theory for the calculation.

Fundamental theories, such as Bernoulli's theory, is used as the basic of calculations because it is applicable for various conditions. The case studies will assist the engineer develop typical selection and sizing for the piping based on their own plant system.

Example Calculation Spreadsheets are included in this guideline. The Example Calculation Spreadsheets are based on case studies in the application section to make them easier to understand.

INTRODUCTION

General Design Consideration

In designing the piping fluid flow there are many factors have to be considered for the suitability of the material selection for the application codes and standards, environmental requirements, safety, performance of the requirements, and the economics of the design and other parameters which may constrain the work.

They should be included engineering calculations for the piping system design. Combined with the piping design criteria, calculations define the process flow rates, system pressure and temperature, pipe wall thickness, and stress and pipe support requirements.

The service conditions should be the consideration as well because the piping system is designed to accommodate all combinations of loading situations such as pressure changes, temperature changes, thermal expansion and contraction and other forces or moments that may occur simultaneously and they are used to set the stress limit of the design.

Design code and the standards are reviewed for the project of the design for the safety purposes and the verification of the applicability. In this design guideline generally follows the codes and the standards of the American Society of Mechanical Engineers

(ASME) Code for Pressure Piping, B31. ASME B31 includes the minimum design requirements for various pressure piping applications.(4)

Normal environmental factors that have the potential for damage due to corrosion must be addressed in the design of process piping. Physical damage may also occur due to credible operational and natural phenomena, such as fires, earthquakes, winds, snow or ice loading, and subsidence. Two instances of temperature changes must be considered as a minimum. First, there are daily and seasonal changes. Second, thermal expansion where elevated liquid temperatures are used must be accommodated. Compensation for the resulting expansions contractions are made in both the piping system and support systems. Internal wear and erosion also pose unseen hazards that can result in system failures.

Most failures of fluid process systems occur at or within interconnect points the piping, flanges, valves, fittings, etc. It is, therefore, vital to select interconnecting equipment and materials that are compatible with each other and the expected environment. Materials selection is an optimization process, and the material selected for an application must be chosen for the sum of its properties. That is, the selected material may not rank first in each evaluation category; it should, however, be the best overall choice. Considerations include cost and availability. Key evaluation factors are strength, ductility, toughness, and corrosion resistance.

Piping material is selected by optimizing the basis of design. The remaining materials are evaluated for advantages and disadvantages such as capital, fabrication and installation costs; support system complexity; compatibility to handle thermal cycling; and catholic protection requirements. The highest ranked material of construction is then selected.

The design proceeds with pipe sizing, pressure integrity calculations and stress analyses. If the selected piping material does not meet those requirements, then second ranked material is used to sizing, pressure integrity calculation and stress analyses are repeated.

For the pressure drop calculation: the primary requirement of the design is to find an inside diameter with system design flow rates and pressure drops. The design flow rates are based on system demands that are normally established in the process design phase of a project. This will involves trial and error procedure to find the suitable inside diameter.

Basically service conditions must be reviewed to determine operational requirements such as recommended fluid velocity for the application and liquid characteristics such as viscosity, temperature, suspended solids concentration, solids density and settling velocity, abrasiveness and corrosively. This information is useful to determine the minimum internal diameter of the pipe for the whole system network.

Normal liquid service applications, the acceptable velocity in pipes is 2.1 ± 0.9 m/s (7 ± 3 ft/s) with a maximum velocity limited to 2.1 m/s (7 ft/s) at piping discharge points. This velocity range is considered reasonable for normal applications.[4]

Pressure drops throughout the piping network are designed to provide an optimum balance between the installed cost of the piping system and operating costs of the system pumps. Primary factors that will impact these costs and system operating performance are internal pipe diameter (and the resulting fluid velocity), materials of construction and pipe routing.

Pressure drop, or head loss, is caused by friction between the pipe wall and the fluid, and by minor losses such as flow obstructions, changes in direction, changes in flow area, etc. Fluid head loss is added to elevation changes to determine pump requirements. A common method for calculating pressure drop is the Darcy-Weisbach equation.

Normally for the line sizing the following rules should be follow

1) Calculate the Pressure drop with expressed in the term “psi/100 ft of pipe”.

2) Select the suitable Velocity which expressed in ft/sec; there is standard for general liquid flow the range of the velocity should be in the suitable range for the basic design.

3) Calculate the Reynolds number to determine the fluid flow. Reynolds number is a factor of pipe diameter, flow rate, density, and viscosity of the liquid; allows

analysis of flow characteristics (slug, laminar, transition, turbulent); sanitary systems always require full turbulence (Reynolds number > 10,000)

4) Determine the suitable of pipe diameter - the inside pipe or tube diameter is used in the several equations to determine the pressure drops, Reynolds number, velocity and etc.

5) Determine the roughness of pipe, the more rough the pipe, the larger the friction factor; the larger the friction factor, the more pressure drop.

6) Incompressible flow - liquids; actual pressure is not a factor in pressure drop calculation.

7) Compressible flow - gases and vapors; actual pressure is a direct factor in pressure drop calculation.

Liquids (Incompressible Flow): Size longer lines for less pressure drop than shorter lines. Most water-like liquids, long lines should be sized for 0.5 to 1.0 psi/100 ft; short lines should be sized for 1.0 to 2.0 psi/100 ft; but there are no hard and fast rules.

For liquids with viscosities 10 cp or less consider just like water; above 10 cp, check Reynolds number to see what equations to use for pressure drop calculation. Careful with sizing lines in the fractional line size range; It may cost more to install ¾" pipe and smaller than 1" pipe due to support requirements.

Usually do not save on header sizing to allow for future increase in capacity without changing out piping. Pipeline holdup of process liquids may be a factor; smaller pipe may be desired to limit holdup even though pressure drop goes up.

Gases and Vapors (Compressible Flow): Supply pressure is a major factor in line sizing calculations; also, overall pressure drop by means of typical calculation methods should not exceed 10% of the supply pressure, otherwise, alternative calculation methods must be used. Typically, consider all gases and vapors (including saturated steam) to behave gases in order to calculate vapor densities (PV = nRT).

DEFINITIONS

Compressible Fluid - Molecules in a fluid to be compacted and the density is varies. Energy is exchanged not only among the kinetic energy and the potential energies due to gravity and pressure, but also with the internal energy [7].

Darcy Friction Factor, f -This factor is a function of Reynolds Number and relative pipe wall roughness, ε/d. For a given class of pipe material, the roughness is relatively independent of the pipe diameter, so that in a plot of f vs. Re, d often replaces ε/d as a parameter.

In-Compressible Fluid - An incompressible flow is one in which the density of the fluid is constant or nearly constant. Liquid flows are normally treated as incompressible [6]. Molecules in a fluid to be cannot be compacted. Generally the flow energy is converted to friction, kinetic and potential energy if available and not the internal energy.

Laminar Flow - Laminar flow occurs when adjacent layers of fluid move relative to each other in smooth streamlines, without macroscopic mixing. In laminar flow, viscous shear, which is caused by molecular momentum exchange between fluid layers, is the predominant influence in establishing the fluid flow. This flow type occurs in pipes when Re < 2,100.

Newtonian Fluids - A fluid characterized by a linear relationship between shear rate (rate of angular deformation) and shear stress.

Non-Newtonian Liquids - Fluids may be broadly classified by their ability to retain the memory of a past deformation (which is usually reflected in a time dependence of the material properties). Fluids that display memory effects usually exhibit elasticity.[8] Fluids in which viscosity depends on shear rate and/or time. Examples are some slurries, emulsions, and polymer melts and solutions.

Relative Roughness - Ratio of absolute pipe wall roughness ε to inside diameter d, in consistent units.

Reynolds Number, Re - A dimensionless number which expresses the ratio of inertial to viscous forces in fluid flow

Resistance Coefficient, K - Empirical coefficient in the friction loss equation for valves and fittings. It expresses the number of velocity heads lost by friction for the particular valve or fitting. The coefficient is usually a function of the nominal diameter.

Shear Rate - The velocity gradient (change in velocity with position).

Shear Stress - Force per unit area. Force in direction of flow; area in plane normal to velocity gradient.

Sonic Velocity (Choked Flow) - The maximum velocity that a gas or gas-liquid mixture can attain in a conduit at a given upstream pressure (except in certain converging-diverging nozzles), no matter how low the discharge pressure is. For gases this maximum velocity is equal to the speed of sound at the local conditions.

Specific gravity - Is a relative measure of weight density. Normally pressure has not significant effect for the weight density of liquid, temperature is only condition must be considered in designating the basis for specific gravity.

Steam Hammer - Steam hammer is excessive pipe vibrations that occur due to the collapse of large vapor bubbles in a cool liquid stream.

Transition Flow - Flow regime lying between laminar and turbulent flow. In this regime velocity fluctuations may or may not be present and flow may be intermittently laminar and turbulent. This flow type occurs in pipes when $2{,}100 < Re < 4{,}000$.

Turbulent Flow - Turbulence is characterized by velocity fluctuations that transport momentum across streamlines; there is no simple relationship between shear stress and strain rate in turbulent flow. Instantaneous properties cannot be predicted in a turbulent flow field; only average values can be calculated. For engineering analyses, turbulent flow is handled empirically using curve-fits to velocity profiles and experimentally determinate loss coefficients. This flow type occurs in pipes in industrial situations when $Re > 4{,}000$. Under very controlled laboratory situations, laminar flow may persist at $Re > 4{,}000$.

Viscosity- Defined as the shear stress per unit area at any point in a confined fluid divided by the velocity gradient in the direction perpendicular to the direction of flow, if the ratio is constant with time at a given temperature and pressure for any species, the fluid is called a Newtonian fluid.

Water Hammer - Water hammer is the dynamic pressure surge that results from the sudden transformation of the kinetic energy in a flowing fluid into pressure when the flow is suddenly stopped. The sudden closing of a valve can cause a water hammer.

NOMENCLATURE

A	Radius-sectional area, ft^2 (m^2)
a	Sum of mechanical allowances plus corrosion allowance plus erosion allowance, in(mm)
C	Flow coefficient for the nozzles and orifices
c	Compressible factor, for perfect gas c =1.0
D	Internal diameter of pipe, ft (m)
d	Internal diameter of pipe, in
d_1	Pipe with smaller diameter in enlargements or contractions in pipes
d_2	Pipe with smaller diameter in enlargements or contractions in pipes
d_e	Equivalent hydraulic diameter, in (mm)
D_o	Outside diameter of pipe, in. (mm)
E	Weld joint efficiency or quality factor from ASME B31.3
f	Dancy's friction factor, dimensionless
f_t	Friction factor for fitting
g	Acceleration of gravity, ft/s^2 (m/s^2) – $32.2 ft/s^2$
ΔH	Surge pressure, ft-liq (m-liq)
h_L	Head loss, ft (m)
k	Ratio of specific heat at constant pressure to specific heat at constant volume = c_p/c_v
K	Resistance coefficient, dimensionless
K_1	Resistance coefficient for enlargement/contraction, dimensionless
L	Length of pipe, ft (m)
L_{eq}	Equivalent length, ft (m)
L_m	Length of pipe, miles
M	Molecular weight
P	Pressure drop in pipe, lbf/in^2(Pa)

P_i	Internal design pressure, psig (kPa gage)
Q	Volumetric flow rate, ft^3/s (m^3/s)
q	Volumetric flow rate, ft^3/hr (m^3/hr)
Q_1	Rate of flow, gal/min
R	Individual gas constant, MR =1544
R_e	Reynolds Number, dimensionless
S	Specific gravity of a liquid, dimensionless (hydrocarbon in API)
S_g	Specific gravity of a gas, dimensionless
S_m	Allowable stress, from ASME B31.3, psi (MPa)
T	Absolute temperature, R (460+°F)
Tv	Valve stroking time (s)
Te	Effective valve stroking time (s)
t	Pressure design minimum thickness, in. (mm)
t_m	Total minimum wall thickness required for pressure integrity, in. (mm)
t_{nom}	Wall thickness, in. (mm)
V	Mean velocity, ft/s (m/s)
$\overline{V}$	Specific volume, ft^3/lbm (m^3/kg)
$\overline{V_1}$	Inlet specific volume, ft^3/lb
V_{max}	The bigger velocity for enlargement / contraction, ft/s (m/s)
ΔV	Change of linear flow velocity, ft/s (m/s)
v_s	Sonic velocity, ft/s (kg/s)
W	Mass flow rate, lbm/hr (kg/hr)
w	Mass flow rate, lbm/s (kg/s)
Y	Expansion factor (dimensionless)
z	Elevation of pipe, ft (m)

Greek letters

ρ	Weight density of fluid, lbm/ft^3 (kg/m^3)
μ_e	Absolute viscosity, lbm.s /ft (kg.s/m)
μ	Absolute (dynamic) viscosity, cp
ε	Absolute roughness, in (mm)
θ	Angle of convergence or divergence in enlargements or contractions in pipes
Δ	Differential between two points

THEORY

A) General Fluid Flow Theory

I) Physical Properties of Fluids

Physical properties of fluid are important for any flow problem and the accuracy of the values will affect the flow of fluid in the pipeline.

Viscosity

A fluid viscosity can be described by its Dynamic viscosity (sometimes called Absolute viscosity), or its Kinematics viscosity. These two expressions of viscosity are not the same, but are linked via the fluid density.

Kinematics viscosity = Dynamic viscosity / fluid density

Density, Specific Volume and Specify Gravity

The weight density or specific weight of a substance is its weight per unit volume.

The specific volume $\overline{\mathrm{V}}$ is the reciprocal of the weight density, is expressed in the SI system as the number of cubic meter of space occupied by one kilogram of the substance.

The specific gravity of a liquid is the ratio of its weight density at specified temperature to that of water at standard temperature, 60F

$$S = \frac{\rho\{\text{any liquid at specific temperature}\}}{\rho(\text{water at } 60\,\mathrm{F})} \qquad \text{Eq (1a)}$$

For hydrocarbon like oil, the API unit is used.

$$S\ (60\ F / 60\ F) = \frac{141.5}{131.5 + \deg.API} \qquad \text{Eq(1b)}$$

Normal water deg. API unit is 10, that mean water S = 1.00

For gas the specific gravity S_g is expressed as

$$S_g = \frac{\mathrm{M(gas)}}{\mathrm{M(air)}} \qquad \text{Eq (1c)}$$

Mean Velocity

Mean velocity is the average velocity in flow across the given cross section as determined by the continuity equation for steady state flow. It normally express as ratio of the volumetric flow rate (Q) to sectional area (A) of the pipe.

$$\text{Mean Velocity, } V = \frac{Q}{A} \qquad \text{Eq (2)}$$

which,

V = mean velocity, ft/s (m/s)
Q = volumetric flow rate, ft^3/s (m^3/s)
A = radius-sectional area, ft^2 (m^2)

Which, Volumetric flow rate in the pipe line is the ratio of the mass flow rate to density of the fluid.

$$\text{Volumetric flow rate, } Q = \frac{w}{\rho} \qquad \text{Eq (3)}$$

which,

w = mass flow rate, lbm/s (kg/s)

ρ = weight density of fluid, lbm/ft^3 (kg/m^3)

and the Sectional Area in pipe formula is expressed as

$$\text{Sectional area, } A = \frac{\pi D^2}{4} \qquad \text{Eq (4)}$$

II) Flow Characteristic in Pipe

There are three different types of flow in pipe and these determine the pipe sizing. There are laminar flow, between laminar and transition zones flow, and turbulent flow. This is very important for the designer to determine the type of flow of the fluid before proceeding with the calculation.

Reynolds Number

The Reynolds Number is used to determine the nature of flow in pipe whether is the laminar flow or turbulent flow. Reynolds Number with symbol R_e, which depend with pipe diameter (D), the density (ρ) and absolute viscosity (μ) of the flowing fluid and it velocity (V) of the flow. This number is a dimensionless group with combination of these four variables which expressed as

$$R_e = \frac{DV\rho}{\mu_e} \qquad \text{Eq (5a)}$$

$$R_e = \frac{50.6\, Q_1 \rho}{d\mu} \qquad \text{Eq (5b)}$$

which,

D = internal diameter of pipe, ft (m)
V = mean velocity of flow, ft/s (m/s)
ρ = weight density of fluid, Ibm/ft^3 (kg/m^3)
μ_e = absolute viscosity, Ibm /ft.s (kg /m.s)
d = internal diameter of pipe, in
Q_1 = Mass flow, gal/min
μ = absolute (dynamic) viscosity, cp

Fluid Flow Equations for the Friction Loss/Pressure Drop in Pipe

Bernoulli's equation is useful in the calculation of the fluid flow. It follows the first law of Thermodynamics and it calculates the energy balance in steady state and incompressible flow. The formula for the friction term in pipe line is expressed as

$$\Delta\left(\frac{P}{\rho}+z+\frac{V^2}{2g}\right)=h_L \qquad \text{Eq (6)}$$

which,

P = pressure drop in pipe, lbf/in^2(Pa – For the SI unit remember to divide the pressure head with the acceleration of gravity.)
z = elevation of pipe, ft (m)
g = acceleration of gravity, ft/s^2 (m/s^2) – 32.2ft/s^2
h_L = Head loss, ft (m)

Dancy's formula of the friction in pipe line is expressed as

$$h_L = f\frac{L}{D}.\frac{V^2}{2g} \qquad \text{Eq (7)}$$

which,

f	= friction factor, dimensionless
L	= length of pipe, ft (m)

Dancy's friction factor, f is determined experimentally. Normally friction factor for the laminar flow conditions (Re <2100) is simple calculated with just function of the Reynolds number only, which can be expressed as

$$f = \frac{64}{R_e} \qquad \text{Eq (8)}$$

In the transition zone which with the Reynolds number of approximately 2100 to 4000. In this zone, the flow is either laminar or turbulent depending upon several factors. In this zone the friction factor is indeterminate and has lower limits based on laminar flow and upper limits based on turbulent flow conditions.

For the turbulent flow with the Reynolds number > 4000, the friction factor is not only factor of the function of Reynolds number it is function of the pipe wall as well. The piping roughness will affect the friction loss as well.