PIPING SYSTEMS FOR INDUSTRIAL PLANTS, Part I: Fluid Mechanics, Materials, Piping Systems, Piping Layout

STUDY NOTES

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Introduction

A piping system is a **set of pipes, normally closed pipes, joined together by fittings for transporting fluids.**

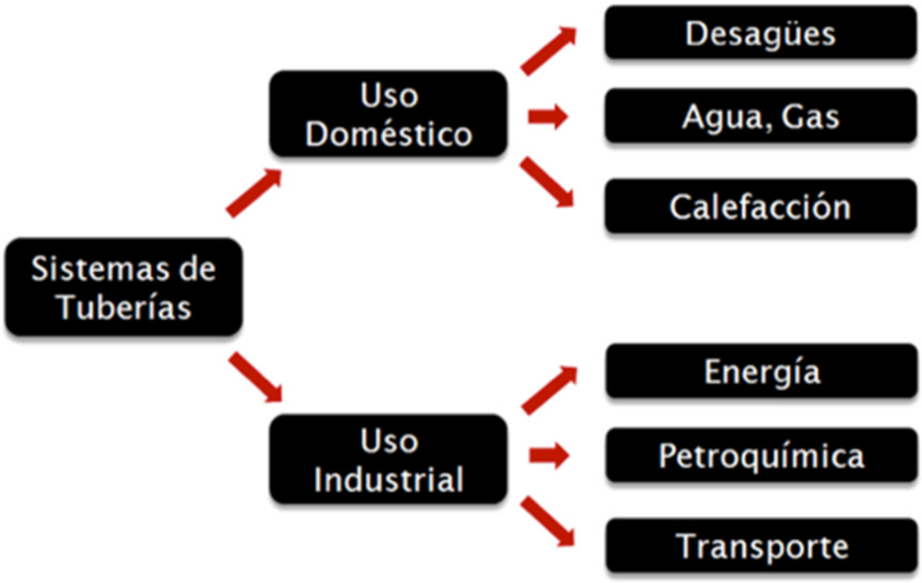
The vast majority of pipes act as pressure containers, in other words, the fluid wets the entire cross-sectional area, except for sewage drains or canals where the fluid can flow in an open surface.

The need for using pipes arises from the fact that the point of storage or flow stream is generally distant from the place where it is required.

There use goes back to antiquity, but the industrial application and commercial manufacture was only developed late nineteenth century due to the need for materials able to resist growing pressures originated by the use of steam.

Piping systems are used to transport all known pourable liquid or gaseous fluids, for pasty materials or pulp and for fluids in suspension, covering the whole range of pressure and temperature used in industrial applications, from the absolute vacuum to pressures up to 400MPa and from absolute zero to the melting temperature of metals.

Circular pipes are the most frequently used, since this form provides not only greater structural strength but also larger cross section for the same outer perimeter than any other shape. Unless specifically noted, the word "pipe" in this study notes always refers to a closed conduit, of circular section with constant inner diameter.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1. Fluid Mechanics

Obtaining the diameter of a pipe is almost always a Hydraulics problem, solved for the required fluid flow, the different elevations of the inlet and outlet, the pressures involved, velocities and the acceptable pressure drop, the nature of fluid, the material and tube type.

These calculations are usually carried out by the design team of the Process Department. Therefore, these study notes do not include all resources, graphs, tables and other related information for these types of calc's, but rather the fundamental concepts and the main equations that must be completed with suggested literature on the subject, if there is a need for more detail.

Fluid Mechanics is the part of physics that deals with the action of fluids, static or in motion, as well as the applications and engineering devices used with fluids. Fluid Mechanics is essential in such diverse fields as aeronautics, chemical engineering, civil and industrial engineering, meteorology, shipbuilding and oceanography.

The hydraulic calculation process is not the determining factor for the diameter selection of a pipe in all cases, but sometimes other design considerations. For example, **in short pipelines connecting equipment it is more convenient to use a pipeline of the same diameter of the flange of equipment, simplifying the installation and using less fittings**. Also, in the case of diameters below 2" NPS, it is sometimes practical to oversize lines, saving supports and foundations although a smaller pipe size is acceptable from the hydraulic point of view.

Very few special Fluid Mechanics problems such as laminar flow through pipes can be solved by conventional mathematical methods. All other problems need solving methods based on experimentally determined coefficients and easy to use equations.

Many empirical equations have been proposed as solutions to different flow of fluids through pipes problems. Being very limited they can only be applied when design conditions approximate to the conditions of the experiments from which the formulas were obtained.

1.1) Flow of fluids in piping systems

A fluid flowing through a pipe will always carry an amount of energy loss, which is spent on overcoming resistance opposing the flow and eventually dissipates in the shape of heat. The resistance that a pipe must overcome is of two types:

a) External, resulting from the friction between the fluid against the pipe walls, acceleration and direction changes and the resulting turbulence produced inside the pipe.

b) Internal, resulting from the friction between the fluid molecules themselves, against each other, called viscosity of the fluid.

External resistance will be greater the higher the fluid velocity and the pipe wall roughness and the smaller the pipe diameter. Internal resistance will be greater the higher the fluid velocity and fluid viscosity.

The energy used to overcome these resistances is called "head loss" or “pressure loss”, results in a gradual decrease in the pressure of the fluid, falling from one point to another in the direction of the flow of the fluid (pressure drop).

Normally, in analysis of flow of fluids it is common to divide the piping network in sections, so that no device (pump, compressor, turbine, etc. capable of absorbing or yielding energy.), with the environment is included. Thus, the only fluid energy variation between the end points of the pipeline is the produced by pressure loss.

1.2) Properties of fluids

The solution of any fluid flow problem requires prior knowledge of the physical properties of the fluid in question. Exact values of the properties of fluids that affect their flow, mainly viscosity and specific gravity, have been established by many authorities on the subject for all fluids normally used, most of this data available in the form of tables.

1.2.1) Viscosity

The viscosity expresses **the ease with which a fluid can flow when an external force is applied.** The coefficient of absolute viscosity, or simply the absolute viscosity of a fluid, is a measure of its resistance to flow or suffer internal strain. Crude oil is a very viscous fluid compared to water; in turn, gases are less viscous than water.

The viscosity of most fluids can be predicted. In some viscosity depends on the work that has been applied to them. Printing ink, wood pulp porridges and tomato sauce are examples of fluids having thixotropic viscosity properties. There is great confusion about the units used to express viscosity, hence the importance of using appropriate units when viscosity values in equations are replaced.

1.2.2) Dynamic viscosity

The dynamic viscosity can be defined as the time it takes a molecule to flow through a capillary tube at a given temperature. The unit in the International System (SI) is the Pascal Second (Pa s) or also Newton Second per square Metre (N s / m2), or Kilogram per Second Metre (kg / ms).

Poise is the corresponding unit in the CGS system of units and has dimensions of Dyne Second per square Centimetre or Grams per Centimetre Second. The Centipoise (cP) is the submultiple, 100 cP are 1 Poise, being the most often used unit to express dynamic viscosity. This, situation will apparently continue for some time into the future.

1.2.3) Kinematic viscosity

Ratio between the dynamic viscosity and density. In the international system of units (SI) the unit of kinematic viscosity is the square Metre per Second (m2 / s). The corresponding CGS unit is the Stoke (St), with dimensions of square Centimetre per Second and the Centistoke (cSt), 100 stokes, which is the most commonly used submultiple.

Kinematic viscosities of the most common fluids appear in numerous publications and are really easy to find. **It is observed that with increasing temperature, the viscosity of the liquid decreases and the viscosity of gases increases.** The effect of pressure on the viscosity of the liquid and ideal gases is so small that it has no practical interest in most fluid flow problems.

1.2.4) Density, specific volume and specific weight

The density of a substance is its mass per volume unit. The density unit in the SI is the Kilogram per cubic Metre and is denoted by ρ (Rho):

$\rho = m / v$

Metric units used are:

Gram per cubic centimetre (g / cm3)

Kilogram per cubic metre (kg / m3) = 1000 g / m3

The corresponding SI unit for the **specific volume is the inverse of the density**, cubic Metre per Kilogram (m3 / kg).

Unless very high pressures are considered, the effect of pressure on the density of liquids is not taken into account in fluid flow problems. However, the densities of gases and vapours vary greatly with pressure. For perfect gases, the density can be calculated from the formula:

Rho = P / RT

Also, the specific weight is the weight per volume unit.

Ps = P / V, where the relationship between weight and mass, is defined by:

P = m x g, where:

P = weight of the body.

m = mass of the body.

g = the acceleration of gravity.

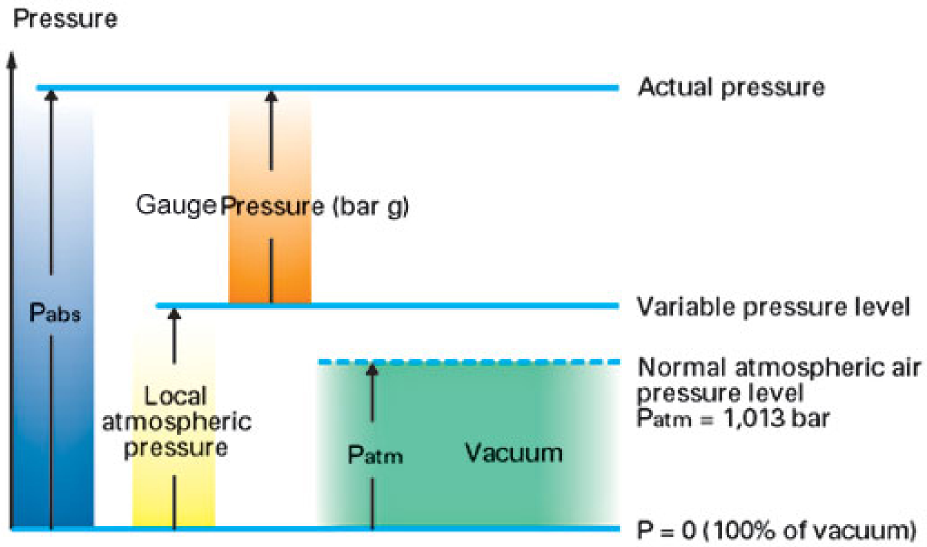
As pressure has a negligible effect on the density of the liquid, temperature is the only variable that must be taken into account when laying the groundwork for specific gravity.

The relative density of a liquid is the ratio of density to a certain temperature, with respect to water at a standard temperature. Often these temperatures are the same and 15.6º C is typically used.

S = any liquid at a certain temperature / water 15,6º.

1.2.5) Pressure measurement

The figure graphically illustrates the relationship between absolute and gauge pressures. Perfect vacuum cannot exist on the surface of the Earth but is, however, a convenient reference point for measuring pressure.



Barometric pressure is the level of atmospheric pressure above full vacuum. The standard atmospheric pressure is 1.013 bar (14.69 psi) or 760 mm of mercury.

Relative pressure is the value measured above atmospheric pressure, while the absolute value always refers to full vacuum.

Absolute pressure is the addition of the atmospheric and the gauge pressure.

1.3) Flow of fluids

All fluids are compressible, including liquids. The volume change that fluids undergo is due to a change in density, which is the result of a fluid flowing. For a fluid to experience a significant volume reduction it is necessary that the flow rate will be close to the speed of sound.

These density changes tend to occur mainly in gases, since it requires pressures up to 1000 atm to reach these velocities in liquids; however, a gas only requires a pressure ratio of 2 to 1 to achieve sonic velocities. **Compressibility of fluids is basically a measure of the density change.** Gases are generally very compressible, however, most liquids have a very low compressibility ratio. For example, a pressure of 500 kPa causes a change in water density at room temperature of only 0.024%, however the same pressure applied to air causes a change of density of 250%.

Within the Fluid Mechanics field and due to practical reasons, fluid flows are classified as compressible and incompressible, depending on the level of variation of fluid density during the flow. Incompressibility is just an approximation term, it is said that a fluid is incompressible if the density remains approximately constant throughout the flow. **In other words, the vast majority of liquids will be considered as incompressible fluids; while most gases will be considered compressible fluids.**

1.3.1) Types of flow

It would be ideal if all the pipes in an industrial installation only transported liquids, or gases or solids in the pure state (not mixed). Reality is quite different. In practice, biphasic or multiphase fluids are normally found in many process plants.

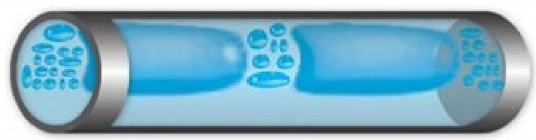
In the case of biphasic fluids, there are various possible configurations:

Dispersed bubble flow

Elongated bubble flow

Stratified flow

Annular flow with



Slug flow

Stratified wavy flow

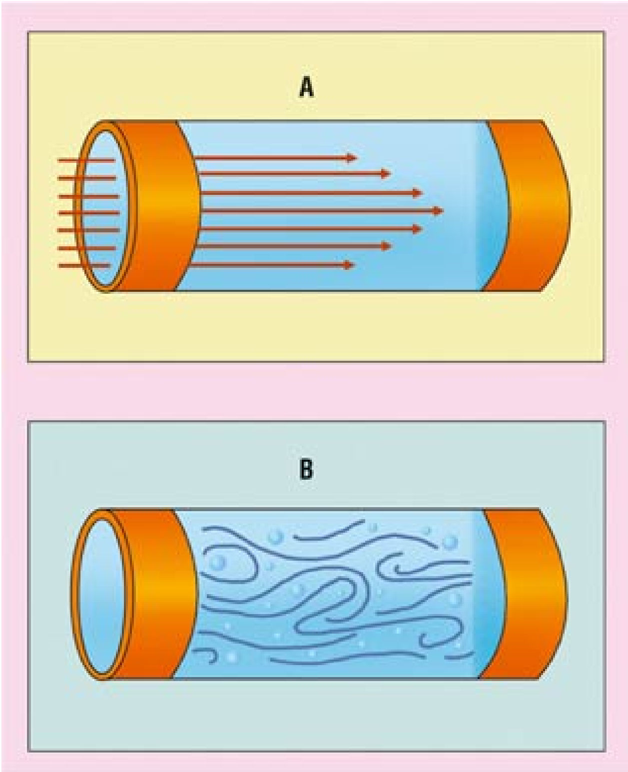
In these cases and in order to determine the diameter of the pipeline, the type of flow (according to that seen above) must be considered, where the relevant considerations should be applied taking into account the loss for each of the phases. **There are different methods for calculating two-phase and multiphase fluid flows. In practice, these developments are carried out with specific software applications and given the complexity of these calculations it requires that the designer to be an experienced professional**, thus, it is the designer who chooses which method to use for each case.

1.3.2) <u>Flow regimes</u>

There are two different types of flow regimes. **If small amounts of a coloured fluid are injected in a water stream flowing through a glass pipe and we observe the behaviour of the coloured filaments in the different areas after the injection points,** the following will be seen:

If mean velocity of the stream is small, the coloured filaments will be seen as straight lines, as shown in Figure A below. As the flow increases, these filaments continue to move in straight lines until a certain velocity is reached where the filaments begin to curl, breaking in an abrupt and fuzzy way; this occurs at the so-called critical velocity. **At higher velocities than the critical, the filaments disperse indeterminately throughout the stream,** as indicated in Fig. B below.

The flow regime that exists at velocities lower than the critical is known as **laminar and sometimes as viscous regime**. This regime is characterized by concentric cylindrical layers sliding over each other in an orderly manner. The fluid velocity is maximum at the central axis of the pipe and decreases rapidly to zero at the pipe wall.



When velocities are greater than the critical, the regime is known as turbulent. In this regime there is an indeterminate and irregular movement of the particles in the fluid, following transversal paths with respect to the main stream. The distribution of velocities in turbulent regime is more uniform across the diameter of the pipe than for laminar regime. Although there is a turbulent motion across most of the diameter of the pipe, there is always a small layer of fluid in the pipe wall, known as the "peripheral layer" or "laminar sublayer" moving in laminar flow.

There are numerous publications where "reasonable" velocities are presented to be used in project applications, sometimes in the form of nomograms and tables. Normally, the flow rate, density and flow velocity are known, thus the diameter of the pipeline can be determined.

1.3.3) Reynolds number

Osborne Reynolds investigations have shown that the flow regime in pipeline, whether Laminar or Turbulent, depends on the pipe diameter, fluid density, viscosity and fluid flowrate. The numerical value gives a dimensionless combination of these four variables, known as the Reynolds number. It may be considered as the ratio of the dynamic forces of the fluid mass with respect to the deformation stresses caused by viscosity.

The Reynolds number is:

$$N_{re} = \frac{Dv\rho}{\mu}$$

Where::

D: pipe diameter

v: fluid velocity

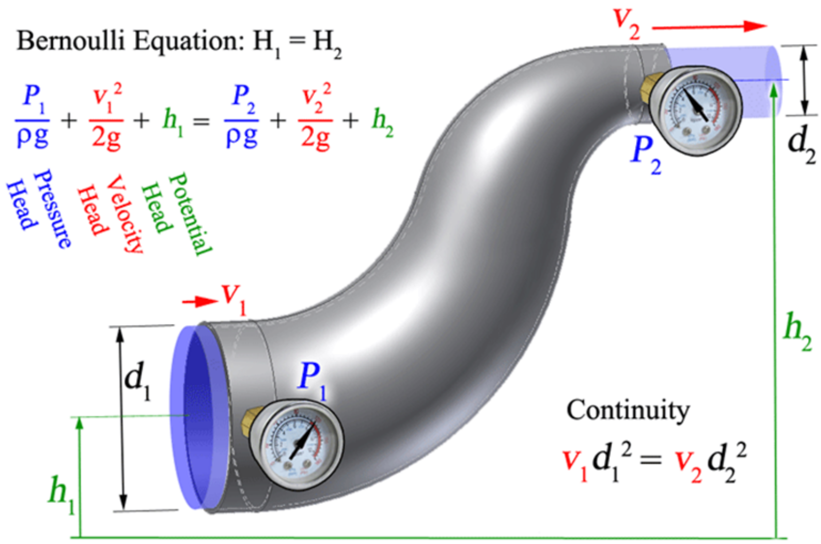
ρ: density of the fluid

μ: dynamic or absolute viscosity

For technical studies, the flow rate in pipes is considered Laminar if the Reynolds number is less than 2,000, and it is considered Turbulent if the Reynolds number exceeds 4,000. Between these two values the so-called "critical" area is found, where the flow is unpredictable, possibly being laminar, turbulent or transition flow, depending on many conditions.

1.4) Energy conservation

Bernoulli's equation is obtained by applying the Energy Conservation law to a fluid. The energy of a flowing fluid consists of different types of energies: the internal energy and the energy due to pressure, both at the velocity and position of the system being analysed. If two sections of a pipeline are analysed in the flow direction as described by the following picture:



Bernoulli's principle states: "Along any flow stream, the sum of the piezo metric heights (due to pressure), the kinetic heights (due to Velocity), and potential heights (due to position) in two different sections of a systems is constant" ... which is nothing different than the energy conservation law, but expressed in the terms described above.

If a perfect liquid is analysed, considering also that there is no friction (energy loss), no turbine or consumer (extracted energy) and no pumps or compressors (added energy) the equation can then be written:

$$\frac{P_1}{\rho g} + \frac{v_1^2}{2g} + h_1 = \frac{P_2}{\rho g} + \frac{v_2^2}{2g} + h_2$$

In the case of incompressible fluids in permanent flow regime, changes in internal energy are negligible, thus the equation can be written:

$$\frac{P_1}{\rho g} + \frac{v_1^2}{2g} + h_1 + h_A + h_f + h_E = \frac{P_2}{\rho g} + \frac{v_2^2}{2g} + h_2$$

$$\frac{Energy}{Section\ 1} + \frac{Energy}{Added} + \frac{Energy}{Lost} - \frac{Energy}{Extracted} = \frac{Energy}{Section\ 2}$$

It is worth mentioning that each of these terms can be expressed in metres (linear unit of MKS system) constituting what is called head:

$$\frac{v^2}{2g} = \frac{m^2/\,s^2}{m/\,s^2} \quad [m]\ Velocity\ Head$$

$$\frac{P}{\rho g} = \frac{kg/m^2}{kg/m^3} \quad [m]\ Pressure\ Head$$

$$h = m \qquad [m]\ Potential\ Head$$

1.4.1) <u>Mass conservation</u>

The flow continuity equation is a consequence of the mass conservation law. For a continuous flow, the mass of fluid passing through any section of the stream per unit of time is constant. This can be calculated as follows:

$$\rho_1 * A_1 * v_1 = \rho_2 * A_2 * v_2 = Constant$$

For incompressible fluids and for all practical applications where the density of the fluid is the same in all sections of the stream, the equation becomes:

$$Q = A_1 * v_1 = A_2 * v_2 = Constant$$

where:

A: sectional area in [m2]

v: average velocity of the stream [m/s]

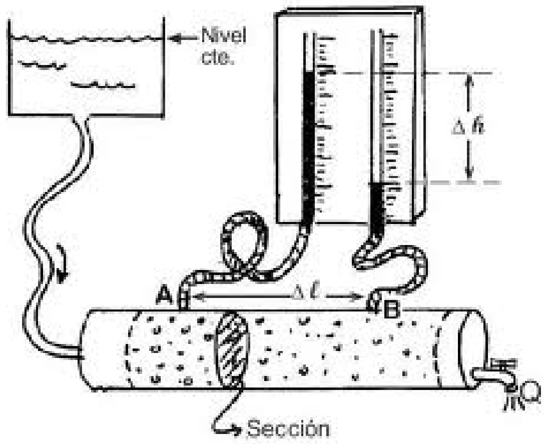
ρ: fluid density [kg/m3]

Q: flowrate measured in [m3/sec] or [l/sec]

1.5) Pressure loss

Flow of fluids in pipes is always accompanied by friction, produced between the particles themselves and between the fluid and the pipe wall, in other words, energy loss. It means that there is a pressure loss in direction of the flow.

Due to this pressure loss, if two manometers are connected to two different sections of a pipe with a running fluid, the manometer at the inlet section of the pipe will indicate a greater static pressure than the one located at the outlet section. **Darcy's equation determines the pressure loss between two sections of a pipeline, and is valid for both laminar and turbulent flow of any fluid in a pipe.**



However, it may happen that due to extreme velocity, the downstream pressure decreases so that just equals the vapour pressure of the liquid, taking place a phenomenon known as cavitation, where flow rates obtained through calculation will be inaccurate. **With the applicable restrictions, Darcy's equation can be used with compressible fluids (vapours and gases).**

The pressure loss due to friction is obtained with the equations indicated below, it can be applied to a fluid flowing through a constant diameter pipe, whose density remains reasonably constant, through a straight pipe, horizontal, vertical or inclined. For vertical, inclined or variable diameter pipes, the pressure change due to changes in elevation, speed or density of the fluid must be taken into account in accordance with Bernoulli's law described above.

$$h_f = f\frac{Lv^2}{d2g} \qquad\qquad h_f = f\frac{8LQ^2}{\pi^2 g d^5}$$

Where:

hf: Pressure loss due to friction [m]

f: Friction Factor [dless]

L: Pipe length [m]

v: flow velocity [m/s]

Q: flow rate [m3/s]

d: pipe diameter [m]

These equations are the most universally used; however, there are other widely used equations such as the Hagen-Poiseuille used for laminar flow, or the

Hazen-Williams equation used for turbulent flow. The designer will have to decide which method or equation to use depending on the variables of the project.

1.5.1) Friction factor

The friction factor for laminar flow conditions (R <2.000) depends only on the Reynolds number; while for turbulent flow (R> 4000), it also depends on the pipe wall roughness.

Darcy's equations could be obtained through dimensional analysis except for the friction factor f, which must be determined experimentally and based on experience.

Between Reynolds numbers from 2000 to 4000 the region known as "critical" is found. In this region the flow may be either laminar and turbulent, depending on several factors; these include changes in section, flow direction and flow obstructions such as valves, upstream the zone under evaluation. The friction factor in this region is undetermined and has lower limits if the flow is laminar and higher limits if the flow is turbulent.

For Reynolds numbers greater than 4000, flow conditions become to be more stable and more accurate friction factors can be established. This is important because it allows the designer to determine the flow characteristics of any fluid flowing through a pipeline, given known viscosity and density of the fluid in the flow conditions.

For this reason, the equations described above are recommended over some empirical equations normally used for water, oil and other liquids and for compressible fluids, always taking into account the mentioned restrictions.

If the flow is laminar (R <2,000), the friction factor can be determined from the (Hagen-Poiseuille) equation:

$$\boxed{f = \frac{64}{R_E}}$$

When the flow is turbulent (R> 4000) the friction factor depends not only on the Reynolds number, but also on the relative roughness of the pipe wall, E / d, that is, the roughness of the pipe wall (E) compared with the pipe diameter (d).

For very smooth pipes, such as extruded brass or glass, the friction factor decreases faster with increasing Reynolds number, compared to pipes walls with higher roughness.

Since the type of the internal surface of commercial pipes is virtually independent from the diameter, wall roughness has a greater effect on the friction factor for small pipe diameters. Consequently, small diameter pipes approach the condition of great roughness and generally have higher friction factors than for pipes of the same material with larger diameters.

The first equation to determine the friction factor for turbulent flow was developed in 1937 by scientists Colebrook-White, and its expression is the following:

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{N_{re}\sqrt{f}}\right)$$

However, the most useful and universally accepted information for friction factors in turbulent flow was developed by Professor L. F. Moody in 1947, as shown below:

5. Bibliography

Bearing in mind that the piping discipline feeds other departments with information, the available literature about piping is almost endless. There are also numerous applications (excel, flash, etc.) primarily developed to facilitate data collection.

While some authors and publications have been mentioned throughout this document, the following books and references are a must **in the library of a good designer:**

- **Flow of Fluids, Crane**
- **Fluid Mechanics, Egon Krause**
- **Gas-flow Calculations: Don't Choke. Chemical Engineering, January 2000**
- **A Tutorial on Pipe Flow Equations. Donald W. Schroeder, August 2001**
- **Useful Properties of Fluids for Piping Design by Robert Kern**
- **Process Piping: The Complete Guide to ASME B31.3 by Dr. Charles Becht**
- **CASTI Guidebook to ASME B31.3 Process Piping by Glynn E. Woodsand Roy B. Baguley**
- **Process Plant Layout and piping design, Roger Hunt**
- **The Piping Handbook, by Mohinder L. Nayyar,**
- **The Piping Guide, Syentek**
- **Process Piping Design, Gulf Pub Co**
- **Rip Weaver, Two Volumes**