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The Effect of Surface Roughness on Fluid Friction
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by: John C. Tverberg
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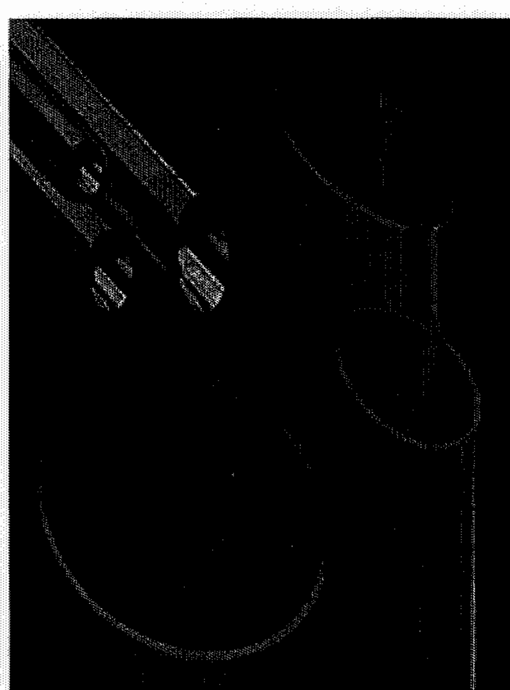
The Effect of Surface Roughness on Fluid Friction

While friction from a pipe system's surface roughness directly influences head (energy) loss, proper selection of materials minimizes erosion of pipe in critical flow regions.

by John C. Tverberg



Control of water was one of the major achievements in the development of our modern civilization. It started in the barren region between the Tigris and Euphrates Rivers of ancient Mesopotamia, the present-day Iraq, where the Sumerians created the world's first engineering works by digging canals to create elaborate irrigation systems.

In time the Arabian nomads displaced the Sumerians and formed the mighty Babylonian empire. Their great King, Hammurabi-The-Law-Giver, established the basis for the world's modern-day legal system. Much of the Code of Hammurabi dealt with water rights and the responsibility of individuals for flood control.[1]

Later the Egyptians, whose agriculture depended on the periodic flooding of the Nile river valley and its annual regeneration of the soil's fertility, developed machines to lift water from the canals for field irrigation. Similar hydraulic developments occurred later with the

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Mayans, Toltecs, and Aztecs of Mexico, and the Papagos and Pimas of the United States.

Over time, formulas developed by the ancient engineers describing the flow and properties of water were modified to include other fluids and the coefficients refined. But the basic equations remain essentially the same.

The past 50 years have spawned tremendous advances in the development of fluid handling materials in both surface smoothness and corrosion resistance. Materials acceptable 50 years ago have been replaced with better materials which, in turn, will be replaced in the future. Prior to World War II we were limited by wooden stave, riveted steel, cast iron, or concrete pipe.

Some of these materials performed admirably and some are in use even today. Recently I saw a 36-inch wooden stave pipe system carrying municipal water -- leaking, but still working.

Today we can select from among hundreds of different materials, of varying properties and price, many of which hold the promise for generations of leak-free service. Further, these materials are capable of maintaining a super-smooth interior surface, exclusive of fouling, for their lifetime.

Fluid Thinking

A fluid is defined as a state of matter, either liquid or gas, in which a uniform isotropic pressure can be supported without significant distortion. Two essential properties which differentiate fluids, density and viscosity, are necessary to solve for a specific flow condition. Fluid density is a thermodynamic property, a function of both pressure and temperature. Viscosity is a measure of the shear stress and strain rate on the fluid.

Liquids are defined as *Newtonian Fluids* if the viscosity is unaffected by the type and magnitude of motion to which it is subjected at a constant temperature. Most common fluids, like water and mineral oil, fall within this classification.

The other class, *Non-Newtonian Fluids*, exhibit other stress-strain relationships in which the viscosity decreases as agitation, or shear, increases. Pseudoplastic and thixotropic liquids -- paint, biological fluids, polymer solutions, as well as melts, adhesives, cement, and various slurries -- are examples of Non-Newtonian fluids. Such liquids require special mathematical treatment, and therefore are not represented in this discussion.

When a fluid flows through a conduit under pressure and the conduit is full, it is called a pipe or tube. When the conduit is only partially full, as in a sewer or drainage tile, it's called an open channel.

This article will review the basic equations used to determine fluid friction and the effect of surface smoothness on the loss of energy during fluid flow. Coverage will be limited to pipe, and the effect of surface roughness on the energy or head loss during fluid flow.

We will use the term "pipe" to describe a tubular cross-section, although "tube" could be used as well. The difference between a pipe and a tube is dimensions and specification. A pipe is measured by its inside diameter, a tube by its outside.

Velocity

In 1895 Osborne Reynolds[2] defined the critical velocity of a fluid in a pipe as that value where the flow changes from laminar to turbulent. Reynolds established a series of constants, later named the Reynolds Numbers, applicable to all fluids. The Reynolds number is dimensionless, independent of the system of units used.

Most commercial pipe with normal surface roughness will experience laminar flow if the Reynolds Number is less than 2100, and turbulent flow if greater than 3000. Water distribution systems usually operate with a Reynolds Number in excess of 10,000, so most water systems are turbulent.

Factors which influence the Reynolds Number include velocity of the fluid, diameter of the pipe, density of the fluid, and viscosity of the fluid. Because both density and viscosity are temperature-dependent, the Reynolds Number will change with the temperature for a given pipe diameter.

To convert from water to any generalized fluid, both the density and viscosity must be considered in the Reynolds number:

$N_R = \rho VD/\mu$ or VD/ν

... where:

$\nu = \mu/\rho$ or the kinematic viscosity

ρ = density of the fluid

μ = viscosity of the fluid

V = average velocity

D = wetted diameter

Laminar Vs. Turbulent Flow

In laminar or streamline flow, the fluid particles occupy essentially the same relative transverse position as the bulk fluid moves through the pipe. However, the fluid particles near the axis will move farther than a fluid particle near the pipe wall. In other words, the velocity of the particle at the pipe axis is higher than that of a particle at the pipe wall. The velocity profile will form a true parabola of circular cross-section.

In turbulent flow the fluid particles take an irregular path, and their longitudinal speed through the pipe is roughly the same whether at the pipe wall or at the axis. Turbulence increases with the Reynolds Number. Velocity is essentially zero at the pipe wall, but within a short distance the velocity distribution becomes more uniform as the Reynolds Number increases.

Stanton and Pannell[3] compared the average-to-maximum velocity ratios to the Reynolds Number, N_R, as presented in Table 1:

N_n	V_n/V_m
1700 and under	0.50
2000	0.55
3000	0.71
5000	0.76

10,000	0.78
30,000	0.80
100,000 and over	0.81

With laminar flow at Reynolds Numbers below 2000, the velocity forms a parabola with the maximum velocity at the center axis of the pipe[4], and an average velocity about half that of the maximum centerline velocity. At N_R >10,000 the flow is turbulent and the velocity distribution curves are much flatter.

The average velocity is about 80 percent of the maximum velocity, and the circle of mean velocity has a radius of 0.375 D. The significance of this number is in the effect of velocity on erosion or erosion-corrosion of the pipe wall. All materials have certain critical velocities where the wall is eroded by the impingement of the fluid particles.

Bends are especially susceptible, because the line of maximum velocity moves from the axis to the convex side. For example, a copper pipe system with a critical erosion velocity of 10 feet per second (fps), operating at an average velocity of 10 fps, a maximum velocity of 12.5 fps, and a bend radius of 0.625 D, over time will erode because the maximum velocity is now on the outer surface and above the critical velocity.

The only way to prevent such erosion is to reduce the velocity, increase the bend radius, or change to a more erosion-resistant alloy. A rule of thumb is that erosion resistance is proportional to the hardness of the material -- provided the material is not corroded by the contained fluid.

Essential Equations

A rigorous mathematical model of fluid flow requires four simultaneous equations to represent the process.

1. The *Continuity Equations* require mass to be conserved at every point in the flow. Typically these are two partial differential equations that relate the velocity in the x, y, z and radial directions.

2. The *Momentum Equations* relate the forces in the fluid to its acceleration according to Newton's Second Law, F = ma. This involves four partial derivatives relating the velocity components, the force, density, and viscosity.

3. An *Energy Equation*, expressing the First Law of Thermodynamics for a fluid element, relates the density, velocity, temperature, and viscosity with respect to time. This function is not required to solve for pressure and velocity if the flow is non-compressible and viscosity is constant, but becomes a dependant equation to calculate the temperature.

4. An *Equation of State*, necessary if the density changes significantly during flow, expresses the density as a function of pressure, temperature, or both.

The first three equations are partial differential formulas usually expressed as integral equations. They are required if the general velocity pattern is not known. Thankfully, most of the calculus has been solved, or empirical equations are available to assist. Discussions here will relate to the algebraic equations only.

Head Loss

Energy loss experienced by a fluid moving through a pipe is called the head loss or pressure drop. This lost energy is transformed into heat and carried away by the fluid.

Manifested by decreased velocity or decreased flow through the pipe, energy loss is called pipe friction (h_f) if it occurs in the straight pipe sections of uniform diameter and roughness. Change in inside surface roughness contributes significantly to continuous head loss, which accounts for the majority of energy loss in the pipe system.

Minor sources -- but still significant toward total energy loss -- include reduction in cross-sectional area (h_c); enlargement of cross-sectional area (h_e); obstructions such as gates, valves, or changes in the direction of flow (h_o); and bends of any deflection angle or any radius of curvature (h_b). This article will not consider any of these minor energy losses.

Total head loss is expressed as: $H_L = h_f + h_c + h_e + h_o + h_b$.

Pipe Friction Loss

Five empirical laws[5] used to express fluid friction in a pipe are generally part of all friction flow formulas:

1. Friction loss in turbulent flow systems generally increases with surface roughness of the pipe. When the flow is laminar, the frictional loss is independent of the interior surface roughness.

2. Friction loss is directly proportional to the area of the wetted surface, or π DL.

3. Friction loss varies inversely as some power of the pipe diameter, or $1/D^x$.

4. Friction loss varies as some power of the velocity, or V^a.

5. Friction loss varies as some power of the ratio of viscosity to density of the fluid, the kinematic viscosity, or $(\mu/\rho)^r$.

Combining these factors yields a generalized equation applicable to any fluid for friction loss:

$$h_f = (K')(\pi DL)(1/D^x)(V^a)[(\mu/\rho)^r]$$

or

$$h_f = [K'\pi (\mu/\rho)^r](L/D^b)(V^a)$$

... where K' is a combined roughness coefficient and proportionality factor, μ the dynamic viscosity, ρ the mass density, and a, b, m, n, r generalized exponents.

All of the original hydraulic flow equations were developed using water at ambient temperatures. Fortunately, viscosity and density effects of water are small and thus neglected in most of the original equations, or included in the general coefficient.

The generalized equations became: $h_f = Z(L/D^m)(V^n)$

... where Z is the modified coefficient and m and n are pipe roughness factors.

Darcy-Weisbach Basis

A number of friction factor equations were developed including one by Chezy in 1775:
$h_f = K(L/D^m)V^n$

and another by Darcy-Weisbach in the early 1900s:

$h_f = f\,(L/D)(V^2/2g)$

... where:

f = friction factor

L = length of pipe

D = diameter of pipe

V = velocity of the fluid

g = gravitation constant

In spite of deficiencies with this equation -- namely the velocity exponent and lack of a diameter exponent -- most of the current equations are based on those of Darcy-Weisbach. The significance of the Darcy-Weisbach equation stems from its inclusion of a friction factor "f." Originally, the friction factor was not related to specific surface roughness, but rather to the pipe diameter and mean velocity.

Prandtl and von Karman further refined the equation, determining that, even in extremely turbulent flow, a very thin layer of laminar flow exists next to the pipe wall. The thickness of this layer increases with the Reynolds Number. They further defined the term "hydraulically smooth" if the height of the protuberances on the pipe wall is less than the thickness of this laminar boundary layer.

Prandtl and von Karman determined that hydraulically-smooth pipes have a value of f that is independent of the relative roughness and is a function of the Reynolds Number only. When turbulence is fully developed, f becomes independent of the Reynolds Number and depends only on the relative surface roughness. This is an important concept because it quantifies the effect of surface roughness.

In 1939 Colebrook and White modified the Darcy-Weisbach equation by developing a means to calculate f by plotting it against N_R. They established minimum values for f for each value of D/k in accordance with Prandtl-von Karman.

"Pipe Type" Roughness Factor

The Manning Formula, one of the better known *open channel* equations applied to pipe friction, includes surface roughness as a function of pipe type:

$V = (0.59/n)d^{2/3}S^{1/2}$

or

$h_f = (2.87n^2)LV^2/D^{4/3}$

... where:

V = average velocity

D = pipe inner diameter

S = energy gradient or loss of head in feet/foot of pipe

n = coefficient of roughness

h_f= friction head loss

L = pipe length

Table 2: Roughness Values "n" for Manning Equation

Type of Pipe	n Range
Stainless steel, brass, glass, plastic	0.009-0.011
Cement, ceramic--smooth	0.010-0.012
Hot-worked carbon steel, cast iron	0.011-0.013
Concrete	0.011-0.017
Clay drainage pipe	0.012-0.014
Dirty or tuberculated cast iron	0.015-0.035
Corrugated iron	0.020-0.022

Colebrook and White later modified the equations for the transition region between laminar and turbulent flow, defined as that with N_R between 2100 and 3000. They included a roughness "k" factor related to the generalized type of pipe such as concrete, cast iron, galvanized iron, etc. varying from 0.00015 foot (smoothest) to 0.030 foot (roughest).

Flexible Formulation

In the early 1930s A. Hazen and G.S. Williams developed a similar equation, known as the Hazen-Williams formula, that applies to either pipe or open channels. The most commonly accepted form is: $V = 1.318C(R^{0.63})(S^{0.54})$

... where:

V = mean or average velocity

C = Hazen-Williams roughness coefficient or "C" factor

R = hydraulic radius, D/4, or total cross-section divided by wetted perimeter

S = slope of energy gradient or loss of head in feet/foot of pipe, or h_f/L

Since the value of "C" is based on surface roughness, materials with equivalent surface roughness will have the same "C" value. The relationship between the Manning "n" factor and the Hazen-Williams/Colebrook-White "C" constant is $C \approx 1/n$.

The surface roughness is controlled by the pipe fabrication process, while material composition dictates corrosion resistance. Cold drawn or tube-reduced material has essentially the same finish as welded tube or pipe made from cold rolled strip, thus essentially the same "C" factor.

This equation was modified somewhat to estimate the friction loss in fire protection systems[6]: $\_p = (4.52\ Q^{1.85})/(C^{1.85}D^{4.87})$

... where:

_p = friction loss in psi/ft

Q = flow rate in gpm

C = Hazen-Williams coefficient

D = pipe inside diameter in inches

Consider Corrosion, Erosion

Corrosion and erosion are critical factors, since corrosion- and erosion-prone materials like carbon steel, cast iron, or copper will deteriorate over time and subsequently increase friction loss. Table 3 illustrates the progression of "C" factor degradation with unlined cast iron pipe.

Table 3: Variation in Hazen-Williams C Factor with Time for Unlined Cast Iron Pipe

Age of Pipe (Years)	C Factor
New	120
10	105
15	100
20	95
30	87
50	75

Stainless steels, corrosion-resistant nickel alloys, and titanium do not degrade appreciably over time, and therefore maintain a fairly constant head loss for the lifetime of the system. Of course, all materials are subject to fouling, which may result in increased roughness and decreased velocity.

However, increasing the fluid velocity so that the flow shear forces exceed the bond strength of the fouling deposits will minimize fouling effect.[7] This will work only if the material has sufficient erosion resistance to prevent erosion at these higher velocities.

Table 4 lists typical "C" factors for the different types of pipe, taking into account the method of fabrication.

Table 4: Hazen-Williams or Colebrook "C" Factor Values

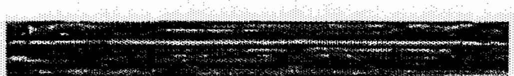
Type of Pipe	Roughness μ -inch	Range for "C"	Typical
Hard plastic, glass, electropolished stainless steel	2-10	150-160	160
Mechanically-polished stainless steel	4-16	140-160	150
Stainless steel, fresh-drawn copper/brass	16-100	120-150	140
Rubber	32-125	100-150	120
Seamless, hot-worked carbon steel	125-500	100-140	120
Cast iron, new	250-500	100-140	100
Old copper/iron pipe	125-1000	80-120	90
Cast iron, old	500-1000	60-80	60
Corrugated steel	> 2000	40-60	60
Tuberculated iron pipe	500-2000	40-60	40

Surface Analysis

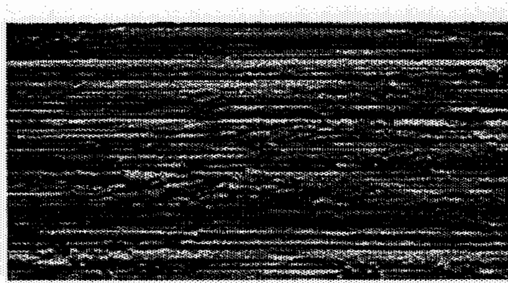
The scanning electron microscope (SEM), an ideal tool for examining the topography of various pipe surfaces, provides a means to understand the significance of the "C" values.

The photomicrograph to the right illustrates an electropolished stainless steel surface wiht a roughness of 4 μ-inch R_a. Keep in mind that these photomicrographs are at a magnification of 450 diameters; increased magnification will acentuate any surface defects.

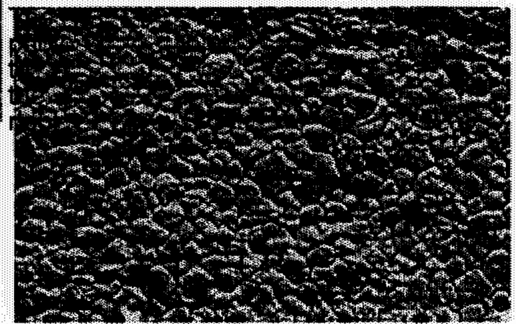
This surface is extremely smooth with very few depressions--only those resulting from the removal of inclusions by the electropolishing operation. Vacuum induction melted and vacuum arc re-melted steel, with almost no inclusions, has an even smoother electropolished surface.



The photo to the left illustrates a mechanically polished stainless steel



surface with a roughness of 8 μ-inch R_a. This is typical of honed or lapped surfaces, and the the unaided eye appears to be highly polished.



represents a drawn- and acid-cleaned stainless steel surface with a roughness of 30 μ-inch R_a. This is typical of most commercial pipe finishes, whether welded or seamless, stainless, copper, or carbon steel.

These SEM photomicrographs clearly illustrate the differences in the three surfaces, which on the macroscopic scale look nearly the same to the unaided eye, but have a significantly different effect on the surface laminar flow layers.

Comparison of Materials

So, how does the "C" factor affect performance? Comparing several different materials having different surface roughnesses affords the best illustration.

For this purpose we will calculate the friction loss using the fire protection piping equation, assuming a 4-inch schedule 40 pipe carrying 500 gallons of water per minute (gpm) or 66.85 cubic feet per minute (cfm) or 1.114 cubic feet per second (cfs).

Four different materials are compared: electropolished stainless steel, commercial-grade stainless steel or copper, hot worked carbon steel, and 20-year-old cast iron. The internal diameter of the pipe is somewhat larger than the stated diameter because pipe usually is made to the minimum wall at a fixed outside diameter. In this case the inner diameter is 4.062 inches.

The cross-sectional flow area is 12.959 in² or 0.090 ft². The calculated mean velocity at this flow is 12.38 fps, which is a safe velocity for stainless steel but not for a softer alloy. The results are tabulated in Table 5.

Table 5: Variation in Friction Loss for Various Types of Pipe Materials

Material	C Factor	Δ p psi/ft.	h_f ft./ft.	Δ p psi/100 ft.	Head loss in 100 ft.
Electropolished stainless steel	160	0.040	0.092	4	9.2
Stainless steel, copper	150	0.045	0.104	4.5	10.4
Carbon steel, cast iron	120	0.069	0.159	6.9	15.9
Cast iron, 20 years old	95	0.106	0.245	10.6	24.5

The higher "C" factor for electropolished stainless steel provides a somewhat lower pressure drop and head loss than that of materials in the second category. However, the major improvement is in the use of corrosion-resistant materials where, over time, a significant improvement in head loss and pressure drop is noted.

Another major improvement attributable to better surface smoothness is lower pump horsepower to maintain velocity and flow. The horsepower requirements may be calculated from the following formula: hp = QwH/550

... where

hp = horsepower

Q = flow in cfs

w = unit weight (for water, 62.4 lbs/cf)

H = available head in feet

Using the calculated head loss value shows the amount of horsepower consumed by friction alone, thus making an even stronger case for smoother surfaces. Electropolished stainless steel will require 0.51 hp in 100 feet to overcome the pipe friction. Twenty-year-old cast iron will require 1.34 hp to overcome the pipe friction, or 2.65 times that required by the electropolished stainless steel.

The total horsepower will depend on the operating pressure of the system. Assuming a pressure of 150 psi, 43.9 horsepower is required. Electropolished stainless steel requires 44.3 hp in 100 feet to maintain the flow, while 20-year-old cast iron requires 45.3 hp, or a 3 percent increase in horsepower over the smoothest surface.

Harder and Smoother

Flow in most systems occurs in the turbulent regime. When operating in this mode it's important to consider the critical erosion velocity of the material of construction to prevent erosion at points where the flow deviates from straight-line conditions. In general, the harder the pipe material the greater the erosion resistance.

Surface roughness or finish has a definite effect on the flow characteristics of piping materials. As the surface becomes smoother the friction head loss decreases, and the additional energy required to maintain flow is minimized.

For long-term performance, a corrosion-resistant material that does not degrade with time will maintain the original design performance of the piping system and not require additional pumping capacity as the system ages.

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