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Pipeline Efficiency Considerations in Natural Gas Networks

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ABSTRACT

The use of an efficiency factor to make pipe equations match physical reality is not a new concept - it's been around as long as there have been flow equations. It fell into some disrepute and was deemed unnecessary by some when sound theoretical equations for pipe flow began to replace the older empirical ones. Efficiency, however, is of more use that just fixing bad equations since it also is useful in adjusting specific pipes for problems and considering operational issues.

A previous paper, *A Tutorial on Pipe Flow Equations*, presented at the 2001 PSIG meeting as a replacement paper in the wake of 9/11 but not published with the proceedings since it was too late, ended with the thought that pipeline efficiency was a valuable tool in calibrating gas models, more so than that of pipe roughness. Since then, I have received much verbal support from people within the industry but continue to hear comments that pipe roughness should be used as “the” tuning parameter. This paper builds on the original paper to explore the concept of pipe efficiency, its effect on flow equations, and its value as a calibration tool. Along the way some concepts regarding system design in the face of load variance within a day are also presented. Also some considerations with using the Panhandle equations that have been lost over time are mentioned.

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1. Introduction and Problem Statement

The flow of natural gas through pipes is well known in the literature and will not be re-derived here. For more details, please refer to the earlier papers referenced in the bibliography, particularly the excellent detailed derivation in the one by Susan Gibson from the 1981 PSIG conference. Flow is described by the following equation, here presented in its implicit form of flow as a function of pressure drop:

$$Q = C \frac{T_b}{P_b} D^{2.5} e \left(\frac{P_1^2 - P_2^2 - \frac{C_H g (H_2 - H_1) P_a^2}{Z_a T_a}}{L g T_a Z_a f} \right)^{.5} \quad (1)$$

Where:

C	Constant, 77.54 (English units); .0011493 (Metric units)
C _H	Elevation correction constant, .0375 (English units); .06835 (Metric units)
D	Pipe diameter (inches) (millimeters)
e	Pipe efficiency (dimensionless)
f	Darcy-Weisbach friction factor (dimensionless)
g	Gas specific gravity (dimensionless)
H ₁	Inlet Elevation (feet) (meters)
H ₂	Outlet Elevation (feet) (meters)
L	Pipe length (miles) (kilometers)
P _a	Average Pressure (PSIA) (Kilopascals)
P _b	Pressure base (PSIA) (Kilopascals)
P ₁	Inlet pressure (PSIA) (Kilopascals)
P ₂	Outlet pressure (PSIA) (Kilopascals)
Q	Flow rate (standard cubic feet/day) (standard cubic meters/day)
T _a	Average temperature (°R) (°K)
T _b	Temperature base (°R) (°K)
Z _a	Compressibility factor (dimensionless)

Let us greatly simplify this equation to get to its essential form significant for this discussion:

$$Q = C_1 e \left(\frac{\Delta P^2}{f} \right)^{.5} \quad (2)$$

where:

$$C_1 = C \frac{T_b}{P_b} D^{2.5} \left(\frac{1}{L g T_a Z_a} \right)^{.5} \quad (\text{constants})$$

and:

$$\Delta P^2 = P_1^2 - P_2^2 - \frac{C_H g (H_2 - H_1) P_a^2}{Z_a T_a} \quad (\text{pressure drop effects})$$

This equation is implicit in that, without some simplifying assumptions, the friction factor *f* is a function of the flow rate *Q* thus putting *Q* on both sides of the equation. The “practical” equations such as the Panhandle A & B, Weymouth, Spitzglass, AGA, and IGT, none more recent than the early 1960’s, all make simplifying algebraic assumptions by stating the friction factor as a function of pipe diameter *D* and Pressures *P*₁ & *P*₂. The advent of more powerful computers has rendered these equations obsolete in favor of true implicit forms such as Colebrook-White and the more modern GERG equation, and their equivalent explicit representations such as those by Swamee/Jain and Chen.

For purposes of determining the friction factor, it has been

found that fluid flow may be characterized by a dimensionless grouping of variables known as the Reynolds’ Number, which is defined as:

$$N_{re} = \frac{D v \rho}{\mu} \quad (3)$$

Where:

N _{re}	Reynolds' number (dimensionless)
D	pipe diameter (feet) (meters)
v	fluid velocity (feet/second) (meters/second)
ρ	fluid density (lb _m /foot ³) (kg/meter ³)
μ	fluid viscosity (lb _m /second-foot) (kg/second-meter)

The Colebrook-White equation represents a combination of two other equations:

The “Smooth Pipe Law” of von Karman and Prandtl, in which *f* is a function of only Reynolds’ Number:

$$\frac{1}{\sqrt{f}} = 2 \log_{10} (N_{re} \sqrt{f}) - 0.8 \quad (4)$$

The “Rough Pipe Law” of Nikuradse for full turbulence in which *f* is a function of only a new concept ϵ called “pipe roughness”:

$$\frac{1}{\sqrt{f}} = 2 \log_{10} \left(\frac{D}{\epsilon} \right) + 1.14 \quad (5)$$

The resulting Colebrook-White equation is then:

$$\frac{1}{\sqrt{f}} = -2 \log_{10} \left(\frac{\epsilon/D}{3.7} + \frac{2.51}{N_{re} \sqrt{f}} \right) \quad (6)$$

In this statement the first term within the logarithm represents the “Rough Pipe Law” while the second represents the “Smooth Pipe Law”, and the two components have been adjusted to achieve a smooth transition. The GERG equation in essence introduces a new term called “*n*” that influences this transition as follows: *n* = 1 implies Colebrook White, *n* = 10 implies a fully sharp corner transition between smooth and rough, and 1 < *n* < 10 implies a transition somewhere in between. The Swamee/Jain and the Chen equations are mathematical equivalences of the Colebrook White equation derived by successively replacing the “*f*” term on the right hand side.

These equations are shown graphically in the familiar Moody Diagram shown in Figure (1) and simplified for clarity in Figure (2). Neglecting the laminar and critical zones, which correspond to low flow rates and are of little interest in gas systems, the blue lines in the transition and complete turbulence zones show friction factor as a function of Roughness and Reynolds’ Number according to the Colebrook White equation. By extension, these also represent the Swamee/Jain and the Chen equations. The GERG equation can be visualized by extending the complete turbulence lines

horizontally until they intersect the “Smooth Pipe” line, and then picking some value in between.

Note that there is both a right and left side to this diagram. No matter which representation is being used, in the right, or fully turbulent side, roughness is a dominant effect, while in the left, or transition, side, roughness appears only marginally, if at all.

Note that equation (1) contains a pipe efficiency e that may be used to adjust the equation to match reality. There have been many authors in the gas engineering literature (including the founder of Stoner Associates and his mentors at the University of Michigan), who belittled the use of efficiency as a modeling tool for aesthetic reasons. Their feeling was that using a “correct” pipe flow equation such as the fundamental one with the Colebrook-White friction factor alleviated the need for including an efficiency factor to correct the equation to reality, implying that tuning could be accomplished with roughness alone. While that surely addresses problems with the equation, there are other problems associated that must be addressed. Their view proved to be somewhat short-sighted and academic, and this fact was recognized by the people charged with doing the modeling. This paper’s task is to show why efficiency is a valid concept and is needed.

As shown above, any fundamentally based approach to tuning based on pipe roughness falls apart when flow rates are changed. Even recognizing that tuning becomes less important at low flow rates due to the associated lower pressure drops, the use of roughness alone can lead to unrealistic roughness values that do not work over the entire required range. Furthermore roughness is intuitively a pipe resistance issue while many of the causes of deviation from ideality intuitively involve pipe cross-sectional area, which efficiency is in a better position to address. This will be further explored in Section III below.

Ultimately the concept of pipeline efficiency really involves four separate issues:

1. Accounting for flow equation problems,
2. Accounting for pipe problems such as bends, fittings, out-of-round, junk inside, and the like,
3. Accounting for operational issues such peak hour to peak day differences, and
4. Accounting for load diversity.

Since no flow equation is without problems, no pipe is ideal, and operational issues abound, the use of efficiency is essential. This suggests that pipe efficiency is really the multiplicative result of the four separate components defined above:

$$e = e_1 \cdot e_2 \cdot e_3 \cdot e_4 \quad (7)$$

Where:

e Overall pipe efficiency (dimensionless)

e_1	Pipe equation efficiency component (dimensionless)
e_2	Pipe condition efficiency component (dimensionless)
e_3	Peak-to-average efficiency component (dimensionless)
e_4	Load diversity efficiency component (dimensionless)

These will be discussed at length in the following sections, but it is important to note that the combination of e_1 and e_2 represent what is most commonly meant by pipe efficiency and applies to all types of analysis, both steady-state and transient. e_3 is a means of applying transient considerations to steady state problems; hence it should be used in steady state analysis but not in transient. e_4 is only valid for low pressure distribution networks in which transient analysis is rarely if ever used.

2. Flow Equation Problems

As stated above, all of the “practical” equations make some simplifying assumption about the variance of friction factor with flow ranging from constant values to explicit exponential functions. This gives rise to the fact that these equations are only valid within some range of conditions and must be corrected as conditions change. For example, my experience with the Weymouth equation has shown that at typical diameters around 20” and appropriate flows, efficiencies of 106% are often required to make the equation match observed data in a truly steady-state case. Since the forms based on the Moody Diagram surmount these problems, the remainder of this discussion, except for the following comments regarding the Panhandle equations, will deal only with the Colebrook-White equation, although its conclusions are equally valid for the GERG equation and its explicit forms. Therefore, this component of efficiency, e_1 , will be considered to be 100% or 1.00 since the equation should not need correcting.

For those still using the Panhandle equations, either “A”, “B”, or some variant thereof, there is a further consideration that seems to have been lost in antiquity. Arthur E. Uhl in IGT’s Report No. 10, published in 1965, pointed-out that both Panhandle equations appeared to imply a base efficiency of 90%. This was echoed in the Hyman, Stoner, and Karnitz paper of 1975, but I have heard little of it since. As the Figure (3) shows, for a typical pipe 90% works well for the Panhandle “A” equation but 85% may be more appropriate for Panhandle “B”. The problem is that the error here is consistently away from conservative design even in the flow ranges for which the equations supposedly “work”, This means that the capability for flow at any given pressure condition is significantly overstated, and this effect only increases with increasing flow rates. For these equations e_1 must be set down to at least 85-90% (0.85-0.90) or even lower

on occasion. The best answer is simply: do not use these equations!

3. Pipe Problems

Trying to define clearly and measure “pipe roughness” is a difficult task. Page A-23 of the Crane Technical Paper No. 410, *“Flow of Fluids Through Valves, Fittings, and Pipe”* shows relative roughness (ϵ/D) values ranging from 0.000005 for drawn tubing to 0.03 for riveted steel. This is quite a range and no advice is given for how to define or measure it. The notion of “pipe roughness” is probably the most vague and ill-defined concept in all of hydraulics.

The assumptions underlying the pipe flow equation defy the concept that calibration is not required since no pipe is perfectly straight or round, contains no dirt or other “gunk”, contains no weld spatter, and has no joint anomalies. In fact, the experimental data that underpins the historical development of the friction factor relationships shows significant scatter on the flow predictions. If we deny the concept of pipe efficiency, “roughness” is the only remaining variable available to adjust mathematical models to match reality. The problem with roughness is clearly shown in equation (3) above and Figure (1) & (4) below. At higher flow rates the friction factor f becomes a function of only pipe roughness, not flow, but at lower flow rates it becomes virtually independent of roughness; hence its effect is not at all uniform. Furthermore, the friction factor is relatively insensitive to pipe roughness. It would not be unreasonable to find that pipe roughness values appropriate to concrete pipe are required to accommodate a mild degradation of facilities. While it is true that certain of the issues mentioned above intuitively infer a relationship to roughness, more of them would appear to affect the cross-sectional area available for fluid transport and would therefore be more amenable to an efficiency-type correction.

The recommended approach, therefore, is to first make a reasonable assumption regarding pipe roughness based on pipe age, material, and condition, and then complete the calibration with efficiency to derive the second efficiency component e_2 .

4. Behavioral Problems

Since natural gas distribution networks do not contain significant capacitance, *i.e.* the ability to store some amount of gas within the pipes over time and use it to dampen load oscillations, their design is inherently a steady-state limiting process. Even when considering transmission systems, steady-state is generally used for design purposes because its implications are far easier to comprehend and realistic limiting design conditions are far easier to establish than transient

ones. Network design generally comprises the following steps:

1. Begin with some mathematical model of either a known network or a proposed network in terms of location of consumers and supplies and also the location and size of piping.
2. Subject this network model simultaneously to a set of limiting flow rate boundary conditions representing “design maximum loading” along with another set of available supply pressures and applicable supply flow constraints.
3. Determine the physical network’s hydraulic response as exhibited by pressures occurring in the network.
4. Compare the pressures to stated required minima and maxima and refine the proposed network as appropriate.

The steady-state assumption is really a complex one. Note that “steady-state” does not mean that pressures and flow rates aren’t changing but they are doing so in a manner in which there is no mass accumulation. In a macroscopic sense, that assumption is fine since this is how most gas distribution and some transmission networks do behave in that at any point in time the sum of the flow rates is very close to the sum of the flow rates out, but in a microscopic sense no network is ever truly steady. In distribution this is due to two factors:

1. The “on/off” digital nature of most gas consuming devices requires some degree of statistical aggregation to produce a continuous average value. This aggregation process is often referred to as “diversity”.
2. The living habits that drive gas consumption such as when during the day heating is desired, when hot water is used, and when cooking happens cause variations with time, but these are often slow enough so as to keep net accumulation very small. This variation process is often referred to as “the diurnal load pattern”.

The true system peak flow rate would have every connected burner fully turned-on simultaneously although this would never occur in reality. Even at peak heating requirements, the burners still exhibit an “on/off” tendency due to bonnet temperature limitations and therefore potential connected load is an unreasonable criterion. Steady-state loading therefore must be viewed as a realistic limiting design condition. One of the first problems is to establish a criterion for determining the time span of limiting load. In the U.S., this is usually called a peak hourly rate, while in the U.K. it is a peak six-minute flow expressed in hourly terms. In the U.S., this is left largely to the discretion of the individual companies subject to the various regulatory agencies but in the U.K. it is built into the law, as is the accepted means for estimating this value. Note that this six minute period is not the time portion of the flow rate unit. It is simply the time duration defining the peak window and shorter time implies higher flow. As loading is passed upstream to higher pressure distribution systems, and ultimately transmission systems, the capacitance and statistical

leveling needed for further aggregation becomes present and the load becomes steadier. This implies that higher pressure level systems need not be designed at as severe loading conditions as lower ones and that even in low pressure distribution, pipes closer to the customers require more stringent design than those of more of a “feeder” nature.

All of this points to a related and often confusing problem: the consistency and meaning of flow units. All supply points within any system are also load points to some upstream system, all of which must be studied and designed. What is important is that there is a significant difference for example in a peak six minute flow rate expressed in hourly terms and a peak hourly flow rate, even though both are expressed in the same units. One would not want to pass the peak six minute flow rate blindly upstream to feeding systems without compensating it for its meaning. Most modern network analysis software has the ability to analyze multiple pressure level cascading systems, but thought is often not given to consistency of flow rates that are going to be summed in the process.

Traditionally the diurnal pattern used to show a roughly sinusoidal shape that peaked during the day and reached a minimum at night. More recently there has been a strong dip occurring during the day due to temperature set-backs when customers are not at home. A variance of about 20% about the mean is relatively normal.

5. Alternative Approaches to Diversity and Diurnal Variance

Fundamentally, both diversity and diurnal variance are effects that decrease the ability of a given pipe to deliver an average gas flow rate. It is essential to realize that what is called peak flow rate is always an average of some sort – the shorter the time period, the greater the average flow rate, but an average nevertheless. This suggests that we can account for the hydraulic effect of both of these in one of two ways: either we can overstate the flow or we can understate the efficiency. Equation (2) can be re-written into a pressure drop form showing pressure drop, ΔP^2 , as a function of flow that shows this clearly:

$$\Delta P^2 = C_1 f \left(\frac{Q}{e} \right)^2 \quad (8)$$

If done properly, either will have the same hydraulic effect on the transmissibility of the gas, and it is a matter of taste which to chose. Interestingly enough, two separate groups of planners within a major U.S. transmission company independently chose opposite alternatives for their parts of the system and when they merged in 1974, their arguments were brutal! I know well because I was caught in the middle.

Efficiency finally won out for reasons similar to those described below.

Since it derives from a process of aggregation, diversity generally has a definite spatial component. By that I mean that moving upstream away from the consumers tends to provide a greater number of items to average and a lesser detrimental diversity effect. For example, the service line feeding a single house over a long distance should be sized for the full simultaneous burner capacity of that house if it is to be adequate. As more houses are included along the line, the benefits of statistical averaging come into play. We could either overstate the requirements, removing the overstatement as we move upstream, or we could state the flows at a peak hour value and de-rate the pipe efficiency. The method of overstating the flow rate has one inherent problem though: what is put in as load inflation must be tracked and taken-out as appropriate when moving upstream. Unfortunately this destroys the concept of mass continuity upon which all modern looped network analysis tools are based. Further, determining how it is appropriate to remove the inflation is no easy task. In strictly branched system (no loops) this has been approached statistically and effectively in the UK, but I am not aware that they have published any conclusive work for true networks. Furthermore, distribution in the UK is always accomplished with low pressure systems and I have seen no evidence that any of their work is applicable to the higher pressure systems used elsewhere. Remember that as pressure increases, more capacitance becomes available and, while it will not be sufficient to handle diurnal variance, it will help to alleviate diversity.

The diurnal variance too has a definite spatial component, but it is based more on sub-system pressure level than distance from the loads. Available capacitance increases with pressure so that the higher capacitance permits the attenuation of load changes to dampen them out, thereby lessening their effect.

In summary, the two fundamental ways to address these problems are:

1. Estimate the loads starting from the lowest system level as the peak design load considering diversity. Move upstream within a sub-system shedding loading as aggregation removes diversity problems. Move further upstream across regulators shedding more loading as higher pressures provide capacitance to accommodate diurnal load.
2. Estimate the loads based on a consistent time scale and de-rate the flowing capacity of pipes closest to the loads for diversity and all pipes within a subsystem for diurnal variations. For example: a relationship that states that the peak is 125% of the average daily load would result in an efficiency of .8.

Although the former method is used in some parts of the world, it presents serious simulation problems in that the flows in and out no longer add-up without some category of

fictional flows. The recommended approach, therefore, is to use method two and use a time scale consistent with the analysis of further upstream systems and gas supply needs and adjust the flow efficiency equation (7) third component, e_3 , accordingly on a sub-system by subsystem basis to account for diurnal load variation. For low pressure systems the efficiency equation (7) fourth component, e_4 , may be adjusted for diversity based on distance from the loads.

6. Load Forecasting

Loading projections are used in many ways within a gas company. They are the basis for all of the necessary financial forecasts and the basic daily company operations as well as the heart of the facility planning process. It is important that all of these uses communicate with each other for the sake of consistency. Most uses talk of daily gas usage while, as we've seen, distribution design talks of peak hourly usage, which is not necessarily the peak usage in an hour. To examine what is a reasonable expectation granularity and establish the "consistent time scale" required for system analysis, it is appropriate to look deeper into the nature of load forecasting.

The gas distribution process involves transporting gas from a few sources where measured flow rates as a detailed function of time are readily available to many sinks where measurement availability is ragged at best. Most load boundary condition processes operate by building system loading from the bottom-up, *i.e.* a customer-by-customer estimate based on actual consumption. Since the primary use of natural gas is for its heating value, usage shows a strong correlation with outside air temperature, normally expressed in degree-days (degrees below a base temperature that is usually 65 °F, and limited at some value based on heating design standards). Gas meters are generally read on at least a monthly or bi-monthly basis, rarely more frequently and sometimes less. For a given customer this historical information provides a series of observations of average daily consumption and average daily degree-days spanning both warm and cold seasons, but rarely do the readings cover warm or cold seasons exclusively. From this raw data, a simple linear regression technique can provide an average daily base load (the constant) and a factor showing usage per degree-day for each customer (the slope). These two numbers in turn may be combined in a linear relationship to provide estimated daily consumption for any stated temperature. When such data are not available or lead to obviously invalid estimates, typical average values may be used. This situation regarding the paucity of raw data is slowly improving due to the development of "smart" meters that record much more information. The exception to this general availability of information is for customers that represent industrial process loads including electric power generation. The nature of these loads may be steady or involve frequent changes but these loads are always large enough to warrant individual estimation

treatment.

There are two interesting aspects of this approach to load estimation:

1. The ready availability of gas source information as a detailed function of time along with the generally quick network response provides many details on the aggregate characteristics of the loads as they vary with time, but few details on the individual loads, and the aggregates are also attenuated to some extent by the system capacitance.
2. The customer forecasts generally provide precise location and magnitude of the loads but little detail of their time variance.

To rephrase this, in #1 we have a very accurate picture of how a network's overall loading varies with time but little idea of where it is going. In #2 we have a very crude estimate of the magnitude of any given load, no idea of how it varies with time, but a reasonably accurate idea of where it is. The solution methodology is fundamentally to make some kind of detailed customer estimate by locating the customers within the network and using whatever consumption data are available, or some substitute, and to then apply the total estimates from #1 to the spatial estimates in #2 to arrive at a complete picture. Note that statistically the individual errors in #2 can be expected to cancel each other. Having built such a customer by customer estimate the aggregate can then easily be determined and compared to actual hourly supply data and adjusted as desired. If this sounds like going to a great deal of effort to build a detailed estimate only to "fudge" it to a predetermined answer, it is, but remember that the objective is to establish the spatial dimension of the load while its temporal dimension is better determined from a different source.

The best that can be done from a customer data perspective is a daily consumption estimate as a function of outside air temperature, and the quality of that will depend greatly on the availability of information. This all leads to the conclusion that the most detailed load generally available from individual consumption data is that for a peak day requirement associated with a stated design temperature. Getting the peak any finer than that requires other observations to develop peak hour to peak day and peak six-minute to peak day relationships. Fortunately, these relationships can be developed from the other end, the available detailed supply data, but they will, by necessity, be average customer relationships. To go from a peak daily flow rate to a peak hourly rate is usually accomplished with by multiplying the peak daily flow rate by an experience-based constant factor that comes from an analysis of the supplies. Generally a factor larger than 1/24, often 5% (1/20), is used. This leads to a peak/average ratio of 120%.

CONCLUSIONS

To reiterate, the use of an efficiency factor for mathematically modeling pipes is essential. While the fundamental flow equation (1) coupled with the Colebrook-White friction equation (6), or any of its explicit forms, is clearly the most realistic approach, the only other variable available for tuning, pipe roughness, is clearly inadequate. The issues that require tuning, pipe and load anomalies, discussed in sections III and IV are best handled with efficiency. For these reasons, Equation (7) is presented to provide a means of segregating the various components of pipe efficiency. The discussion of equation (7) shows that at least two multiplicative components of pipe efficiency, one for pipe condition and one for peak-to-average, are required for non-ideality of pipe and diurnal problems, and an additional one or two are required if diversity is an issue or if one is not using a fundamental equation. One component, e_1 , can be removed very simply by using only fundamental equations. With the power of current computers and the state of current technology, there is simply no valid reason in the year 2010 to cling to any of these completely obsolete equations.

The separation of efficiency into its components is important for three reasons:

1. The separate components are more easily managed in different groupings within the simulation software's user interface.
2. If one wants to change flow equations, component e_1 , the flow equation correction, should be changed appropriately but the others not changed.
3. If one wants to perform both steady-state and transient analysis on the same system, component e_3 , the diurnal load correction, should be set to 1.0 for transient but not changed for steady-state...

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FIGURES

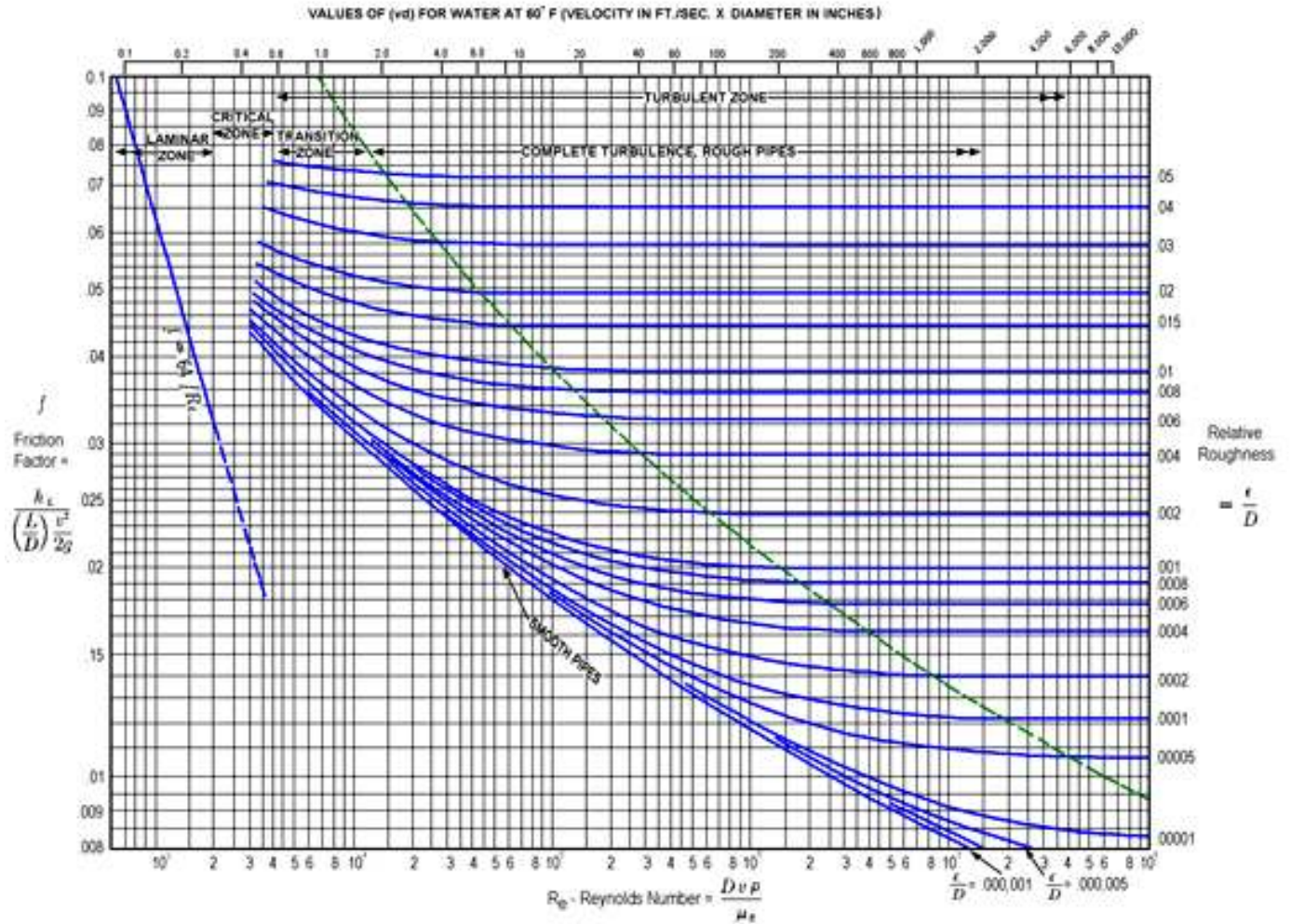


Figure 1 – The Moody Diagram

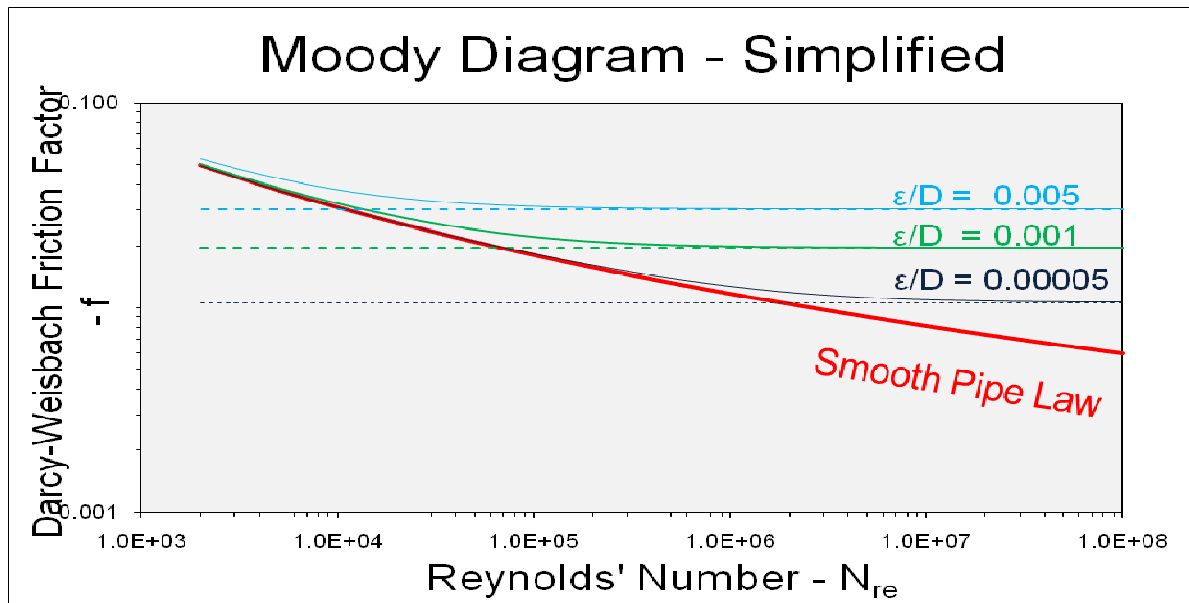


Figure 2 – The Moody Diagram - Simplified

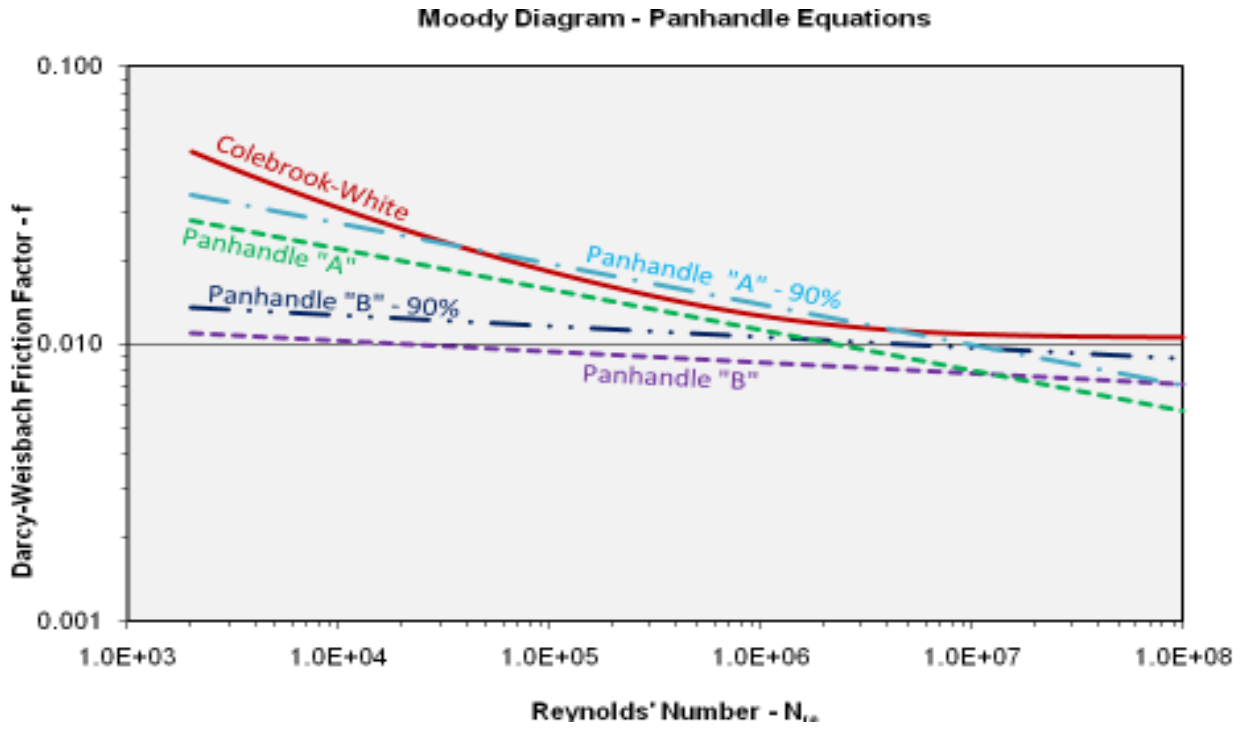


Figure 3 – The Moody Diagram - Panhandle Equations

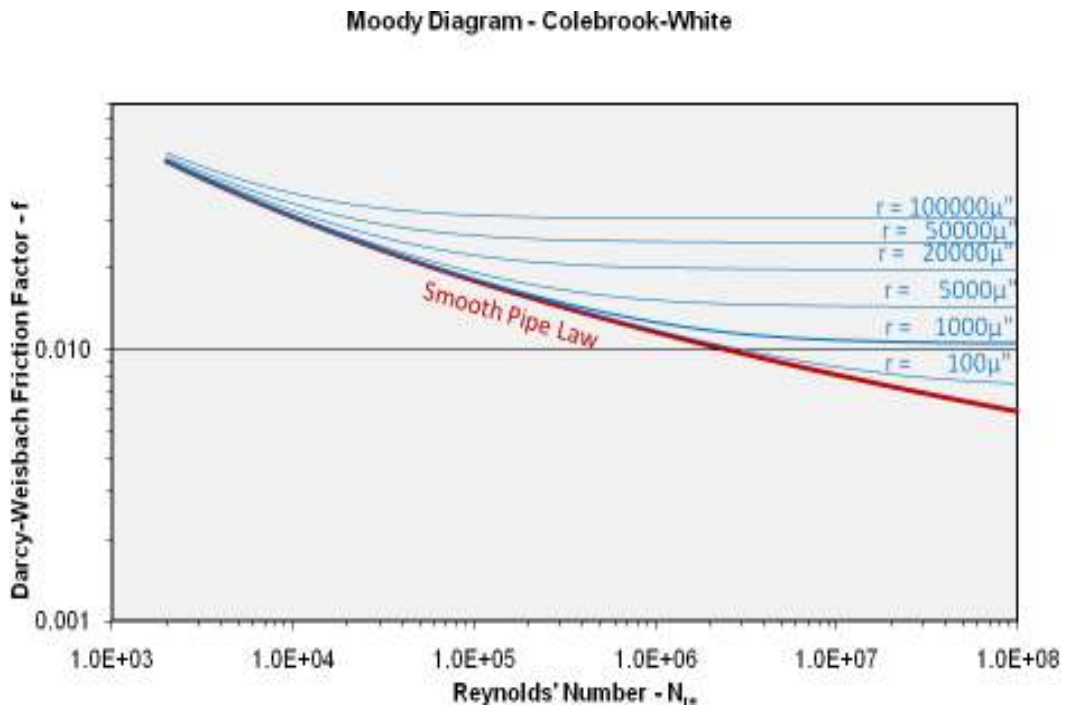


Figure 4 – The Moody Diagram - Colebrook-White