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Full Length Research Paper

Newly developed friction factor correlation for pipe flow and flow assurance

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The purpose of this research is to present petroleum and chemical engineers with a new, practical, and fundamental equation that accurately determines the friction losses in traditional and modern piping systems. The results of this study begin with a necessary mathematical and historical review of determining pipe friction factors under smooth and rough conditions. These formulas provided a base for a statistical evaluation of the calculated friction factors associated with rough and smooth pipes. A new formula is developed, making it easy to calculate explicitly without carrying out rigorous iterative methods. Our new friction factor correlation was based on the nonlinear multivariable surface fitting tool in MATLAB. The final equation correlates the friction factor to the Reynolds number and relative roughness by means of simple logarithmic and exponential functions. The validation and accuracy of the model was tested by using statistical analysis and comparison to other existing correlations. The Ghanbari–Farshad–Rieke's correlation generates superior results over the existing standard friction factor equations.

Key words: Friction factor, piping, relative roughness, Reynolds' number.

INTRODUCTION

Our intention is to present petroleum and chemical engineers with a new, practical and fundamental equation that accurately determines the friction losses in traditional and modern piping. This is a part of an ongoing research which focuses on establishing the broad application of obtaining surface roughness measurements in modern pipes and even in naturally occurring rock fractures. The surface roughness measurements coupled with our new friction factor equation for accurate pipe flow calculations are used in Computational Fluid Dynamics (CFD) modeling to optimize flow assurance during oil and gas production operations (Farshad et al., 2001; 2007; 2009; Farshad and Rieke, 2004; 2005; Kolajo, 2009; Basniev et al., 2010).

The introduction of probabilistic evaluation of Oil Country Tubular Goods (OCTG) in the 1990s has provided a more focused approach to tubular surface roughness design values. The current piping design is more concerned with the ability of pipes to transport fluids at a substantial reduced drag. This resistance to flow is caused mainly by inherent surface roughness due to pipe fabrication, scale buildup, and corrosion. The tubing must be selected so that production operation can be carried out efficiently; it must be designed against failure from tensile forces, internal and external pressure, and corrosion actions. In addition, it must be designed in such a way that the lowest friction pressure loss occurs and maximum production rate and total optimization of the production system is achieved.

It is important to note that after 126 years, Reynolds' 1883 pioneering study on the transition between laminar and turbulent state of fluid flowing in a cylindrical pipe is not clearly understood. It is obvious that surface roughness can contribute to this transition. An important and integral part of the pressure drop in a pipe involves the determination of the friction factor. The importance centers on the friction factor which influences the pressure/energy losses that occur in a pipe due to friction This value of friction factor is used in the calculation of friction pressure losses in pipe. The estimation of the friction pressure loss controls the optimization of oil and gas wells production rates.

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REVIEW OF CORRELATIONS FOR PREDICTING FRICTION FACTOR

Many correlations have been presented and the most promising ones are thus listed in the order of publication.

(1) Wood (1966) proposed the following correlation which is valid for $N_{Re} > 4000$ and $10^{-5} < \varepsilon/D < 0.04$.

$$f = a + bN_{\text{Re}}^{c} \tag{1}$$

Where $a = 0.53(\varepsilon/D) + 0.094(\varepsilon/D)^{0.225}$; $b = 88(\varepsilon/D)^{0.44}$; and $c = 1.62(\varepsilon/D)^{0.134}$.

(2) Churchill (1977) claimed that his equation holds for all N_{Re} and ε/D and has the form:

$$f = 8.\left(\left(\frac{8}{N_{\text{Re}}}\right)^{12} + (A+B)^{-3/2}\right)^{1/12} \tag{2}$$

Where

$$A = \left[-2\log.\left(\left(\frac{\varepsilon/D}{3.70}\right) + \left(\frac{7}{N_{\text{Re}}}\right)^{0.9}\right)\right]^{16}$$

$B = (37530/N_{Re})^{16}$

(3) Chen (1979) proposed the following equation:

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.7065} - \frac{5.0452}{N_{\text{Re}}}\log\left(\frac{(\varepsilon/D)^{1.1098}}{2.8257} + \frac{5.8506}{N_{\text{Re}}^{0.8981}}\right)\right) \tag{3}$$

This equation correlating friction factor, pipe roughness, diameter, and Reynolds number for transition and turbulent flow regions has the same accuracy as the implicit Colebrook equation (Chen, 1979). The equation proposed by Chen is valid for N_{Re} ranging from 4000 to 4×10^{8} and values of ε/D between 5×10^{-7} and 0.05.

(4) Barr (1981) proposed the following expression:

$$\frac{1}{\sqrt{f}} = -2\log.\left(\frac{\varepsilon/D}{3.70} + \frac{4.518\log(\frac{1}{7}N_{\text{Re}})}{N_{\text{Re}}(1+\frac{1}{29}N_{\text{Re}}^{0.52}(\varepsilon/D)^{0.7})}\right) \tag{4}$$

(5) Zigrang and Sylvester (1982) proposed the following equation:

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.7} - \frac{5.02}{N_{\text{Re}}}\log\left(\frac{\varepsilon/D}{3.7} - \frac{5.02}{N_{\text{Re}}}\log\left(\frac{\varepsilon/D}{3.7} + \frac{13}{N_{\text{Re}}}\right)\right)\right) \tag{5}$$

(6) Haaland (1983) proposed a variation in the effect of relative roughness by the following expression.

$$\frac{1}{\sqrt{f}} = -1.8\log.\left(\left(\frac{\varepsilon/D}{3.70}\right)^{1.11} + \frac{6.9}{N_{\text{Re}}}\right) \tag{6}$$

(7) Manadilli (1997), proposed the following expressions valid for N_{Re} number ranging from 5235 to 10^{8} and for any value of ε/D:

$$\frac{1}{\sqrt{f}} = -2\log.\left(\frac{\varepsilon/D}{3.70} + \frac{95}{N_{\text{Re}}^{0.983}} - \frac{96.82}{N_{\text{Re}}}\right) \tag{7}$$

This equation is similar to that proposed by Churchill (1977) for the transition regime.

(8) Romeo et al. (2002), based on what they call the generalization of the best previously proposed correlations, proposed the following correlation:

$$\frac{1}{\sqrt{f}} = -2\log.\left(\frac{\varepsilon/D}{3.7065} - \frac{5.0272}{N_{\text{Re}}}\log.\left(\frac{\varepsilon/D}{3.827} - \frac{4.567}{N_{\text{Re}}}\log\left((\frac{\varepsilon/D}{7.7918})^{0.9924} + (\frac{5.3326}{208.815+N_{\text{Re}}})^{0.9345}\right)\right)\right) \tag{8}$$

Gregory and Fogarasi (1985) conducted an extensive study and suggested Chen's (1979) equation for Fanning friction factor, providing the best accuracy in light of inherent uncertainty in specified values of pipe roughness. One should be cautious about friction factor charts as the Moody friction factor is four times that of the Fanning friction factor.

DATA DESCRIPTION

In this work data was collected from Moody's diagram using a data digitizer by ×10 zooming and the accuracy of 10 digits decimal. Along each curve on the Moody's diagram (that is, curves ε/D = 0 to ε/D = 0.05) at sixty-two different Reynolds' numbers ranging from 2100 to 10^{8}, friction factor data has been collected. All these data which constructs Moody's diagram, is the base data for the current model.

RESULTS

The general model is thus;

$$f = \left(a\log\left(\left(\frac{\varepsilon/D}{b}\right)^{c} + \left(\frac{d}{N_{\text{Re}}}\right)^{e}\right)\right)^{g} \tag{9}$$

In this model both simplicity and accuracy has been considered; it was intended to be as short and simple as possible, showing at the same time a reasonable amount of coefficients. All the data except for curve ε/D = 0.03 (data which was reserved in order to be used as a

Table 1. Adjusted R^2 and SSE for all equations using ε/D = 0.03.

Equation	Adjusted R^2	SSE
Ghanbari-Farshad-Rieke	9.602977E-01	7.458304E-06
Barr (1981)	9.051838E-01	1.781177E-05
Chen (1979)	9.148071E-01	1.600398E-05
Churchill (1977)	9.066240E-01	5.511239E-05
Colebrook (1938-1939)	9.041581E-01	1.800445E-05
Haaland (1983)	8.509656E-01	2.799697E-05
Manadilli (1997)	9.010414E-01	5.616111E-05
Romeo (2002)	9.163614E-01	1.571200E-05
Zigrang (1982)	9.041041E-01	1.801460E-05
Wood (1966)	7.075750E-02	1.898767E-04

Table 2. Adjusted R^2 and SSE for all equations using all data.

Equation	Adjusted R^2	SSE
Ghanbari-Farshad-Rieke	9.993723E-01	9.698157E-05
Barr (1981)	9.988641E-01	1.755054E-04
Chen (1979)	9.990429E-01	1.478797E-04
Churchill (1977)	9.972551E-01	4.241221E-04
Colebrook (1938-1939)	9.989877E-01	1.564121E-04
Haaland (1983)	9.985215E-01	2.284409E-04
Manadilli (1997)	9.977307E-01	3.506372E-04
Romeo (2002)	9.990189E-01	1.515878E-04
Zigrang (1982)	9.989892E-01	1.561700E-04
Wood (1966)	8.433916E-01	2.419763E-02

benchmark to establish the accuracy of the equations) were introduced into MATLAB's surface fitting tool and the coefficients of the model were obtained with a confidence interval of 95%. Equation 10 presents the result obtained by replacing the coefficients into Equation 9.

$$f = \left(-1.52 \log . \left(\left(\frac{\varepsilon / D}{7.21} \right)^{1.042} + \left(\frac{2.731}{N_{\mathrm{Re}}} \right)^{0.9152} \right) \right)^{-2.169} \quad (10)$$

The range of applicability of this equation is N_{Re} between 2100 and 10^8 and relative roughness between 0 and 0.05.

DISCUSSION OF THE RESULTS

The comparison has been carried out in two levels; first friction factor data has been generated for a wide range of N_{Re} numbers and ε / D = 0.03 (spectator data which was reserved in order to be used as a bench mark to establish the accuracy of the equations which is presented in Table 1) using all equations including the current model. Then these data have been compared statistically to the real data obtained by digitizing the Moody's diagram; the results are also presented in Table 1.

In the second level, friction factor data for a wide range of N_{Re} numbers and all relative roughness' have been generated using all equations including the current model, and then, compared statistically to the real data obtained by digitizing the Moody's diagram. The results are presented in Table 2.

The statistical comparison of the different equations, both those in the literature and those developed in the present work, has been carried out using the adjusted R^2 defined as:

$$R^2 \equiv 1 - \frac{SS_{err}}{SS_{tot}}$$

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$$SS_{tot} = SS_{reg} + SS_{err}$$

Where

$SS_{err} = \sum_i (y_i - f_i)^2$, the sum of squares of residuals, also called the residual sum of squares

$SS_{reg} = \sum_i (f_i - \bar{y})^2$, the regression sum of squares, also called the explained sum of squares

$SS_{tot} = \sum_i (y_i - \bar{y})^2$, the total sum of squares (proportional to the sample variance), and The Adjusted R^2 is an indication of the accuracy of the model. The higher the Adjusted R^2, the more accurate the model would be. The *error sum of squares* SSE is a measurement of the amount of variation explained by the regression; the smaller the *SSE*, the better the regression model. As can be seen from the analysis, the best equations from the literature are Chen, Romeo, and Zigrang with respect to the whole data fitting. The Ghanbari-Farshad-Rieke model, however, is more accurate and reliable. The RMSE for this model is 0.0003945 which shows the accuracy and reliability of this model.

Conclusion

Based on the statistical analysis which has been done in this work, the most accurate and one of the easiest equations for use is known to be the Ghanbari-Farshad-Rieke equation. Being explicit, easy to use and very accurate are the most important characteristics which cannot be found all together in any of the previous equations. Based on the results of this study, one can state that this equation could be a better alternative to the existing ones.

Nomenclature

f **,** friction factor, dimensionless; ρ **,** density of fluid, lbm/ft^3; v**,** velocity of fluid, ft/s^2; ***D*** = inside diameter of pipe, ft; g_c**,** gravitational conversion factor, lbm · ft / s^2 · lbf. **RMSE,** root mean square error; **SSE,** sum of squared errors.

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