American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-11, Issue-04, pp-15-25
www.ajer.org
Research Paper Open Access

Improving Bingham Plastic Frictional Pressure-Loss Predictions for Oil Wells

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ABSTRACT : *Accurate estimation of drilling fluid friction pressure losses during well planning and onsite is necessary to perform drilling and well completions without serious problems. Improper hydraulics can result in costly problems. This study focused on evaluating most commonly used methods for calculating Bingham Plastics drilling fluid pressure losses particularly those based on two viscometer readings. Most of these flow equations are already in use by the drilling industry, and are all direct and simple enough to use in a spreadsheet program. Though these calculations methods utilize only two viscometer readings to estimate rheological parameters, however they employ different equivalent diameter for annulus, different turbulent flow friction factors and different critical Reynolds-number/velocity or different turbulence criteria. Frictional pressure losses predicted by Bingham Plastic model as per different methods were compared statistically to field data. Results show that methods under investigation agree in predicting laminar pressure losses and differ in predicting turbulent pressure losses. Several dissimilarities of methods are responsible for different pressure loss predictions such as different turbulence criteria, equivalent diameter and turbulent friction factor. Improved pressure loss predictions were possible by calculating Reynolds number using effective viscosity, using modified Blasius equation for estimating friction factor and using hydraulic diameter definition. Total average absolute percentage errors between 3 - 5% have been obtained.*

KEYWORDS *Bingham Plastic, Frictional Pressure Losses, Friction Factor, Annular Equivalent Diameter, Critical Reynolds Number.*

Date of Submission: 01-04-2022 Date of acceptance: 10-04-2022

I. INTRODUCTION

Rig hydraulics optimization includes planning for optimum flow rates, bit nozzle sizes and acceptable equivalent circulation densities (ECD). Generally, the most important aspects of the hydraulic system include ensuring proper hole cleaning, evaluating pressure increases in wellbore during circulation, minimize hole erosion, increase penetration rate, control surge and swab pressure, size surface equipment and mud pumps, keeping ECD and bottom hole pressure below formation fracture pressures. [1]-[2]. Therefore, well hydraulics play an essential role during drilling and perfect estimations of pressure losses are of utmost importance for a successful drilling job.

Drilling in deep water horizons presents many challenges and is characterized with narrow margins between formation pore pressure and fracture pressure gradients. Estimating drilling fluid frictional pressure loss values to be considerably higher or lower than actual values will result in circulating the drilling fluids with either higher or lower velocities than required. Higher velocities will increase cost for unnecessary additional fluid, require higher pumping and fluid handling capacities, consume more power, increase erosion of uncased sections [3]. The annulus frictional pressure loss may significantly increase up to the extent that violates allowable ECD. As the drilling continues this way, the ECD becomes more critical and formation fracturing and loss of circulation, becomes the role than the exception [4]. Accordingly, prediction of frictional pressure loss with a considerable degree of accuracy will assist in determining optimal circulation rate that will provide sufficient hole cleaning and yet minimizes fluid volume, power, and equipment requirements.

During drilling, any change in stand pipe pressure (SPP) is probably an indication of downhole problems. Depending on magnitude, increase or decrease of SPP, several problems may be identified. A sudden decrease in SPP may be interpreted as bit washout/lost jet, opening of already plugged bit nozzles, drill string washout and twist-off, kick flows and mud loss. Meanwhile, a sudden increase in SPP may be interpreted to be a result of bit nozzles plugging, tight holes, cuttings accumulations [5]-[6].

Wellbore hydraulic optimization involves selecting the proper rheological model that represents the drilling fluid under consideration. Drilling fluids commonly used are non-Newtonian in nature and the friction pressure loss predictive equations are complex and less accurate due to many simplifying assumptions. The most rheological models for the past half-century are Newtonian, Bingham Plastics (BP) and Power Law (PL) model [7].There are several sources of errors in conventional pressure loss calculations which has been discussed by several authors [5] such as ignorance of tool joints in pressure loss calculations, ignoring pipe roughness, assumption about effective viscosity, using different critical Reynolds number, ignoring temperature and pressure effects on mud rheology, ignoring rotation and eccentricity effects, use of different discharge coefficient (Cd) in conventional bit pressure drop equation, ignoring presence of cuttings in annulus and their effect on mud weight found in annulus.

Chowdhury et al. [6] estimated SPP using Newtonian, BP, PL and Herschle-Bulkley models. The rheological constants associated with each of the four models are calculated using regression analysis and the SPP predicted values were compared with measured values. The BP model produces best SPP estimates for all the three flow rates for the drilling conditions considered. BP model have been reported by Rostami [9] to overestimate drilling fluid pressure losses. On the other hand, Ashena et al. [5] reported that BP under-estimates frictional pressure losses. Ashena et al. have improved SPP predictions of BP fluids by applying a coefficient in to its turbulent pressure loss calculations. They argues that this coefficient encompasses the effects of the drillpipe rotation, tool joint, and other effects in estimation of pressure losses.

During annular flow, shear forces will act between the fluid and the outside of the drillpipe and the inside diameter of the wellbore. For concentric annuli, the geometry of conduit can be expressed by the equivalent diameter. Pipe flow equations are extended to annular geometry and the same equations which are used for pipe flow are used for annulus flow by simply replacing the pipe diameter with an equivalent diameter. Several equivalent diameter definitions are proposed in literature, however, two equations are widely used [10]-[11]. The first equation is based upon the definition of hydraulic radius, which is the ratio of the cross sectional area to the wetted perimeter of the flow channel. Based on this definition, the equivalent diameter is equal to four times the hydraulic radius and for concentric annulus it is the difference between the internal diameter of the inner conduit, i.e. $D_{hyd} = (D_h - D_p)$. If there is no inner pipe, $D_p = 0$, the equivalent hydraulic diameter correctly reduces to the inner diameter of the outer pipe, D_h. This definition is adopted by major drilling text books [12]-[14]. Bourgoyne et al. [11] argue that the wider use of this definition is probably due to the simplicity of the method rather than a superior accuracy. The second most popular equivalent diameter equation used is the slot flow approximation for annulus [11].

It is widely accepted that in laminar flow shear resistance is dependent solely on the sliding action of layers. However, in turbulent flow the additional shear resistance is dependent on the magnitude of the velocity [13]. Hence, it becomes necessary to use criteria to determine the flow regime. This criterion is simply depends on the critical Reynolds number. The Reynolds number is dimensionless and is found by multiplying the mud density, velocity, and hydraulic diameter and dividing by the effective viscosity. However, there is a discrepancy in researcher's opinion on the values of the critical Reynolds number that should be considered to delineate the threshold between laminar and turbulent regimes. Some researchers, considered the value of 2000 as the critical Reynolds number [14]. Similarly, others consider a critical Reynolds number of 2100 [11]. On the other hand, Moore and Rabia [12]-[13] used a critical Reynolds number of 3000.

In this paper, in depth investigation has been researched on Bingham Plastic frictional pressure loss calculations methods. Investigations include the effect of using different critical Reynolds number, the effect of using different equivalent annulus diameters and different friction factor in turbulent flow pressure loss estimation. For validation, we make use of data published by Ashena et al. [5]. The frictional pressure loss were calculated using different methods for Bingham Plastic model. The methods described by Moore [12], Rabia [13] Adams [14], Bourgoyne et al. [11], and Carden et al. [15] are considered.

II. PRESSURE LOSS PREDICTIVE EQUATIONS

Different equations for calculating pressure losses are customary used in literature. Several assumptions were made when developing these flow equations. These assumptions are: (1) the drillstring is placed concentrically in the casing or open hole –ignoring eccentricity; (2) the drillstring is not being rotated – ignoring effect of pipe rotation; (3) sections of open hole are circular in shape and of known diameter – ignoring hole erosions; (4) the drilling fluid is incompressible; (5) the flow is isothermal – ignoring effect of temperature on fluid rheology; (6) the annulus is treated as a rectangular slot. Based on different rheological models, expressions to calculate average velocity, Reynolds number and pressure drops, both in circular and annular sections, has been developed. Those expressions have been obtained solving simultaneously the equations of momentum and mass conservation [16].

Fluid Rheology

Rheology is defined as the study of the deformation and flow of matter. From a rheological perspective, drilling fluids are thixotropic (time-dependent) as well as temperature and pressure dependent [4]. There are many publications in the literature that deal with the flow of non-Newtonian drilling fluids in pipes. The Bingham Plastic, BP, [17] is often used for non-Newtonian fluid pipe hydraulic calculation because of its simplicity and good description of rheology of bentonite drilling fluid. In conventional drilling, BP drilling fluids behavior is defined with only two points of the rheological relation (R_{600} and R_{300}). The BP widely used in the drilling fluid industry to describe characteristics of many types of drilling fluids. Fluids obeying this model exhibit a linear shear-stress/shear-rate behavior after an initial shear stress threshold has been exceeded "YP". A rheogram of BP model on rectilinear coordinates is a straight line that intersects the zero shear-rate axis at a shear-stress greater than zero (YP). Equation 1 describes the BP model. The term "YP" is the yield point which is the threshold stress (intercept) and "PV" is the plastic viscosity demonstrated by the slope of the line. The model deviates from a Newtonian model by the YP term. When YP equal to zero the model reverts back to the Newtonian model.

$$\tau = \mathrm{YP} + \mathrm{PV}(\gamma) \quad \ldots\ldots \text{Eq. (1)}$$

To calculate BP "PV" and "YP", a mud's Fann 35 VG meter dial readings and corresponding revolutions per minute are required. Two data pairs are required for a solution. Generally, R_{600}/R_{300}, are in common use. Equations 2 and 3 are general equations for determining the BP plastic viscosity and yield point, respectively.

$$PV, cP = \frac{300(R_{600} - R_{300})}{(600-300)} \quad \ldots\ldots \text{Eq. (2)}$$

$$YP = R_{300} - \frac{300(R_{600} - R_{300})}{(600-300)} \quad \ldots\ldots \text{Eq. (3)}$$

Frictional Pressure Losses

The drilling fluids are circulated during operations starting from mud suction tanks and ending to them. During which they passes through three distinct phases: (1) entering the surface connections and down the drillstring; (2) exiting the drillstring through the bit and entering the annulus; (3) climbing up the annulus to arrive the surface tanks. During this trip frictional pressure losses are resulted. These are the losses in pressure during flow, as a result of contact between the drilling fluid and the walls of the flow conduit. A boundary layer is formed along the surface of a flow conduit carrying the fluid. The viscous property of the fluid creates a variation in the flow velocity normal to the direction of flow representing a loss in momentum and a resistance to flow. The associated pressure loss is directly proportional to the length of the flow conduit, the density, and the square of the fluid velocity, and is inversely proportional to the conduit diameter [18]. For Newtonian fluids, equation (4) shows the pressure loss inside a conduit of diameter D and length ΔL and in case of non circular flow conduit, the diameter is replaced by the equivalent diameter (Eq. 5 and 6) and thus the frictional pressure will be expressed as in equation (7). However, drilling fluids are non-Newtonian in nature. Thus, the corresponding pressure loss equations are derived using rheological parameters pertinent to the model under consideration. Bingham Plastic (BP) rheological models is used in this study.

$$\Delta P_f = \frac{2f\rho v^2}{D}\Delta L \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. (4)}$$

$$D_{hyd} = \frac{4\,A_{ann}}{P_{wet}} = 4\frac{\frac{\pi}{d}(D_h^2 - D_p^2)}{\pi(D_h + D_p)} = D_h - D_p \quad \ldots \text{Eq. (5)}$$

$$D_{slot} = 0.816\left(D_h - D_p\right) \quad \ldots\ldots\text{Eq. (6)}$$

$$\Delta P_f = \frac{2f\rho v^2}{D_h - D_p}\Delta L \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. (7)}$$

Where: ρ is the fluid density, v is the fluid velocity, f is the fanning friction factor, A_{ann} is the cross sectional area of the annulus; P_{wet} is the wetted perimeter of the annulus; D_h is the inner diameter of the wellbore; D_p is the outer diameter of the drillpipe.

Laminar flow of a drilling fluid, when using the BP model, can be described by equation (8) for pipe flow. Equation (9) is used for annulus flow which has been derived with a slot flow approximation of the annulus. Laminar flow equations of BP model are robust and well accepted by industry and adopted in many text books [11]-[15][19]-[20]. However, equations are sometimes presented in different units. Moore [12], Rabia [13], Carden et al. [15] and Hossain & Al-Mejed [20] expressed fluid velocity in foot per minute while Adams [14], Bourgoyne et al. [11], and Guo & Li [19] expressed velocity in feet per second. For turbulent pipe flow of BP equations (10 -13) are normally used. Equations (14 – 17) are used for turbulent annular flow. These are empirical equations and are slightly different because they used different relationships between friction factor and Reynolds number. Moore [12] used a different linear relationship between the friction factor and the Reynolds number ($f = 0.046/Re^{0.2}$) than those used by Adams [14] ($f = 0.0791/Re^{0.25}$) and Rabia [13] ($f = 0.057/Re^{0.2}$). Similarly, Carden et al. [15] used different linear relationships ($f = 0.058/Re^{0.22}$). Bourgoyne et al. [11] provide an alternative method for calculating pressure losses of BP fluids during turbulent pipe flow by using fanning equation of Newtonian fluids (Eq. 4) and modified for annular flow by using the slot diameter definition (Eq. 6). Equations (18 & 19) are the field-units version of the Fanning equation for pipe and annular flow, respectively. The friction factor in these equations are determined using the Colebrook [21] function for smooth pipes (Eq. 20) or one of the simplified explicit alternatives (Eq. 21 – Moody [22]; Eq. 22 – Chen [23]). The Reynolds number (Eq. 23) is calculated by using an apparent viscosity (Eq. 24) and compared to a critical Reynolds number of 2100 and used for the estimation of the friction factor. Hank's [24] Hedstrom number (Eq. 25) can be used as an alternative turbulence criteria for BP fluids from which a critical Reynolds number is identified (Eq. 26-27). This Reynolds number is then compared to a Reynolds number that is calculated using the BP plastic viscosity (Eq. 28).

$$\Delta P_p(All-BP) = L\left[\frac{PV\times V}{1500D^2}+\frac{YP}{225D}\right] \text{ ….. Eq. (8)}$$

$$\Delta P_{ann}(All-BP) = L\left[\frac{PV\times V}{1000(D_h-D_p)^2}+\frac{YP}{200(D_h-D_p)}\right] \text{ ….. Eq. (9)}$$

$$\Delta P_p[Moore] = \frac{7.7\times10^{-5}\rho^{0.8}Q^{1.8}PV^{0.2}L}{D^{4.8}} \text{ …… Eq. (10)}$$

$$\Delta P_p[Rabia/H\&A] = \frac{8.91\times10^{-5}\rho^{0.8}Q^{1.8}PV^{0.2}L}{D^{4.8}} \text{ ……. Eq. (11)}$$

$$\Delta P_p[A/B/G\&L] = \frac{\rho^{0.75}V^{1.75}PV^{0.25}L)}{1800D^{1.25}} \text{ ……. Eq. (12)}$$

$$\Delta P_p[Carden\ et\ al] = \frac{7.86\times10^{-5}\rho^{0.78}Q^{1.78}PV^{0.22}L}{D^{4.8}} \text{ …… Eq. (13)}$$

$$\Delta P_{ann}[Moore] = \frac{7.7\times10^{-5}\rho^{0.8}Q^{1.8}PV^{0.2}L}{(D_h-D_p)^3(D_h+D_p)^{1.8}} \text{ …… Eq. (14)}$$

$$\Delta P_{ann}[Rabia/H\&A] = \frac{8.91\times10^{-5}\rho^{0.8}Q^{1.8}PV^{0.2}L}{(D_h-D_p)^3(D_h+D_p)^{1.8}} \text{ ……. Eq. (15)}$$

$$\Delta P_{ann}[A/B/G\&L] = \frac{\rho^{0.75}V^{1.75}PV^{0.25}L}{1396(D_h-D_p)^{1.25}} \text{ ……. Eq. (16)}$$

$$\Delta P_{ann}[Carden\ et\ al] = \frac{7.86\times10^{-5}\rho^{0.78}Q^{1.78}PV^{0.22}L}{(D_h-D_p)^3(D_h+D_p)^{1.78}} \text{ ……. Eq. (17)}$$

$$\Delta P_f = \frac{f\rho v^2}{25.8D} \text{ …………. Eq. (18)}$$

$$\Delta P_f = \frac{f\rho v^2}{21.1(D_h-D_p)}\Delta L \text{ …………. Eq. (19)}$$

Where: ΔP_p in psi; L in feet; PV in cp; V in ft/s; Q in gal/min; YP in lb/100ft^2; D in inches; ρ in lb/gal;"A" for Adams; "B" for Bourgoyne et al.; "G&L" for Guo and Li; "H&A" for Hossain and

$$\frac{1}{\sqrt{f}} = -4log\left[0.269\frac{\epsilon}{D} + \frac{1.255}{N_{Re}\sqrt{f}}\right] \text{ ……. Eq. (20)}$$

$$f_t - Moody = 0.001375\left[1 + \left(2\times10^4\frac{0.00001}{D} + \frac{10^6}{N_{Re_p}}\right)^{1/3}\right] \text{ …….. Eq. (21)}$$

$$f_t - Chen = \left[-4log\left[\frac{\epsilon}{3.7065} - \frac{5.0452}{N_{Re}}log\left[\frac{\varepsilon^{1.1098}}{2.8257} + \left(\frac{7.149}{N_{Re}}\right)^{0.8981}\right]\right]\right]^{-2} \text{ …….. Eq. (22)}$$

$$N_{Re_p} = \frac{928\rho vD}{\mu_a};\ N_{Re_a} = \frac{757\rho v(D_h - D_p)}{\mu_a} \text{ …….. Eq. (23)}$$

$$\mu_a = PV + \frac{6.66YPD}{v};\ \mu_a = PV + \frac{5YP(D_h - D_p)}{v} \text{ …….. Eq. (24)}$$

$$N_{He} = \frac{37100\rho YPD^2}{PV^2};\ N_{He} = \frac{37100\rho YPD_{slot}^2}{PV^2} \text{ …… Eq. (25)}$$

Where: ΔP_p in psi; L in feet; PV in cp; V in ft/s; Q in gal/min; YP in lb/100ft^2; D in inches; ρ in

$$For\ N_{He} < 10^5;\ N_{Rec} = 10^3\left[1 + \sqrt{1 + \frac{N_{He}}{3000}}\right] \text{ …… Eq. (26)}$$

$$For\ N_{He} > 10^5;\ N_{Rec} = 970\left[1 + \sqrt{1 + \frac{N_{He}}{2700}}\right] \text{ …… Eq. (27)}$$

$$N_{Re_p} = \frac{928\rho vD}{PV};\ N_{Re_a} = \frac{757\rho v(D_h - D_p)}{PV} \text{ …….. Eq. (28)}$$

Turbulence Criteria

In order to calculate frictional pressure loss, it must be determined if the flow regime is laminar or turbulent, this is done by calculating the Reynolds number. However, there is a discrepancy in researcher's opinion on the values of the critical Reynolds number that should be considered to delineate the threshold between laminar and turbulent regimes. Bourgoyne et al. [11] adopted alternative criteria for BP as presented in the previous section. Other researcher are confronting between $N_{Re} = 2000$ and $N_{Re} = 3000$. It should be noted that the term critical velocity is used to define the single velocity at which the flow regime changes from laminar to turbulent (Eq. 29-32). This variable is derived from the Reynolds number equation ($N_{Re} = \rho DV/\mu$) is the most important since all other members of the equation are considered constant. However, the equations are different according to the critical Reynolds number used, i.e. 2000 or 3000.

$$V_c(ft/s)[N_{Rec} = 2000][BP - A] = \frac{1.08PV + 1.08\sqrt{PV^2 + 12.3\rho D^2 YP}}{\rho D} \text{ …… Eq. (29)}$$

$$V_c(ft/s)[N_{Rec} = 2000][BP - A] = \frac{1.08PV + 1.08\sqrt{PV^2 + 9.26\rho D_e^2 YP}}{\rho D_e} \text{ …… Eq. (30)}$$

$$V_c(ft/m)[N_{Rec} = 3000][R/H\&A] = \frac{97PV + 97\sqrt{PV^2 + 8.2\rho D^2 YP}}{\rho D} \text{ …… Eq. (31)}$$

$$V_c(ft/m)[N_{Rec} = 3000][R/H\&A] = \frac{97PV + 97\sqrt{PV^2 + 6.2\rho D_e^2 YP}}{\rho D_e} \text{ ……..(32)}$$

Where: D in inches; PV in cp; YP in lb/100ft^2; ρ in lb/gal; "R" stands for Rabia;"A" for Adams; "H&A" for Hossain & Al-Mejed

Friction Pressure Losses at Bit and Surface Connections

$$\Delta P_{SC} = 4.2\times10^{-5}\rho^{0.8}Q^{1.8}PV^{0.2} \text{….. Eq. (33)}$$

$$\Delta P_B = \frac{156Q^2}{[d_{n1}^2+d_{n2}^2+d_{n3}^2+d_{n4}^2+..]^2} \quad \text{….. Eq. (34)}$$

Where: ΔP_{SC} is pressure loss at surface connections in psi; ΔP_B is pressure loss at bit in psi; d_n is nozzle diameter in 1/32 inches; PV in cp; ρ in lb/gal

III. RESULT AND DISCUSSION

We present in this section a method to simulate the drilling hydraulics using BP model while considering data from a two speed viscometer. Circulation pressure-losses are then calculated using different methods described earlier. A spread sheet Microsoft Excel program is developed to predict, flow regime, frictional pressure losses at different segments of circulation for BP. Generally, these methods have similarities and differences. The major difference are in defining the critical Reynolds number, the equivalent diameter and the friction factor applied for turbulent flow. Field data of Ashena et al. [5] are adopted for validation.

Field Data

Ashena et al. [5] provided a total of 15 case studies collected from seven wells, some of these cases have very similarities. For every case only PV and YP are available. All cases are in 8 1/2-in borehole; drillpipe outside diameter 5-in and inside diameter 4.276-in; drillcollar outside diameter 6 1/2-in and inside diameter 3-in. Borehole depth spans from 5810-ft to 11057-ft and the corresponding drillpipe length spans from 5315-ft to 10473-ft. Mud density ranges from 8.82 to 10.6 lb/gal with one exceptional mud weight (19.6 lb/gal). Plastic viscosities ranges from 5 cp to 32 cp with one exceptional PV (56 cp). Yield point ranges from 6 to 14 lb/100ft2 with one exceptional YP (19 lb/100ft2). Circulation rate spans from 238 gallon/min (gpm) to 490 gpm. Case no 2 and 3 are very similar except for borehole depth, accordingly we selected one of them. Similarly, case no 10 to 14 are identical except for borehole depth we therefore selected only one of them. Case no 1 is excluded because of presence of downhole motor. Finally, we consider a total of 8 cases from Ashena data these are: cases no 2, 4, 5, 6, 7, 8, 9, 10 and 15. The validation is based on using the average absolute percent error (AAPE) for every case and for all the cases as follows (Eq. 35-36).

$$AAPE\% = \left|\frac{SPP_{measured} - \Delta P_{predicted}}{SPP_{measured}}\right| \times 100 \quad \text{….. Eq. (35)}$$

$$AAPE_T\% = \left[1/N \sum \left|\frac{SPP_{measured} - \Delta P_{predicted}}{SPP_{measured}}\right|\right] \times 100 \quad \text{….. Eq. (36)}$$

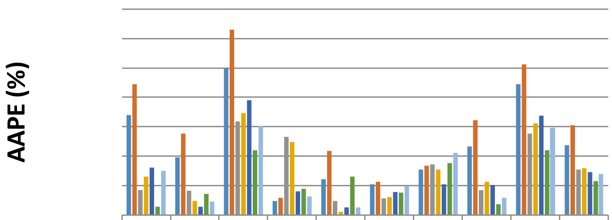
Stand Pipe Pressure Predictions

(1) AAPE Comparisons of Different Methods

Calculations of stand pipe pressure (SPP) for BP fluids are estimated for every part of the circulatory system. All methods provide similar predictions for surface equipment, bit losses and whenever the flow regime is laminar. The only difference is for turbulent flow predictions. AAPEs for each method and for the cases examined are shown in Fig. 1. It is clear that Moore [12] and Carden et al. [15] methods give the worst predictions for all the cases studied except for case 6. This case is considered as a possible miss measured SPP. The other methods gave similar predictions with the method modified by Ashena et al. [5] giving slightly improved predictions.

(2) Flow Regime Comparisons

All methods are in harmony while predicting the flow regime for the cases no 2, 4, 7, 8 and 12. Conflictions in flow regime predictions appeared for the cases no 5, 6, 9 and 15. For case no 5 and 15 Adams [14] and Carden et al. [15] methods predict turbulent flow in annulus opposite drillpipe/hole and drillcollar/hole, respectively while the other methods predict laminar flow. For case no 6 and 9 Adams [14], Carden et al. [15] and Bourgoyne et al. [11] predict turbulent flow inside drillpipe while Rabia [13] and Moore [12] methods predict laminar flow. This can be explained by the different critical Reynolds number adopted by each method. As has been shown previously, Adams and Carden et al. prefer using critical velocity equations that are based on a critical Reynolds number of 2000. Similarly, Bourgoyne et al. adopted the Hedstrom number criteria. Rabia and Moore adopted critical velocity equations that are based on 3000 critical Reynolds number. This mean that Rabia and Moore methods will predict laminar flow earlier than other methods. Bourgyone et al. adopted two different turbulence criteria, one is based on Hedstrom number and the other calculated Reynolds number from apparent viscosity and is compared to critical Reynolds number of 2100. This results in different SPP predictions. As has been mentioned before, all methods give similar predictions for surface equipment, bit losses and laminar flow while differ in turbulent flow estimations. Therefore, different flow regimes will result in different SPP predictions. It becomes awesome however, to isolate the effect of different flow regime for the purpose of evaluating the predictability power of the methods.

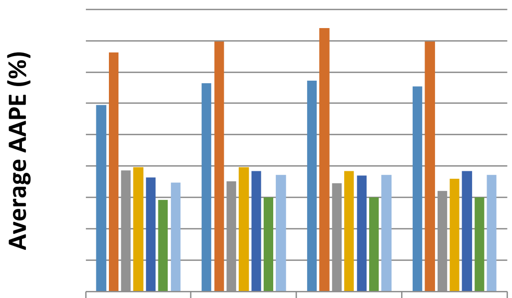


	C2	C4	C5	C6	C7	C8	C9	C12	C15	Ave
Moore	17.0	9.80	24.9	2.37	6.09	5.18	7.73	11.6	22.2	11.8
Carden	22.2	13.8	31.5	2.93	10.8	5.71	8.41	16.1	25.6	15.2
Adams	4.26	4.13	15.9	13.3	2.42	2.81	8.62	4.25	13.8	7.73
Bour	6.58	2.44	17.3	12.4	0.53	2.99	7.73	5.67	15.5	7.92
Rabia	8.01	1.46	19.5	4.04	1.34	3.88	5.18	5.14	16.9	7.28
Ashena-M	1.38	3.57	10.9	4.50	6.54	3.82	8.81	1.81	11%	5.82
Ashena	7.50	2.31	15.1	3.10	1.25	4.92	10.5	2.96	14.8	6.95

Fig.1. AAPE Comparison of Different Methods

(3) Turbulent-Flow Friction Factor Comparisons

To isolate the effect of flow regime and equivalent diameter from the effect of turbulent friction factor we unified the critical Reynolds number and the equivalent diameter for all the methods. Bourgoyne et al. turbulence criterion based on Reynolds number calculated from the apparent viscosity and compared to a critical Reynolds number of 2100 is selected instead of Hedstrom number. We then unified the critical Reynolds number by using a critical Reynolds number of 2000, 2500 and 3000. The hydraulic equivalent diameter is adopted for all methods. The total average AAPE are then plotted for each critical Reynolds number (Fig. 2). All methods are in harmony regarding flow regime predictions. It clear from Fig. 2, that Moore and Carden et al. showed the lowest performance with high total average error for all the cases under consideration. All the other methods have similar performance. These methods differ in turbulent flow pressure loss predictions. Moore used a different linear relationship between the friction factor and the Reynolds number ($f = 0.046/Re^{0.2}$) than those used by Adams, Bourgoyne et al. ($f = 0.0791/Re^{0.25}$) and Rabia ($f = 0.057/Re^{0.2}$). Similarly, Carden et al. used different linear relationships (f=$0.058/Re^{0.22}$). Moore and Carden et al. methods underestimate measured SPP for all cases. Generally, the other methods underestimate SPP for cases no 2, 5, 8, 12 and 15 meanwhile overestimate SPP for cases no 4, 7 and 9. Both trends have been reached at in previous studies. BP model have been reported by Rostami [9] to overestimate drilling fluid pressure losses. On the other hand, Ashena et al. [5] reported that BP under-estimates frictional pressure losses.



	Original	Nrec =2000	Nrec=2500	Nrec=3000
Moore	11.89%	13.29%	13.44%	13.08%
Carden	15.26%	15.96%	16.81%	15.95%
Adams	7.73%	7.02%	6.91%	6.43%
Bour	7.92%	7.94%	7.68%	7.18%
Rabia	7.28%	7.70%	7.40%	7.68%
Ashena-M	5.82%	5.99%	5.99%	5.99%
Ashena	6.95%	7.43%	7.43%	7.43%

Fig. 2. Average AAPE Comparison at different N_{REC}

(4) Improving PB Predictions

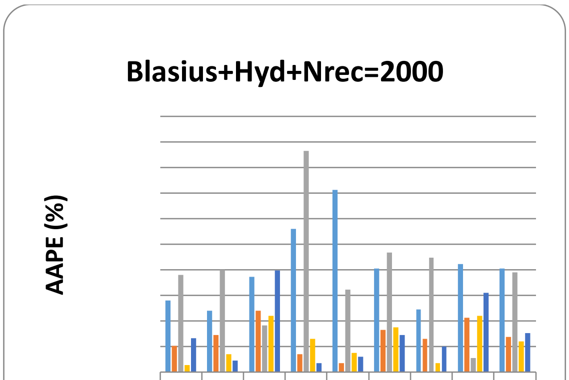
To improve PB predictions, we select Bourgoyne method for further analysis. It has been shown that the turbulent flow predictions are responsible for lower performance of previous methods particularly the friction factor term. The friction factor term is a function of the Reynolds number. The Blasius equations includes a term for the Reynolds number. The Reynolds number is a function of effective viscosity. In turbulent flow, it is assumed that the effective viscosity is equal to the plastic viscosity divided by 3.2 [11]-[14]. Therefore, we suggested different methods for estimating the effective viscosity and hence the Reynolds number and the friction factor. These are (1) using the apparent viscosity (Eq. 24), the effective viscosity (Eq. 37-38) and the plastic viscosity to calculate the Reynolds number; (2) using the Moody (Eq. 21) and Chen (Eq. 22) approximations for Colebrook correlation; (3) using two different equivalent diameter (hydraulic (Eq. 5) and slot (Eq. 6), (4) using two critical Reynolds number (2000 & 3000). SPP predictions and AAPE have calculated however, the result have shown very poor predictions.

$$\mu_{eff} = \frac{\tau_s \times 100}{\gamma};\ \tau_s = YP \times 4.79 + \frac{PV\gamma}{100}; \qquad \text{…….. Eq. (37)}$$

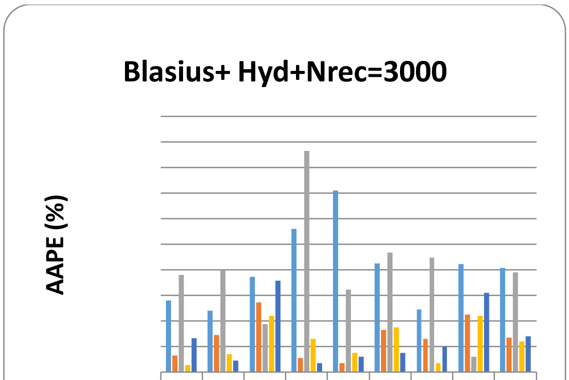
$$\gamma_{pipe} = \frac{96v}{D} + 159.7\frac{YP}{PV};\ \gamma_{ann} = \frac{144v}{(D_h - D_p)} + 239.5\frac{YP}{PV} \qquad \text{…….. Eq. (38)}$$

Where: μ is effective viscosity in cp; τ_s is shear stress in dyne/cm^2; γ is shear rate in s^{-1}; PV is BP plastic viscosity in cp; V is average velocity in ft/s; YP is the BP yield point in lb/100ft^2; D in inches

The next step was to use the Blasius equation ($f = 0.0791/\mathrm{Re}^{0.25}$) to estimate the friction factor while using the previously proposed viscosities in estimating the Reynolds number. The hydraulic diameter definition has been used to represent the annular flow. Fig. 3 show the results for a critical Reynolds number of 2000 and 3000. As shown in figures, improvements in SPP predictions are possible using the Blasius equation and the effective viscosity. Total AAPE of nearly 7% have been achieved for both critical Reynolds number. These values are slightly better than the values predicted by Bourgyone et al.



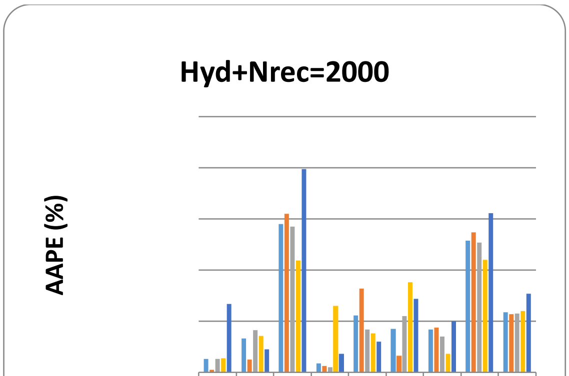
	C2	C4	C5	C7	C8	C9	C12	C15	Ave
Plastic	14.0	12.0	18.6	27.9	35.6	20.2	12.2	21.2	20.2
Effective	5.23	7.33	12.0	3.58	1.84	8.28	6.49	10.7	6.94
Apparent	19.0	20.0	9.21	43.1	16.1	23.4	22.4	2.78	19.5
Ashena-M	1.38	3.57	10.9	6.54	3.82	8.81	1.81	11.0	5.99
Bourg	6.71	2.26	19.8	1.81	3.00	7.23	4.99	15.5	7.68



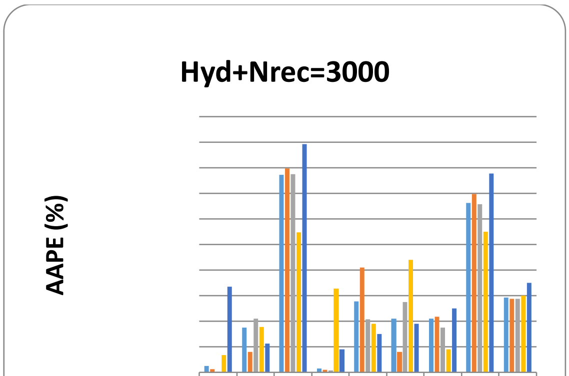
	C2	C4	C5	C7	C8	C9	C12	C15	Ave
Plastic	14.0	12.0	18.6	27.9	35.5	21.3	12.2	21.2	20.3
Effective	3.31	7.25	13.6	2.74	1.84	8.28	6.49	11.2	6.84
Apparent	19.0	20.0	9.39	43.1	16.1	23.4	22.4	3.07	19.5
Ashena-M	1.38	3.57	10.9	6.54	3.82	8.81	1.81	11.0	5.99
Bourg	6.71	2.26	17.8	1.81	3.00	3.81	4.99	15.5	7.00

Fig. 3. AAPE Comparisons of using N_{REC} = 2000

Finally, coefficients of the Blasius equation have been regenerated while using the effective viscosity to calculate the Reynolds number. Fig. 4 shows the results for a critical Reynolds number of 2000 and 3000. As shown in figures, further improvements in SPP predictions are possible using the modified Blasius equation and the effective viscosity. Total AAPE of nearly 6% have been achieved for both critical Reynolds number. These values are comparable to those obtained by the Ashena et al. method if not better. It should be noted that the AAPE values could be reduced further if we neglect case no 5 and 15 as these give marginal values for all methods. This could be seen clearly in Fig. 5 AAPE values that are better than those obtained by Ashena et al. and Bourgoyne et al. have been achieved.

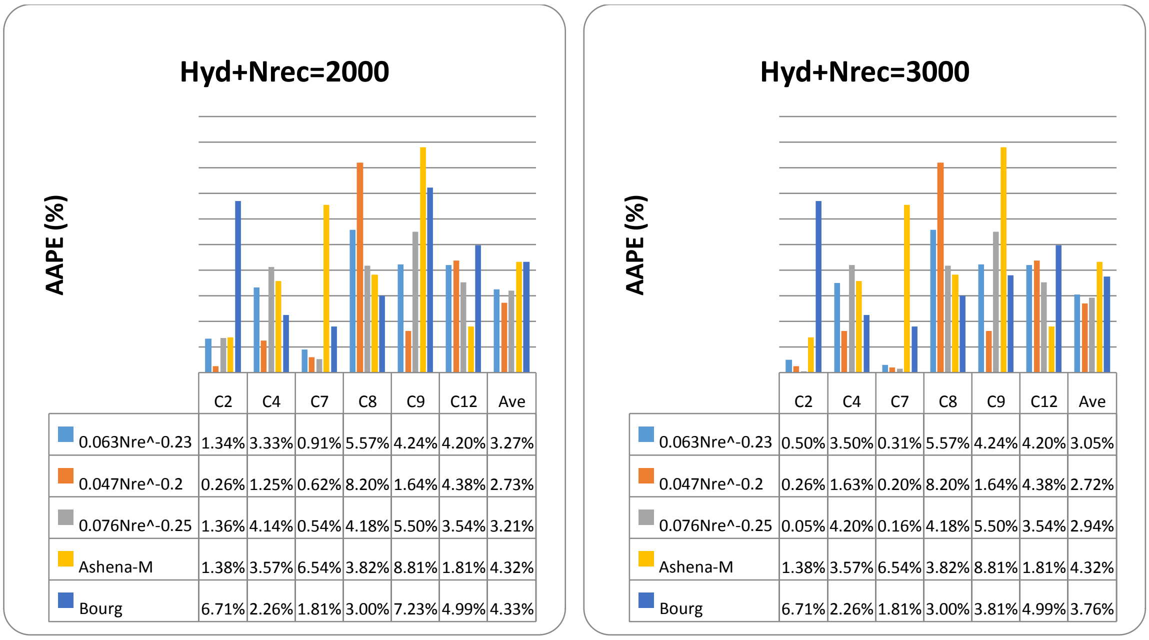


	C2	C4	C5	C7	C8	C9	C12	C15	Ave
0.063Nre^-0.23	1.34	3.33	14.5	0.91	5.57	4.24	4.20	12.8	5.87
0.047Nre^-0.2	0.26	1.25	15.4	0.62	8.20	1.64	4.38	13.6	5.69
0.076Nre^-0.25	1.36	4.14	14.2	0.54	4.18	5.50	3.54	12.7	5.78
Ashena-M	1.38	3.57	10.9	6.54	3.82	8.81	1.81	11.0	5.99
Bourg	6.71	2.26	19.8	1.81	3.00	7.23	4.99	15.5	7.68



	C2	C4	C5	C7	C8	C9	C12	C15	Ave
0.063Nre^-0.23	0.50	3.50	15.4	0.31	5.57	4.24	4.20	13.2	5.88
0.047Nre^-0.2	0.26	1.63	15.9	0.20	8.20	1.64	4.38	13.9	5.78
0.076Nre^-0.25	0.05	4.20	15.4	0.16	4.18	5.50	3.54	13.1	5.78
Ashena-M	1.38	3.57	10.9	6.54	3.82	8.81	1.81	11.0	5.99
Bourg	6.71	2.26	17.8	1.81	3.00	3.81	4.99	15.5	7.00

Fig. 4. AAPE Comparisons – modified Blasius equation



Hyd+Nrec=2000

	C2	C4	C7	C8	C9	C12	Ave
0.063Nre^-0.23	1.34%	3.33%	0.91%	5.57%	4.24%	4.20%	3.27%
0.047Nre^-0.2	0.26%	1.25%	0.62%	8.20%	1.64%	4.38%	2.73%
0.076Nre^-0.25	1.36%	4.14%	0.54%	4.18%	5.50%	3.54%	3.21%
Ashena-M	1.38%	3.57%	6.54%	3.82%	8.81%	1.81%	4.32%
Bourg	6.71%	2.26%	1.81%	3.00%	7.23%	4.99%	4.33%

Hyd+Nrec=3000

	C2	C4	C7	C8	C9	C12	Ave
0.063Nre^-0.23	0.50%	3.50%	0.31%	5.57%	4.24%	4.20%	3.05%
0.047Nre^-0.2	0.26%	1.63%	0.20%	8.20%	1.64%	4.38%	2.72%
0.076Nre^-0.25	0.05%	4.20%	0.16%	4.18%	5.50%	3.54%	2.94%
Ashena-M	1.38%	3.57%	6.54%	3.82%	8.81%	1.81%	4.32%
Bourg	6.71%	2.26%	1.81%	3.00%	3.81%	4.99%	3.76%

Fig. 5. AAPE Comparisons – modified Blasius equation

IV. CONCLUSION

Bingham Plastic model has been investigated to improve their ability to predict SPP with sufficient accuracy using the conventional pressure loss methods. The following conclusions are drawn from this study:

1. The investigated methods agree in predicting laminar pressure losses and differ in predicting turbulent pressure losses. Several dissimilarities of methods are responsible for different pressure loss predictions such as different turbulence criteria, equivalent diameter and turbulent friction factor.
2. Moore and Carden et al. methods poorly predict SPP mainly because of unsuitable coefficients of the Blasius equation used to estimate turbulent friction factor.
3. Very poor SPP predictions were obtained when Moody and Chen correlations were used to estimate the turbulent friction factor. No sensible differences were found when using apparent and effective viscosity to calculate the Reynolds number. Similarly, hydraulic and slot equivalent diameter give similar results so do the different critical Reynolds numbers.
4. Improved pressure loss predictions were possible by calculating Reynolds number using effective viscosity, using the Blasius correlation for estimating friction factor and using the hydraulic diameter definition.
5. It was shown that turbulent friction factor can better be estimated using a modified Blasius equation and a Reynolds number estimated from an effective viscosity. Total average absolute percentage errors between 3 - 5% have been obtained.

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Mazen A. Muherei, et. al. "Improving Bingham Plastic Frictional Pressure-Loss Predictions for Oil Wells."*American Journal of Engineering Research (AJER)*, vol. 11(04), 2022, pp. 15-25.