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Investigation of the Effects of Temperature on Annular Friction Pressure Loss

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ABSTRACT

Accurate estimation of annular friction pressure loss is necessary to perform drilling and well completion operations without lost circulation, pipe sticking or more serious well control problems. Determination of friction pressure loss for Newtonian and non-Newtonian fluids has been investigated in several experimental and theoretical works by considering the effects of eccentricity, pipe rotation or pipe geometry. However, there is a gap in the studies about the experimental investigation of temperature effect that is important especially in geothermal wells.

This study experimentally examined the effect of temperature on friction pressure loss through vertical concentric annulus by using water and the polymer based drilling fluid including Polyanionic Cellulose and Xanthan Gum. Experiments were conducted in flow loop having 21-ft smooth and concentric annular test section (2.91 in ID casing x 1.85 in OD pipe).

The effects of temperature on rheological model parameters, apparent viscosity, Reynolds number calculated with Herschel-Bulkley model having less error than Bingham Plastic and Power Law models for all temperature values were examined. It was found that consistency index and yield point were more sensitive to change in temperature than flow behavior index. Also, apparent viscosity decreased exponentially with increasing temperature and this decrease was more obvious in low shear rate values. Then, according to Reynolds number – temperature plot, earlier regime transition was observed with increasing temperature.

As a result, increasing temperature caused the decrease in friction pressure loss, and temperature effect should be considered in future experimental and theoretical studies in order to estimate friction pressure loss in annuli precisely.

1. INTRODUCTION

For drilling and well completion operations, friction pressure loss should be estimated precisely to prevent lost circulation, pipe sticking, kicks or other serious problems. These problems can lead to interrupt operations and even abandon the well. In order to simulate real drilling conditions, several factors such as eccentricity, inner pipe rotation, annular geometry or flow regime have been examined theoretically and experimentally by now.

In literature, Metzner and Reed (1955) investigated pipe flow firstly for non-Newtonian fluids by finding a relationship between friction pressure loss and generalized Reynolds number for laminar and turbulent flow regimes. Then, Dodge and Metzner (1959) studied turbulent pipe flow conditions with Power Law Model, and they proposed a correlation between friction factor and generalized Reynolds number. To extend the studies from pipe to annular flow, equivalent diameter definitions were presented. Commonly used definitions are hydraulic diameter(D_h), slot flow approximation(D_{sa}) (Bourgoyne Jr. et al., 1991), Lamb's diameter(D_{lc}) (Lamb, 1945) and Crittendon's diameter(D_{cc}) (Crittendon, 1959).

$$D_h = 4 * \frac{(\pi/4)\left(D_o^{\,2} - D_i^{\,2}\right)}{\pi(D_o + D_i)} = D_o - D_i$$

$$D_{sa} = 0.816(D_o - D_i)$$

$$D_{lc} = D_o^{\,2} + D_i^{\,2} - \frac{\left(D_o^{\,2} - D_i^{\,2}\right)}{\ln(D_o/D_i)}$$

$$D_{cc} = \frac{1}{2}\left(\sqrt[4]{D_o^{\,4} - D_i^{\,4} - \frac{\left(D_o^{\,2} - D_i^{\,2}\right)^2}{\ln(D_o/D_i)}} + \sqrt{D_o^{\,2} - D_i^{\,2}}\right)$$

where D_o and D_i are outer and inner diameter of annular space, respectively.

Jensen and Sharma (1987) studied about finding the best combination of friction factor and equivalent diameter definitions in order to calculate friction pressure loss by applying Bingham Plastic and Power Law model. They found a correlation for friction factor and combined with hydraulic diameter and then, this gave the best result for these rheological models.

Herschel-Bulkley model was used to predict friction pressure loss through the annulus by Reed and Pilehvari (1993). They presented a model in order to estimate annular friction pressure loss by finding a relationship between Newtonian Pipe flow and non-Newtonian annular flow. For this reason, they introduced "effective diameter" term for laminar flow. This term includes combined geometry shear-rate correction factor (G) and it changes with rheological models. Subramanian & Azar (2000) examined the flow of different non-Newtonian fluids including polymer-based drilling fluid through pipe and annulus. Results showed that Herschel-Bulkley model gave the best fit for concentric annulus in laminar flow regime. For turbulent flow, polymer drilling fluid acted as drag reducing fluid and thus the term of pipe roughness in friction pressure loss prediction caused larger results than experiments. Zamora et al. (2005), Demirdal and Cunha (2007) and Dosunmu and Shah (2015) also investigated the effects of different flow regimes, rheological models and equivalent diameter concepts. Studies about the effects of inner pipe rotation and eccentricity in addition to these parameters were conducted by Ozbayoglu and Sorgun (2010), Anifowoshe and Osisanya (2012) and Rooki (2015).

Temperature effect has been considered by Ulker et al. (2017) in estimation of friction pressure loss of Newtonian fluid through annulus. They found an empirical correlation for friction pressure loss by considering Reynolds number, Taylor number and Prandtl number. Literature survey showed that although annular friction pressure loss has been examined theoretically and experimentally with the effects of types of fluids, eccentricity of pipe, pipe rotation, pipe roughness, different equivalent diameter definitions, friction factor correlations and flow patterns for non-Newtonian fluids. There is a gap in experimental investigation of temperature effects. The main aim of this paper is to experimentally investigate the effect of temperature on friction pressure loss of polymeric drilling fluid through vertical concentric annulus.

2. EXPERIMENTS

2.1 Setup

Experiments were conducted at the flow loop laboratory of Middle East Technical University Petroleum and Natural Gas Engineering Department. The schematic of flow loop is demonstrated in Figure 1.

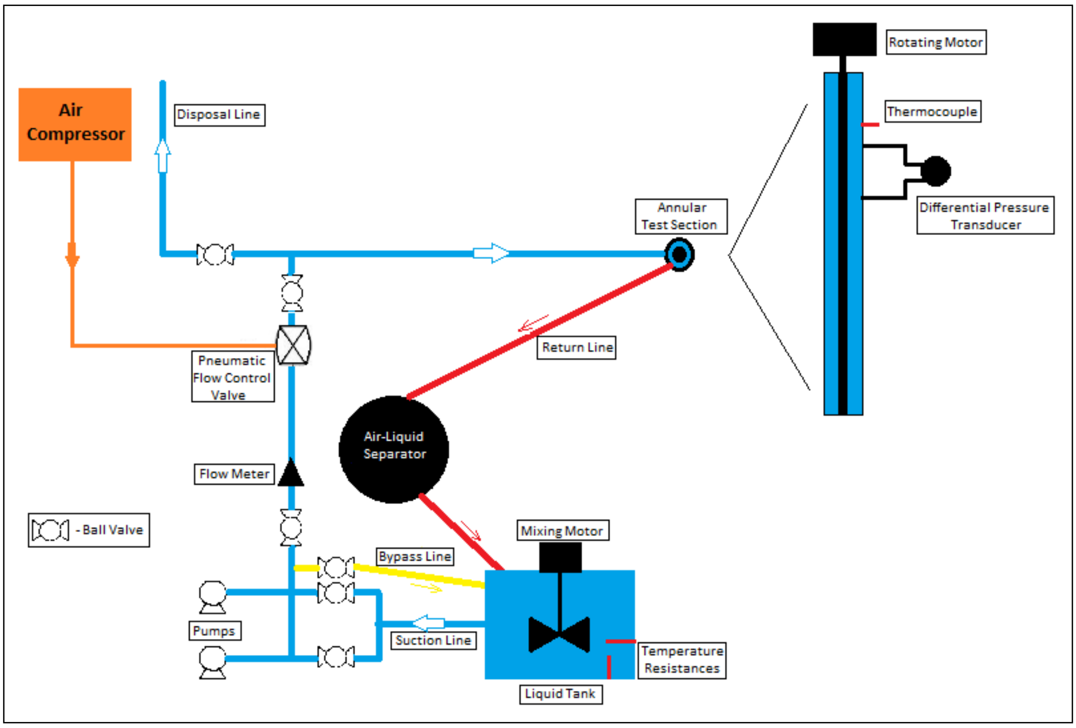

Figure 1: Schematic of Flow Loop

The flow loop has a liquid tank equipped with mixer and temperature resistances, centrifugal pumps, valves to control flow, flow meter and annular test section with differential pressure transducer and thermocouples.

Friction pressure loss measurements were performed for 1 ft of annular test section. The length of test section is 21-ft and it has 2.91” ID transparent plexi-glass pipe representing casing and 1.85” OD drill pipe. Also, dial readings at different shear rates are measured using a viscometer with a capacity of six readings.

2.2 Drilling Fluid Preparation

Experiments were conducted with polymeric drilling fluid. Drilling fluid was prepared by using polyanionic cellulose (REOPAC HV) (0.50 lb/bbl), xanthan gum (REOZAN D) (0.75 lb/bbl) and triazine based biocide (GEOCIDE T) (1 lt/1000 lt) provided by GEOS Energy Inc. REOPAC HV is used as viscosifier and fluid loss control additive, REOZAN D is used as viscosifier, and GEOCIDE T is added to the liquid tank to control bacteria growth. Those are mostly used in geothermal drilling applications.

2.3 Procedure

Polymeric drilling fluid experiments were conducted at 24°C, 30°C, 37°C and 44°C with flow rates between 25 gpm and 110 gpm. Before taking friction pressure loss and temperature data, the system was checked for steady state conditions. Rheological measurements were also conducted at steady state for each temperature.

3. RESULTS AND DISCUSSION

3.1 Rheological Measurements

Rheological parameters for Bingham Plastic, Power Law and Herschel-Bulkley models were calculated by using dial readings at 600, 300, 200, 100, 6 and 3 rpm using viscometer during experiments with polymeric drilling fluid for different temperatures after reaching steady state. Relationship between shear stress and shear rate values was examined to determine rheological parameters for each model. Theoretically obtained shear stress values were statistically compared with experimental ones in terms of average error, standard deviation and coefficient of determination. The following table demonstrates the statistical comparison of rheological models and estimated parameters for 24°C.

Table 1. Model Comparison and Parameters at 24°C

	Bingham Plastic Model	Power Law Model	Herschel-Bulkley Model
Average Error (%)	27.21	3.57	1.64
Standard Deviation	9.30	9.12	9.64
R^2	0.9314	0.9966	0.9980
Plastic Viscosity	0.02		
Yield Point	6.41		2.18
Flow Behavior Index		0.38	0.52
Consistency Index		1.98	0.74

Other temperature values gave the similar results in terms of statistics (Gürçay, 2018). In order to find the most suitable rheological model for polymeric drilling fluid at four different temperatures, all results were examined. As a result, based on average error and coefficient of correlation results, and also for being consistent with American Petroleum Institute Recommended Practice 13D for Rheology and Hydraulics of Oil-Well Drilling Fluids. (American Petroleum Institute (API), 2009), Herschel-Bulkley model gave more accurate prediction than other models.

3.2 Friction Pressure Loss Estimation

Friction pressure losses for each temperature were calculated with Herschel-Bulkley rheological model by applying the procedure represented in API RP 13D for Rheology and Hydraulics of oil-well drilling fluids. In this context, hydraulic radius concept is used for representing annular geometry. In addition to this definition, other equivalent diameter definitions that are slot flow approximation, Lamb's criteria and Crittendon's criteria were utilized in calculations. Also, API RP 13D uses basic field formulas to find out rheological parameters. In this study, Herschel-Bulkley model parameters were optimized with SOLVER function of Microsoft Excel by minimizing the square of difference between calculated and measured shear stress values. Since, the error values with parameters from field measurement were more than SOLVER results. As a results, friction pressure loss vs. flow rate graph at 24°by using four different equivalent diameter definitions was plotted with experimental results and demonstrated below.

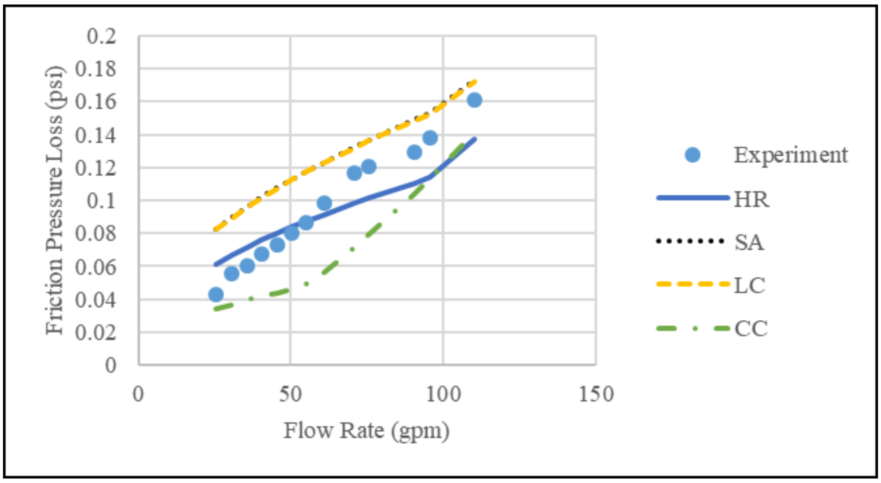

Figure 2: Friction Pressure Loss vs. Flow Rate at 24°C

According to API RP 13D, hydraulic radius was used to represent annular geometry but, when flow regime changed from laminar to transition by examining the lower critical Reynolds number, experimental results did not match with theoretical results and started to close to friction pressure loss estimated by using Lamb's criteria and slot flow approximation. Therefore, friction pressure loss was calculated by using hydraulic radius in laminar flow regime and slot flow approximation after the end of laminar flow regime at 24°C (Figure 3). All temperature values gave the best fit with this combination of equivalent diameter definitions (Gürçay, 2018).

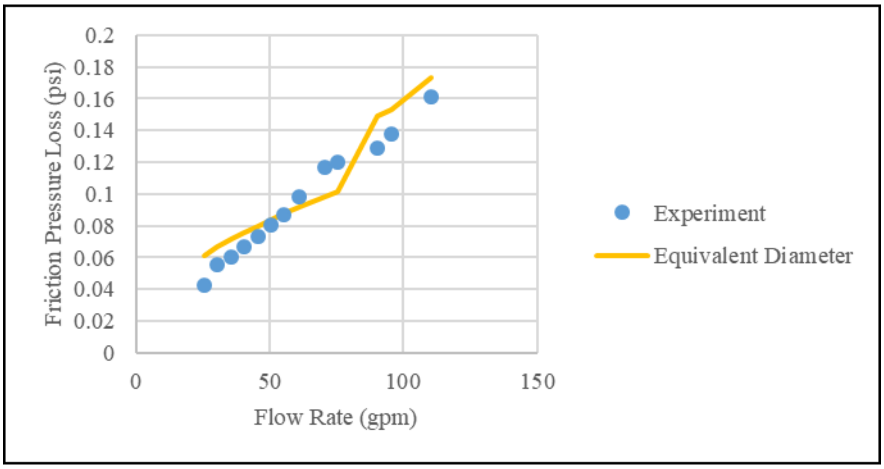

Figure 3: Friction Pressure Loss vs. Flow Rate at 24°C

3.3 Investigation of Temperature Effect

In order to find out the effect of temperature, relationship between temperature and rheological parameters, apparent viscosities, Reynolds numbers and then friction pressure losses were examined. Change in Herschel-Bulkley parameters with temperature are shown below. According to the graphs, it was observed that flow behavior index was not affected by temperature increase. However, consistency index initially increased and then decreased. Normally, increasing temperature changes consistency index reversely since it represents the viscosity of the fluid at low shear rates. (MI Swaco, 1998) Therefore, the effect of temperature on flow behavior index and consistency index could not be understood. On the other hand, yield point decreased with increasing temperature as expected.

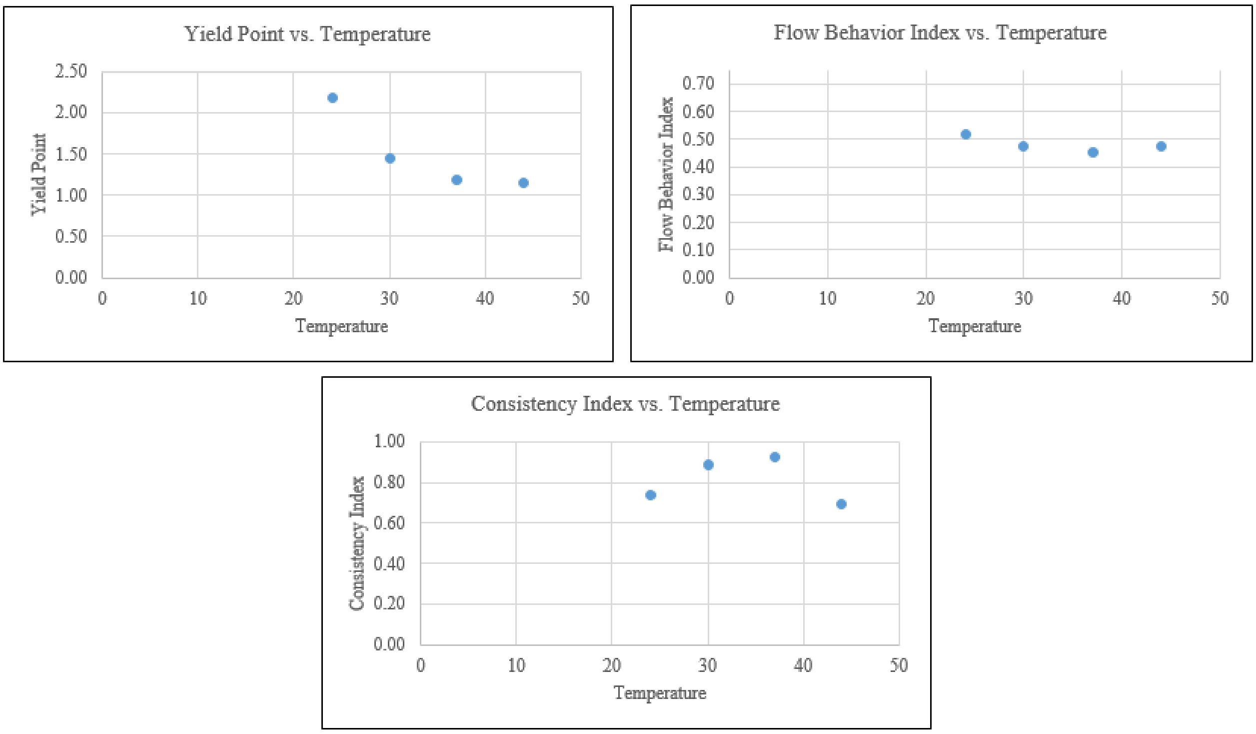

Figure 4: Herschel-Bulkley Parameters vs. Temperature

In order to see the combined behavior of these parameters, apparent viscosity values were examined. In calculation of apparent viscosity, like friction pressure loss estimation, hydraulic radius in laminar flow regime and slot flow approximation after the laminar flow regime were used. For different flow rates, apparent viscosity vs. temperature graph is shown in Figure 5. Apparent viscosity changed with temperature inversely as expected and high viscosity was influenced by temperature much more than low viscosity. Also, decrease in apparent viscosity had also inverse relationship with increasing flow rate due to shear thinning behavior of polymer-based fluids.

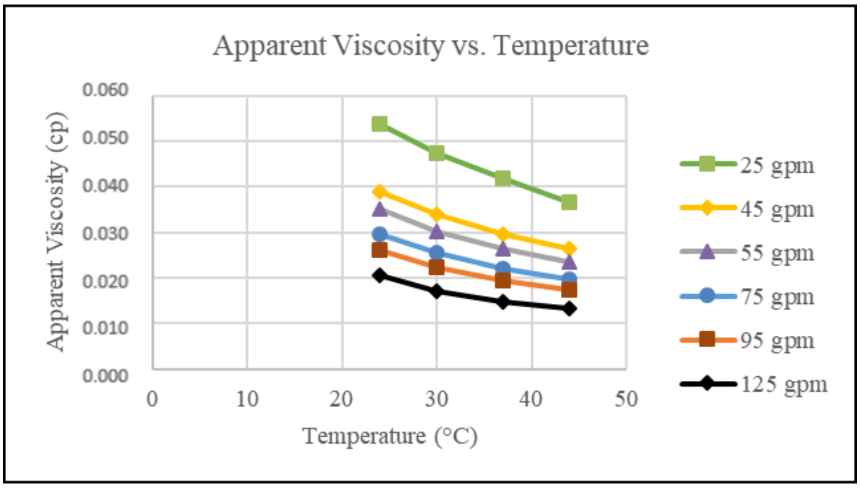

Figure 5: Apparent Viscosity vs. Temperature

Generalized Reynolds number was also investigated. Like apparent viscosity, this number was calculated by using same equivalent diameter definitions. Figure 6 shows the graph of generalized Reynolds number vs. temperature with different flow rates. For higher flow rates, increase in Reynolds number became more distinct. Since, apparent viscosity and density that are temperature dependent variables affect Reynolds number. In other words, since the decrease in viscosity is larger than density, Reynolds number starts to increase. Therefore, regime transition became earlier with the effect of temperature. Also, measured friction pressure loss vs. Reynolds number plot shows the decrease in friction pressure loss with increasing temperature. This plot is shown in Figure 7.

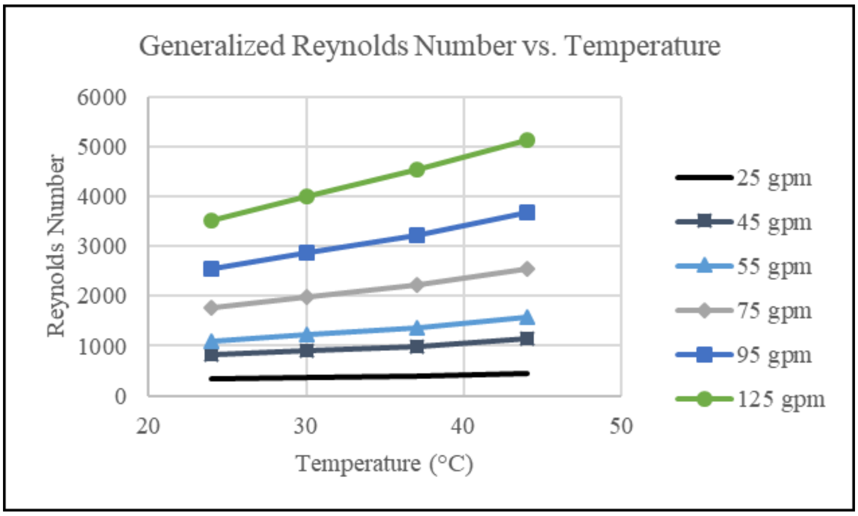

Figure 6: Generalized Reynolds Number vs. Temperature

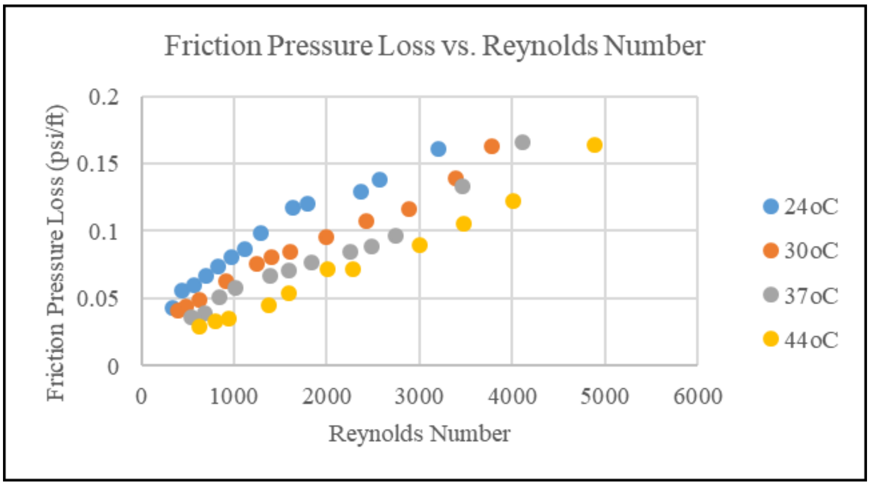

Figure 7: Friction Pressure Loss vs. Reynolds Number

4. CONCLUSIONS

1. When rheological measurements for six different viscometer speeds were examined, it was observed that Herschel-Bulkley rheological model gave the best description of our polymeric drilling fluid compared to Bingham Plastic and Power Law models in the range of test temperatures in terms of average error and coefficient of determination.

2. In the calculation of friction pressure loss by using Herschel-Bulkley model, parameters obtained from SOLVER rather than field measurements used in API RP 13D since SOLVER results gave less average error.

3. Slot flow approximation gave the same results with Lamb's diameter as equivalent diameter definitions in calculation of friction pressure loss. In laminar flow regime, hydraulic radius agreed with experiments, after transition from laminar flow regime, slot flow approximation and Lamb's diameter gave more accurate results than other equivalent diameter definitions.

4. Consistency index and yield point parameters of polymeric drilling fluid are more sensitive to change in temperature than flow behavior index. Also, only yield point showed the expected behavior with increase in temperature.

5. Apparent viscosity that gave the combined behavior of rheological parameters showed exponential decrease with increasing temperature especially in lower shear rates. The reason of this behavior was the effect of temperature and shear-thinning behavior of polymeric fluids.

6. Transition of laminar to turbulent flow became earlier with increasing temperature due to change more pronounced change in Reynolds number at higher shear rates.

7. Friction pressure loss decreased with increasing temperature when examining measured friction loss vs. Reynolds number plot.

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