UDC 622.244

DRAG REDUCTION BEHAVIOR OF POLYMERS IN STRAIGHT AND COILED TUBING AT ELEVATED TEMPERATURE

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Abstract. *The drag reduction resulting from the addition of small amount of linear macromolecules has found various applications in many areas of the oil & gas industry; including well completion, workover, drilling operations, and hydraulic fracturing.*

Temperature is among the factors affecting the extent of drag reduction. Other factors include salinity, polymer type and concentration, molecular weight and distribution, solvent chemistry, pH, ionic strength, molecular conformation, flow geometry, and degree of mechanical shearing. Despite the widespread use of brine solutions as base fluids in fracturing the deep hot formations, the effects of temperature on the drag reduction characteristics of polymers have received the least attention. Most studies have considered the ambient temperature conditions. Therefore, the aim of the present study is to experimentally investigate the effect of temperature on the extent of drag reduction of polymers flowing in straight and coiled tubing.

The most commonly used anionic polyacrylamides; Nalco ASP-820 is investigated. ASP-820 is a sulfonate containing a partially hydrolyzed polyacrylamide (PHPA). The pre-determined optimum concentration of ASP-820 polymer of 0.07 % (vol.) is used. A small flow loop with straight and coiled tubing sections is employed. To investigate the effect of temperature, tests are conducted with fresh water at 22, 38 and 55 °C.

It is found that ASP-820 polymer is a quite effective drag reducer in circular pipes. Drag reduction in the range of 30-80 % is noticed. Drag reduction is more significant in straight tubing than in coiled tubing. Temperature shows a drastic effect on the drag reduction characteristics and its effect differs from straight to coiled tubing. Correlations to predict drag reduction at elevated temperature are developed. These results are presented and discussed in detail.

Keywords: *coiled tubing, straight tubing, drag reduction, polymers, temperature, well completion*

1. Introduction

Coiled tubing (CT) has been extensively used in the oil and gas industry due to various advantages it has over conventional straight tubing. However, they exhibit significant friction pressure losses due to their small sizes and secondary flows. Therefore, the application of drag reducing fluids in coiled tubing is necessary to overcome such high losses.

Toms (Toms, 1948) discovered that adding small quantities of high molecular weight polymers known as “Drag Reducers” to a fluid flowing in pipes in the turbulent region could significantly reduce drag exerted by the fluid. This phenomenon is referred to as drag reduction. In petroleum industry, fluids are pumped through straight and coiled tubing during operations such as hydraulic fracturing, acidizing, wellbore cleanup, cementing and drilling. These operations are usually executed under turbulent flow conditions. High friction pressure losses are encountered when fluids are pumped, thus limit their pumping capacity. Polymers, surfactants, and fibers are known to lower the friction pressure losses up to 80 percent over the solvent. Numerous studies (Lumley, 1969; Virk, 1975; Berman, 1978; Hoyt, 1985) provide extensive reviews on this topic.

Several factors during operations can affect drag reduction performance of fluids. Temperature is among the most common factors that may differ from one treatment to another. Although drag reduction phenomenon has been studied extensively, there is very little information available on the effect of temperature on drag reduction characteristics. Most drag reduction research has been restricted to ambient conditions of temperature and pressure.

The present study is undertaken to better understand the effect of elevated temperature on drag reduction efficiency. For this purpose, a widely used anionic AMPS copolymer (drag reducing agents), Nalco ASP-820, was chosen. The optimum concentration for ASP-820 polymer determined earlier as 0.07 % (Shah et al., 2006) was employed in the investigation of the effect of temperature.

A 1.27 cm OD smooth drawn straight (3.05 m long) and coiled tubing (5.74 m long) with an internal diameter of 1.1 cm was used. It was planned to conduct tests at different temperatures, but due to the limitations of the equipment, the 83 ^{o}C test was not completed. New equipment and design are required to conduct this high temperature test. So, tests were only conducted at 22, 38 and 55 ^{o}C using fresh water as solvent.

2. Experimental Work

2.1. Experimental setup

The experimental setup used in this study is shown in Fig. 1. The flow loop consists of a 208-liters and 825-liters tanks for fluid mixing and storage. A Model 5M Deming centrifugal pump is used to feed the fluid to a Model 6P10 Moyno progressive cavity pump used to pump the fluid. It can achieve a flow rate of up to 0.009 m^3/s at

$4.1 \cdot 10^6$ Pa. A glass inspection cell is used to allow a visual inspection of the circulating fluid.

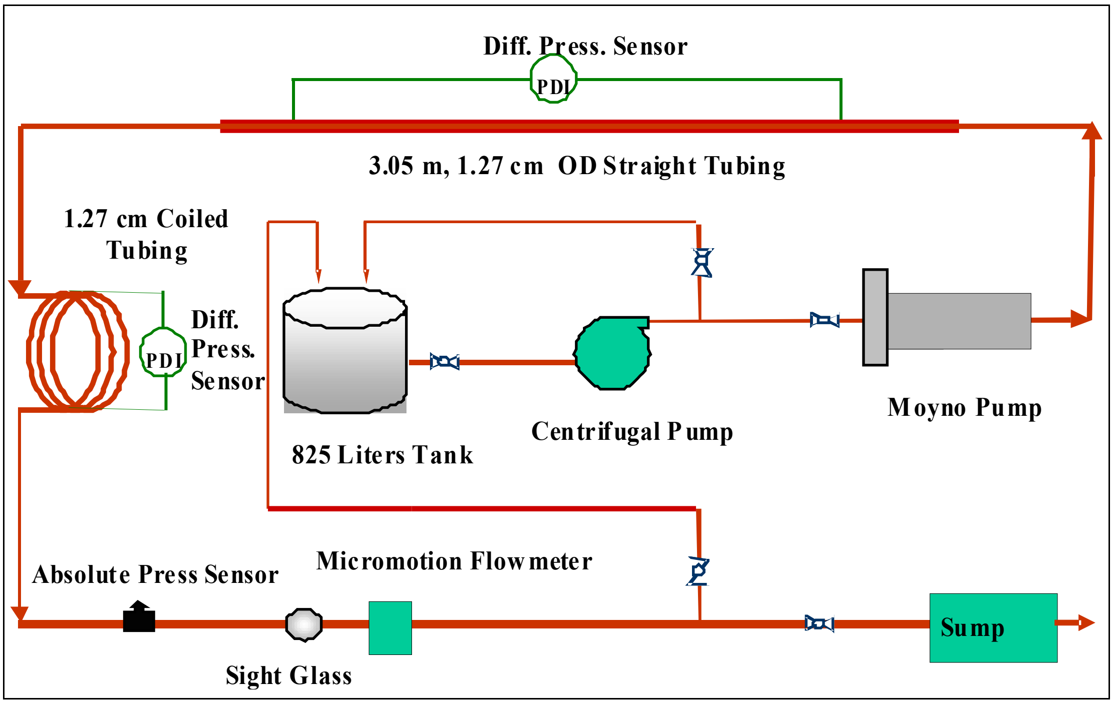

Figure 1. Schematic of the fluid flow loop

A 1.27 cm OD smooth straight pipe is used as flow conduit (1.1 cm ID and 3.05 m long). A coiled tubing section (curvature ratio of 0.019) with the same ID and a length of 5.74 m is also used as flow conduit. A differential pressure sensor measures the frictional pressure losses in the straight and coiled tubing sections and an absolute pressure sensor to measure system pressure. Maximum working pressure of the system is $6.9 \cdot 10^6$ Pa.

A 1.27 cm MicroMotion® flow meter is used to measure fluid flow rate, density, and temperature. The wireless Fluke Hydra data logger system is used for data acquisition. Data are transmitted to a personnel computer and displayed live on the screen.

2.2. Fluid preparation

The mixing procedure recommended by the polymer product supplier was followed. For ambient temperature (22 °C) test, polymer at a desired concentration was added to fresh water in the 825-liters mixing tank while operating mixer at a moderate speed and allowing it to hydrate for 10 minutes.

For elevated temperature tests, polymer was first mixed with 3 liters of tap water (at ambient temperature) in a laboratory blender and then allowed to hydrate for 10 minutes. This fully pre-hydrated, pre-mixed polymer was then added to hot fresh water in the tank as a base fluid.

For elevated temperature tests, an external source of heat was used to heat the fluid in the 208-liters tank. Meanwhile, hot tap water was re-circulated through the system to bring it to the test temperature and to conduct system calibration. Due to limited fluid volume (208-liters) and conducting tests in a single-pass mode, only one data point was recorded with each fluid mixture at a given temperature. This was repeated for other flow rates, i.e. it is a batch process.

2.3. Test procedure

In all tests, the base fluid (solvent) was first circulated through the straight pipe to calibrate the system. The results were used as the baseline for data analysis. The water in the system was then completely displaced by pumping the test fluid. The flow rate was set at a desired value and the steady state pressure drop data across 3.05 m straight pipe and 5.74 m coiled tubing were recorded.

The flow rate was then increased and the corresponding pressure drop was noted. At each flow rate, adequate time was allowed for the fluid to achieve steady state conditions. This was confirmed by monitoring the live display of the measured flow rate and pressure drop signals. The fluid containing friction reducer was not subjected to excessive shear and was also not re-circulated as it can degrade.

A fluid sample was collected from the tank at the start of each test for viscosity measurement. Another fluid sample was collected from the flow loop at the end of the test and analyzed for any possible degradation due to heating and/or shear effects.

3. Results and Discussion

3.1. Data reduction and analysis

The data recorded from the wireless logger consist of flow rate, pressure drop across straight and coiled tubing sections, fluid density, and temperature. The steady state data values were averaged and used in the analysis.

The pressure drop data were converted to Fanning friction factor, *f*, which is a dimensionless variable used to determine the friction pressure gradient. It is given by the following expression:

$$f = \left[\frac{d_i \Delta p}{2 l \rho v^2}\right], \tag{1}$$

where *l* is the pipe length across which the differential pressure is measured.

Drag reduction can be calculated as:

$$DR = \left[1 - \frac{f_t}{f_s}\right], \tag{2}$$

where, f_t and f_s are Fanning friction factors of the treated fluid (drag reducing fluid) and solvent respectively. Both can be calculated using Eq. 1.

The drag reduction characteristics of fluid can be examined by plotting Fanning friction factor versus solvent Reynolds number. The solvent Reynolds number is determined from the following equation:

$$N_{\mathrm{Re}s} = \left[\frac{\rho_s v d_i}{\mu_s}\right], \tag{3}$$

where ρ_s and μ_s are the solvent density and viscosity respectively. Solvent density and viscosity are used at the same conditions as the test fluid.

Because of the less viscous nature of the polymeric solutions tested, a Cannon-Fenske capillary viscometer was used to measure their viscosities. Table 1 shows the effect of temperature on the viscosity. It can be seen from this table that the viscosity decreases with increasing temperature. Moreover, data showed no difference in fluid viscosity before and after the test; indicative of no shear or degradation effect.

Table 1. Effect of temperature on viscosities of 0.07 % ASP-820

Temperature, °F	Average Efflux Time, sec		Absolute Viscosity, cP	
	Before	After	Before	After
72	152	151	2.28	2.28
100	135	133	2.03	2.02
130	120	122	1.80	1.81

3.2. Water tests

Fig. 2 and 3 are composite plots of Fanning friction factor versus solvent Reynolds number for water flowing in straight and coiled tubing pipe at various temperatures. Fig. 2 shows the straight pipe water data at various temperatures while Fig. 3 shows the coiled tubing water data.

For ambient temperature test, the data over a wide range of solvent Reynolds number were gathered. However, because of the difficulties associated with heating the fluid and flow loop, fewer data points were gathered for tests conducted at 38 and 55 ºC.

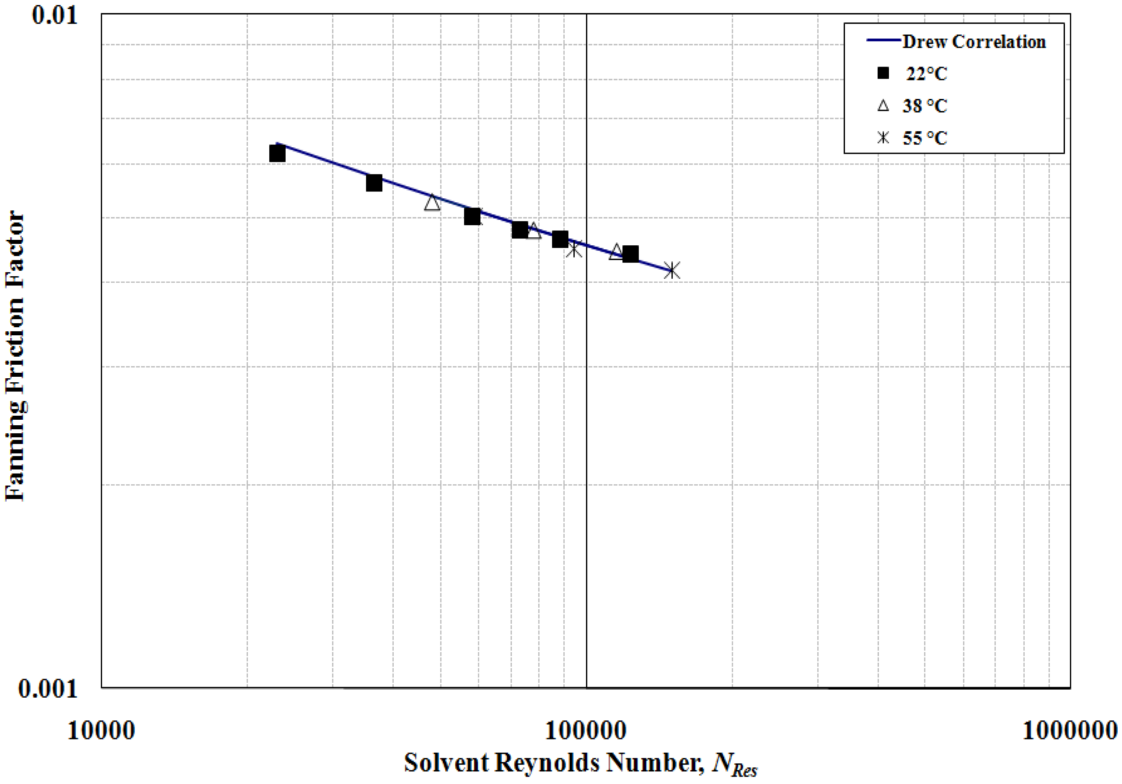

Figure 2. Water data in 1.27 cm OD straight pipe at various temperatures

As shown in Fig. 2, the friction factors of water, as expected, match very well with the predictions from the following Drew correlation (Drew et al., 1932) for turbulent flow of Newtonian fluids in straight smooth pipes:

$$f_s = 0.0014 + 0.125 (N_{\mathrm{Re}s})^{-0.32} . \qquad (4)$$

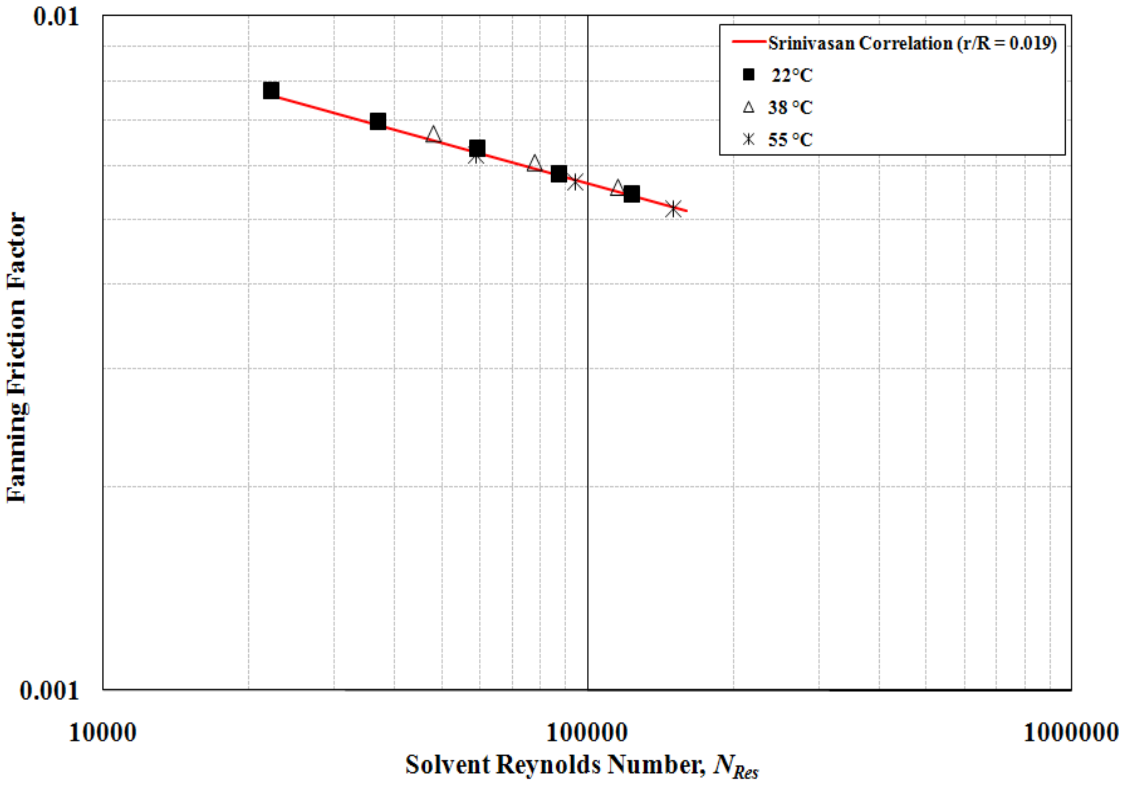

Figure 3. Water data in 1.27 cm OD coiled tubing (*r/R* = 0.019) at various temperatures

Data from coiled tubing were compared with the following Srinivasan correlation (Srinivasan et al, 1970) which is valid for smooth coiled tubing in the turbulent flow regime as shown in Fig. 3.

$$f = \frac{0.084}{N_{\mathrm{Re}\,s}^{0.2}}\left({r}/{R} \right)^{0.1}, \tag{5}$$

where *r/R* – curvature ratio, *r* – radius of coiled tubing and *R* – radius of coiled tubing reel.

The figure shows that water data agree well with Srinivasan correlations for turbulent flow of Newtonian fluid in coiled tubing. In coiled tubing, secondary flow effects occur due to the centrifugal forces and hence, Fanning friction factor values are greater for the coiled tubing case.

Both figures also show that all experimental data points at different temperatures for straight and coiled tubing fit the corresponding correlation which validates the accuracy of the system used.

Table 2 shows the values of the average and maximum percentage deviations. It can be seen from this table that the average deviations are less than 2 % and the maximum deviations are less than 3 %. This ensures the accuracy and validity of the flow loop. Another conclusion to be drawn is that this excellent agreement between the experimental data and Drew correlation confirms the smoothness of the inside pipe surface.

Table 2. Deviation between experimental and Drew correlation friction factors

Temperature, °C	Deviation, %	
	Average	Maximum
22	1.91	3.07
38	1.21	2.07
55	1.62	2.22

3.5 Effect of Temperature on DR in ST

Effect of temperature on drag reduction characteristics of ASP-820 in fresh water is shown in Fig. 4. It shows percent drag reduction as a function of solvent Reynolds number. It can be seen from this figure that the highest drag reduction is achieved at ambient temperature and it decreases with increasing temperature. For example, at 100,000 Reynolds number drag reduction decreases from 76 % at ambient temperature to about 68 % at 38 °C and 64 % at 55 °C. It can also be seen that the effect of temperature is more severe at lower Reynolds numbers. As Reynolds number increases, turbulence intensity increases and the effect of temperature is minimized.

It is known that polymeric fluids can respond to changes in their environment such as pH, temperature, and salinity where chemical degradation can be significant. Rise in temperature leads to a drop in Tom’s effect due to many factors. This may include the deterioration of the solvent-polymer interaction, diminishing of the macromolecules size, decreasing the hydrodynamic radius of the molecules, and changes in the conformational state of the polymer (Clifford and Sorbie, 1985; Nesyn et al, 1989).

It is known that water is a good solvent but its solvent power is drastically decreased by increasing temperature due to a decrease in hydrogen bonding ability. This reduces the interactions between the polymer and the bulk solvent which translates to a decrease in drag reduction. Another consequence of decreased polymer-solvent interaction is the decrease in the radius of gyration of the molecule. Therefore, intrinsic viscosity decreases as temperature increases. As a result, drag reduction decreases (Dey and Laik, 1986; Choi et al, 2000).

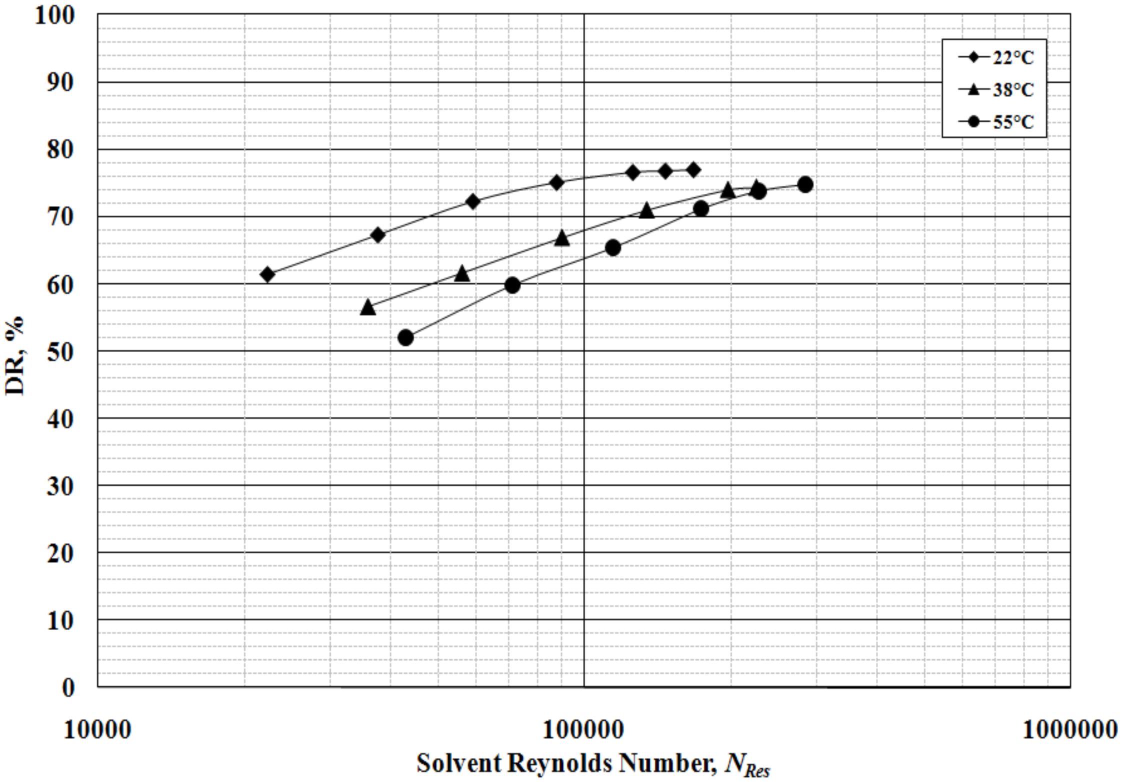

Figure 4. Drag reduction characteristics of ASP-820 polymer
at elevated temperatures in ST

Another parameter is the decrease in solution viscosity at higher temperature which results in decreasing the elongational viscosity. As a result, turbulent fluctuations and eddies will increase which increases drag (Peyser and Little, 1971).

Another important notice is that, the effect of temperature on percentage drag reduction decreases with increasing flow rate in straight tubing. This may be due to the fact that, the shape of the molecules can be changed due to thermal motion (at elevated temperature) or due to the effect of external field (turbulence). In our situation, the macro-molecules are affected by both factors. At moderate flow rates, the effect of external field on the macromolecules as well as the thermal motion is of approximately the same order of the magnitude and hence any variation in temperature results in a substantial change in the shape of the molecules and as a result a change in drag reduction. As the flow rate increases, the turbulent effect increases as compared to the thermal field and so, the change in drag reduction due to change in temperature is not as much as the previous case and this reduces temperature effect on drag reduction.

3.5.1 Development of correlations

The data gathered at various temperatures were used to develop a correlation that can predict drag reduction at elevated temperature once the drag reduction value at ambient temperature is known. The ratio of drag reduction at elevated temperature to drag reduction at ambient temperature, $(DDR)_T = (DR)_T/(DR)_o$ was used to develop the following correlation:

$$(DRR)_T = A\ln(N_{\mathrm{Re}s}) + B\ . \tag{6}$$

The constants *A* and *B* in Eq. 6 are function of temperatures and are given by the following correlations:

$$A = 0.0026T - 0.1995\ ; \tag{7}$$

$$B = 3.3405 - 0.0312T\ . \tag{8}$$

The above correlation is valid for smooth pipes at the optimum polymer concentration of 0.07 % (vol.) and over wide range of solvent Reynolds number [20,000 < N_{Res} < 200,000].

Fig. 5 depicts a comparison between the predicted and experimental drag reduction ratio as a function of solvent Reynolds number for ASP-820 polymer. It can be seen that there is a good agreement between the experimental and predicted values. The average deviation was 2.0 % with the corresponding maximum percentage deviation of less than 3.7 %. This ensures the validity of the newly developed correlations.

Therefore, using the above equations, one can predict the drag reduction value for Nalco ASP-820 polymer in straight tubing at elevated temperature.

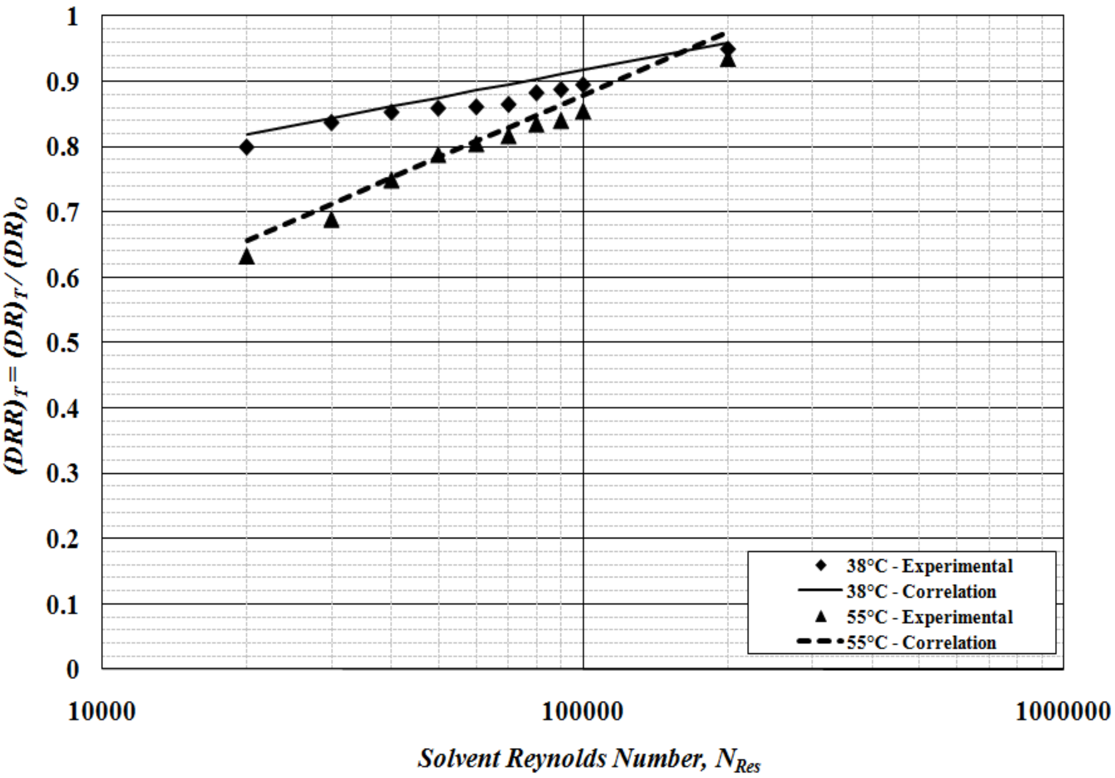

Figure 5. Experimental data and predicted values of $(DDR)_T$
for 0.07 % ASP-820 polymer in ST

3.6 Effect of Temperature on DR in CT

Effect of temperature on drag reduction in coiled tubing is a new subject and not well understood. In coiled tubing, central part of the fluid is forced outwards due to the centrifugal force and at the same time, the slower part along the wall is forced inwards which may offset temperature effect.

It is important to emphasize that, there are some publications available regarding the effect of temperature on drag reduction in straight tubing but there are no similar publications available for the case of coiled tubing.

Effect of temperature on drag reduction characteristics of the optimum concentration of ASP-820 in coiled tubing is shown in Fig. 6. Solvent Reynolds number is used in this analysis to eliminate the change in viscosity and density as a result of changing test temperature and at the same time, base fluid used for each test was at the same temperature as the polymeric fluid. The figure shows that there is no significant effect of temperature on drag reduction in coiled tubing at the same solvent Reynolds number.

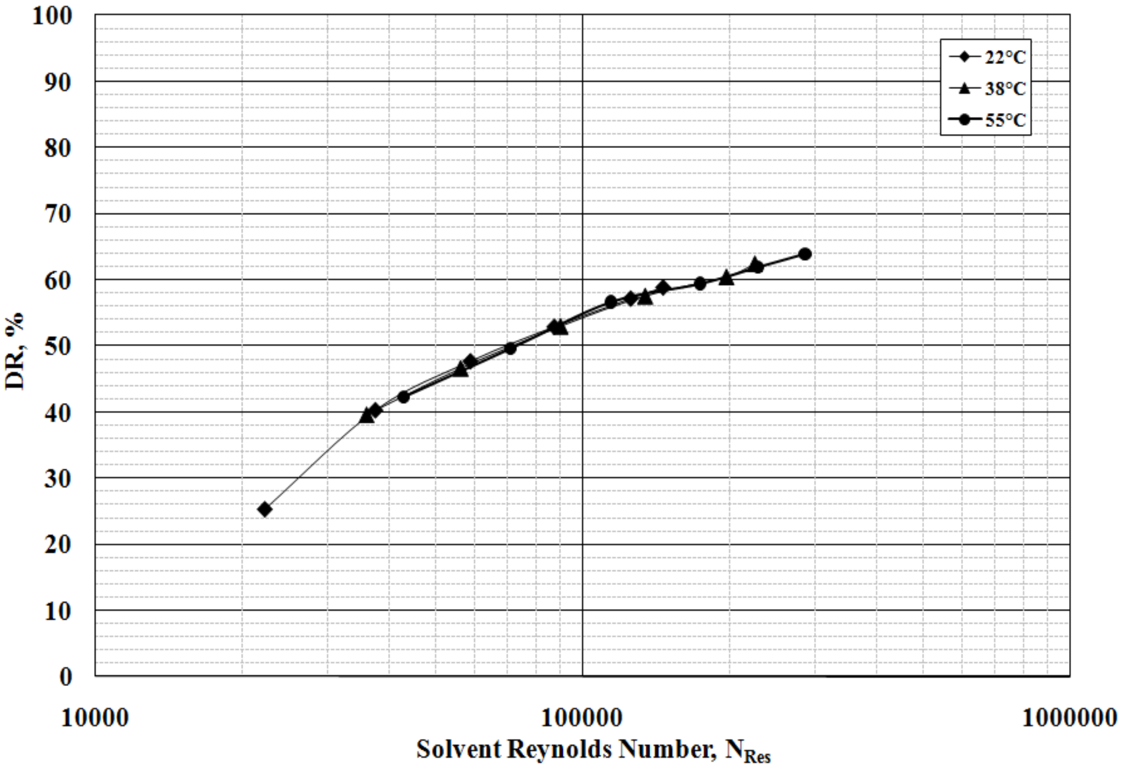

Figure 6. Drag reduction characteristics of ASP-820 polymer at elevated temperatures in CT (*r/R* = 0.019)

To understand the effect of temperature on drag reduction in coiled tubing, one should recall the basics of this phenomenon and how it occurs. The main reason as discussed by Lumely (Lumely 1969; 1973) is increasing the elongational viscosity by a factor of the order of ten thousands. This increases the thickness of the viscous sublayer and thus dampens and suppresses small eddies and turbulent fluctuations, reduces the velocity gradient at the wall and wall shear stress as well and so reduces the drag.

Increasing fluid temperature, will result in decreasing polymeric fluid viscosity and thus decreasing elongational viscosity and as a result turbulent fluctuations and eddies will increase which increase drag. However, in coiled tubing, secondary flows may play a part in reducing the effect of thermal degradation and thus, keeps the drag reduction at almost a constant level.

Further investigation and more detailed study at more elevated temperatures are needed for better understanding of the effect of temperature on drag reduction in coiled tubing.

3.6.1 Development of correlations

From the previous discussion, it can be said that, in coiled tubing, the effect of temperature is not as significant as in straight tubing. This may be due to the difference in the nature of fluid flow resulted from coiled tubing curvature. The difference between results at various temperatures can be considered to be within the experimental error. This suggests that one can use the previously developed correlation (Ahmed Kamel and Shah, 2009) to predict the Fanning friction factor at elevated temperature and hence, drag reduction. Therefore, the proposed correlation for drag reduction ratio at elevated temperature in coiled tubing can be given as:

$$(DRR)_T = 1.0\,. \tag{8}$$

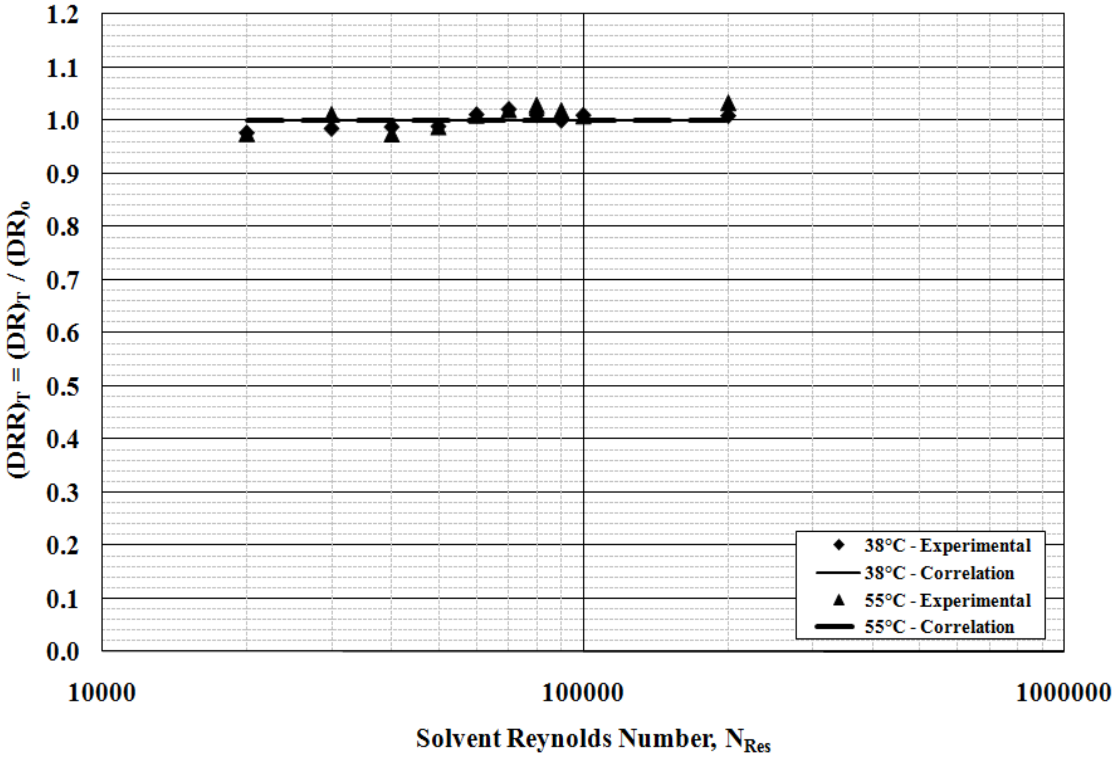

Figure 7. Experimental data and predicted values of (DDR)
for 0.07 % ASP-820 polymer in CT (r/R = 0.019)

The comparison is shown in Fig. 7, from which, it can be seen that there is a good agreement between the experimental and predicted values. The deviation is within the experimental error. The average deviation was 2.1 % with the corresponding maximum percentage deviation of less than 2.9 %. Therefore, one can predict the drag reduction value in coiled tubing at elevated temperature.

3.7 Onset of Drag Reduction

On the Prandtl-Karman coordinates, $1/\sqrt{f}$ vs. $N_{\mathrm{Re}s}\sqrt{f}$, drag reduction behavior of fluid can be better understood since the data are plotted along with the drag reduction envelope (Fig. 8). Virk (Virk, 1975) has defined three main laws which are used to determine the drag reduction envelope. These laws are:

– Poiseuille's Law,

$$\frac{1}{\sqrt{f_s}}=\frac{N_{\mathrm{Re}s}\sqrt{f_s}}{16}\,. \tag{9}$$

In laminar pipe flow, dilute polymer solutions do not show unusual behavior and the majority of them obey the above Poiseuille's Law.

– Prandtl-Karman Law,

$$\frac{1}{\sqrt{f_s}}=4.0\log_{10}N_{\mathrm{Re}s}\sqrt{f_s}-0.4\,. \tag{10}$$

This is the regime without drag reduction in which the friction factor relationship is the same as for the solvent. Fluids with zero drag reduction in turbulent flow follow this correlation.

– Maximum Drag Reduction Asymptote,

$$\frac{1}{\sqrt{f_t}}=19.0\log_{10}N_{\mathrm{Re}s}\sqrt{f_t}-32.4\,, \tag{11}$$

where, $N_{\mathrm{Re}s}$ is the solvent Reynolds number. This is an asymptotic regime of the maximum possible drag reduction in which the friction factor is sensitive to the polymer solution employed.

The following comments may help in understanding the drag reducing behavior of polymeric fluids. Firstly, intersection of the data line or its extrapolation with the bottom base line indicates the onset of drag reduction. Secondly, the data line almost parallel to bottom base line indicates that increase in drag reduction can be achieved by increasing the concentration of drag reducing fluid. Thirdly, the data line with slope higher than the bottom base line indicates higher drag reduction can be achieved by increasing the flow rate but not by increasing the polymer concentration.

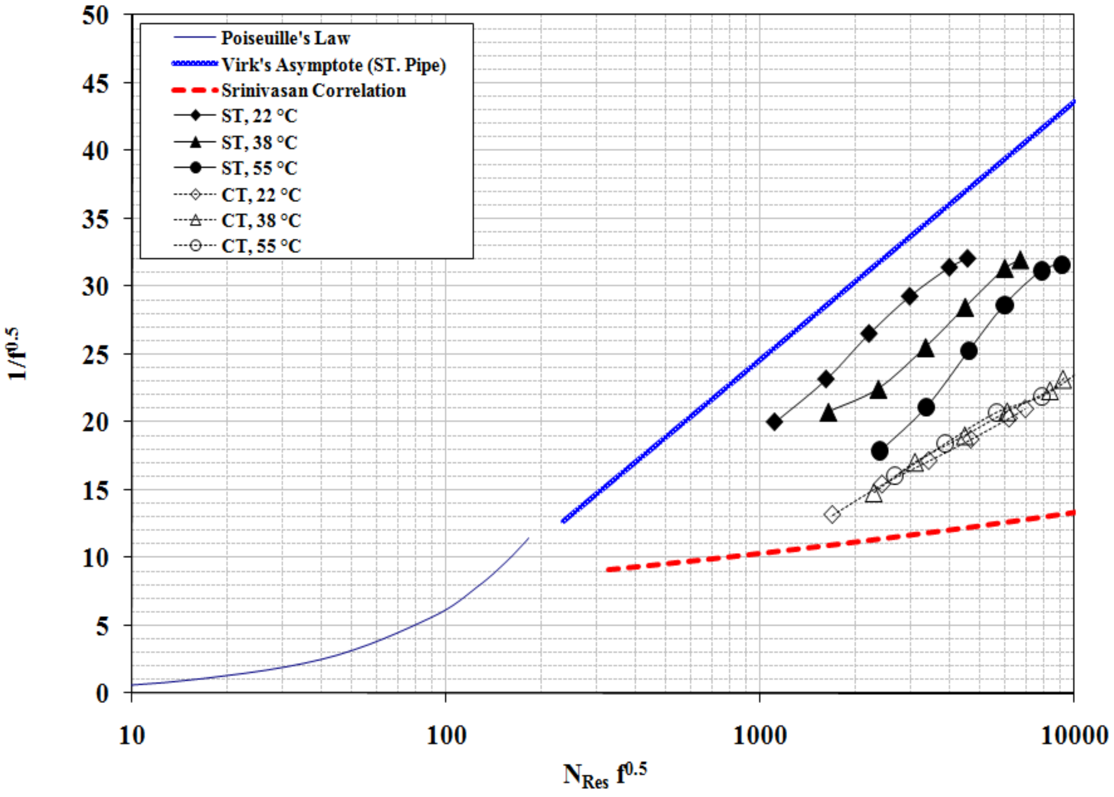

Figure 8. Onset of drag reduction for 0.07 % ASP-820 polymer
in 1.27 cm OD ST and CT (*r/R* = 0.019) at elevated temperatures

Fig. 8 shows the drag reduction envelope in Prandtl-Karman coordinates for 0.07 % polymer concentration at elevated temperatures in straight pipe and coiled tubing. This figure substantiates the claim made before, that drag reduction in straight tubing is higher than coiled tubing and it increases as the Reynolds number increases.

It is known that, drag reduction occurs only in turbulent flow region and it takes place once the wall shear stress is larger than what is called threshold shear stress. In other words, drag reduction occurs only at a certain value of Reynolds number. This value can be determined by extrapolating the data line to intersect the bottom base line.

By comparing the data lines, it can be noticed that the temperature has delayed the onset of drag reduction in straight tubing. For 22 ºC, the onset point was at solvent Reynolds number of 4000 while it moves further to right for 38 ºC to a value of 8000.

This means that the temperature has delayed the onset of drag reduction in straight tubing.

It can be observed from the figure that, increasing the temperature from 22 to 38 to 55 ºC, delayed the onset of drag reduction in straight tubing. But for coiled tubing, the drag reduction occurs almost at the same values. This figure also confirms the idea that, temperature effect in straight tubing is more significant than coiled tubing.

The reason for delaying the onset of drag reduction in coiled tubing might be that, the flow of drag reducing polymer solution in coiled tubing remains in laminar flow regime for significantly higher solvent Reynolds number than in the case of straight tubing. This delayed transition of turbulence could possibly because of two mechanisms: the first one is the delayed transition caused by drag reduction as in the case of straight tubing and the other one is the suppression of turbulence in curved flow geometry. As the curvature ratio increases, it increases secondary flow, delays the onset of turbulence, and so delays the onset of drag reduction in coiled tubing (Ahmed Kamel and Shah, 2009).

4. Applications

In conventional gel fracturing treatments, the damage induced by the gel can have a significant impact on well performance, particularly in low permeability gas formations. Slick-water treatments have been shown to be more successful because of reduced gel damage and limited height growth (Liu et al, 2006). Production and economic analysis have shown that high rate slick-water fracturing treatments are more effective for enhancing long term production.

With the development of light weight proppant (1.0 < sp.gr. < 1.25) slick-water fracturing has become more efficient in tight, low permeability formations (Posey and Strickland, 2005). Slick-water fracturing has the advantages of reducing job costs significantly without impacting ultimate recovery over conventional polymer. Due to low viscosity of slick-water, higher pump rates are needed to create the fracture width necessary to place proppant and avoid screen-out (Shaefer, 2005; Britt et al, 2006; Mills, 2006).

With the universal trend of using small diameter pipes (especially in coiled tubing applications), reduced pipe diameters (and secondary flows in coiled section of the tubing) generate high friction pressure losses, thus limiting the pumping capacity. Use of drag reducers helps avoid these problems. The present study gives the necessary correlation to better design hydraulics necessary for the slick-water fracturing treatments under conditions of elevated temperature. An illustrative example is shown below to emphasize the importance of such study.

Illustrative example

Given: A vertical well at a depth of 4,800 ft is hydraulically fractured with a 2 ⅜-in. (1.995-in. ID) tubing. Fresh water containing 7 % (vol.) Nalco ASP-820 friction reducer is pumped at 5 bbl/min.

Calculate:

(a) Friction pressure loss gradient (psi/ft) of fresh water at ambient conditions;

(b) Friction pressure loss gradient (psi/ft) of fresh water containing 7 % ASP-820 at ambient conditions;

(c) Percent drag reduction obtained at flow rate of 5 bbl/min;

(d) Percent drag reduction if fresh water is used as base fluid at 100 °F;

Solution:

(a) Fresh water calculations

1. Average fluid velocity is calculated using the following equation:

$$v(ft/s)=\frac{17.16Q(bbl/\min)}{d_{i}^{2}(in.)}=\frac{17.16\times 5}{(1.995)^{2}}=21.6\,\text{ft/sec}\,.$$

2. Fresh water has viscosity and density of 1.0 cP and 8.34 lb/gal respectively at ambient conditions. Therefore, solvent Reynolds number is calculated using Eq. 3.

$$N_{\text{Re}}=928\left(\frac{\rho v d_i}{\mu}\right)=928\left[\frac{(8.34)(21.6)(1.995)}{1.0}\right]=333{,}511>2{,}100\,.$$ (turbulent flow)

3. Fanning friction factor for the flow of solvent in straight tubing can be calculated using Eq. 4:

$$f_s=0.0014+0.125(N_{\text{Re}s})^{-0.32}=0.0014+0.125(333511)^{-0.32}=3.5\times 10^{-3}\,.$$

4. Friction pressure loss gradient for water can be calculated using Eq. 1.

$$\Delta p/l=\frac{f\rho v^2}{25.8\,d_i}=\frac{3.5\times10^{-3}\times8.34\times(21.6)^2}{25.8\times1.995}=0.26\,psi/ft\,.$$

(b) Fresh water containing 0.07% ASP-820

1. Fanning friction factor for fresh water containing 0.07% ASP-820 polymer in straight tubing at the same solvent Reynolds number is calculated using the previously developed correlation (Ahmed Kamel and Shah, 2009) and it is:

$$f_p=9.2\times10^{-4}\,.$$

2. Friction pressure loss gradient can be calculated as shown earlier.

$$\Delta p/l=\frac{f\rho v^2}{25.8\,d_i}=\frac{9.2\times10^{-4}\times8.34\times(21.6)^2}{25.8\times1.995}=0.07\,psi/ft\,.$$

(c) Drag reduction for fresh water

Drag reduction for water as base fluid can be calculated using Eq. 2:

$$(DR)_o=100\left(1-\frac{f_p}{f_s}\right)=100\left(1-\frac{9.2\times10^{-4}}{3.5\times10^{-3}}\right)=73.7\%\,.$$

Thus, a reduction in pump pressure of 73.7 % can be achieved. In other words, at the same pump pressure, by adding 0.07 % ASP-820 fluid flow rate can approximately be doubled.

(d) Drag reduction for fresh water at 100°F

For elevated temperature calculations, a correction factor to drag reduction value can be estimated using Eq. 8:

$$(DRR)_s=0.94\,.$$

Thus, drag reduction for water at 100 ºF containing 7 % ASP-820 is:

$$(DR)_s=(DRR)_s\times(DR)_o=0.94\times73.7=69.3\ \%\,.$$

Therefore, the reduction in pump pressure for water at 100 ºF is 69.3 % or the increase in pump rate is about 1.8 times.

The above example shows the importance of using the appropriate correlation for hydraulic calculations while designing fracturing treatments to avoid job failure due to limited pump capacity or improper fracture dimensions due to unexpected high pump rates.

5. Summary

In this study, the effect of temperature on drag reduction characteristics of Nalco polymer (ASP-820) flowing in circular straight and coiled tubing have been investigated. The results reported here indicate Nalco polymer is quite effective drag reducer. This study is conducted under laboratory conditions and using smooth pipe as flow conduit. This is not the case under field application. In the field, polymer can degrade due to rough inside surface of the pipe. The solvent may contain some impurities. Pipe sizes used are also large. Therefore, the obvious question is – are the correlation valid under field conditions? Since the correlations are developed with the use of dimensionless quantities of Fanning friction factor and solvent Reynolds number, they would scale up to larger pipe sizes reasonably good. However, the drag reduction observed under field conditions would be somewhat lower than the predicted from the correlations because of the presence of pipe roughness in the field tubular goods. Previous study (Shah et al, 2006) has shown as much as 20 % difference between the laboratory and field conditions. In order to answer this question thoroughly, however, the large-scale experiments with actual field tubular are recommended.

6. Conclusions

1. From the practical point of view, ASP-820 polymer is found to be effective in exhibiting adequate drag reducing properties under various conditions of elevated temperature that will be encountered in many industrial applications. The drag reduction in the range of 30-80 % is reported.

2. A decrease in drag reduction efficiency of the polymers is seen at elevated temperature. Effect of temperature on drag reduction is more severe in straight tubing than coiled tubing.

3. As the temperature increases drag reduction in straight tubing decreases while it remains almost the same in coiled tubing.

4. The effect of elevated temperature is more pronounced at low solvent Reynolds numbers. However, at higher Reynolds numbers – increased turbulence intensity – the effects are minimized.

5. Correlations have been developed to predict drag reduction as a function of temperature for both straight and coiled tubing. The developed correlations show a reasonably good agreement with the experimental data.

6. Large scale tests are recommended for further evaluation of the drag reducing polymers and the proposed correlations.

7. Higher temperature delays the onset of drag reduction in straight tubing. This is not true for coiled tubing since drag reduction occurs at almost the same value of Reynolds number.

Nomenclature

C_S – Salt concentration, *%;*
DR – drag reduction, $(1-f_t/f_s)$;
$(DR)_O$ – drag reduction for reference case (fresh water or ambient temperature);
$(DR)_T$ – drag reduction at elevated temperature;
$(DRR)_T$ – drag reduction ratio at elevated temperature;
d_i – inside diameter of pipe, *in;*
f_s – Fanning friction factor of solvent;
f_t – Fanning friction factor of treated fluid;
FR – friction reducer;
ID – inside pipe diameter, *in;*
l – pipe length, *ft*;
$N_{\mathrm{Re}s}$ – solvent Reynolds number $\left(\rho_s v d_i / \mu_s\right)$;
OD – outside or nominal pipe diameter, *in*;
Δp – differential pressure, *psi*;
T – temperature, °*F*;
v – average fluid velocity, *ft/s*;
μ – fluid viscosity, *cP*;
μ_s – solvent viscosity, *cP*;
ρ_s – solvent density, lb_m/gal.

Acknowledgments

The author acknowledges gratefully the research team of the Well Construction Technology Center for their help with the experiments. He is also thankful to the members of the Coiled Tubing Consortium for their continued support and Nalco Company for providing the polymers. The author is also thankful to K.T. Chang and J.V. Mello, Adomite Research, Nalco Company for fruitful discussion and suggestions.

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SI METRIC CONVERSION FACTORS

bbl × 1.589 873 E–01 = m^3
ft × 3.048 * E–01 = m
cP × 1.0 * E–03 = Pa·s
gal × 3.785 412 E−03 = m^3
in. × 2.54 * E+00 = cm
lbm × 4.535 924 E−01 = kg
psi × 6.894 757 E+00 = kPa