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FULL LENGTH ARTICLE

Studying the rheological properties and the influence of drag reduction on a waxy crude oil in pipeline flow

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Abstract The present work studies the effect of a commercially type of drag reducing agent on the crude oil production flow lines located in the Egyptian western desert (Fagour field) and owned by Khalda Petroleum Company. The drag reducing agent used in this study is a high molecular weight poly alpha olefin prepared by emulsion polymerization technique and supplied under trade name of LP-111. The results showed that this drag reducing agent (DRA) has great effects on the pressure drop and fanning factor. After the field application of 60 ppm of the DRA, the pressure drop was decreased by 36% at the pipeline capacity of 18,804 bbl/day. The fanning number and shear stress were decreased by the same percentage of 47%. The capacity of production line can be increased by 38% all over the two pipeline section due to the great reduction of pressure drop.

The rheological behaviors of tested waxy crude oil were studied at different temperatures (varies from 67 to 102 °F) and different DRA concentrations (10, 20, 30, 40, and 50 ppm). The results showed that at all constant DRA concentrations, the viscosity highly decreased until 80 °F (above pour point by 15 °F). However, by increasing the DRA concentration, the viscosity is increased at temperatures lower than 80 °F. This is because the DRA is a high molecular weight polymer which participates in increasing viscosity by increasing its concentration. After 80 °F, the DRA concentration has an insignificant effect on viscosity. So the effect of the DRA is not in reducing viscosity but mainly in reducing the degree of turbulence energy. The field studies were performed at a normal

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temperature of tested pipeline sections (100 °F). The tested DRA has an improving effect on reducing the pressure drop of pipeline which leads to reduction in crude oil pumping energy or an increase in the pipeline capacity with a high efficiency of the DRA.

Nomenclature

DR	drag reduction	CO	temperature scale by celsius
DRA	drag reduction agent	bbl/day	barrel fluid per day
ΔP	pressure gradient for the drag solution	Psi	pound per square inch
ΔPs	pressure gradient for the solvent	h_f	head loss due to friction (SI units: m)
V	liquid velocity	L	the length of the pipe (m)
τ	shear stress	g	the local acceleration due to gravity (m/s^2)
Γ	shear rate	f_D	a dimensionless coefficient called the Darcy friction factor
η	viscosity		
D	diameter		

1. Introduction

Turbulent friction of fluids can be reduced by adding small amounts of certain polymers or surfactant [1–4], the first report was created by Forrest and Grierson [5], they observed a reduction in energy loss in the turbulent pipe flow of wood pulp fiber suspensions in water. This first report of drag reduction was unnoticed. Later, Mysels [6] found that the skin friction for gasoline in pipe flow was significantly reduced by the addition of an aluminum disoap (an anionic surfactant). In 1948 Toms [7] observed the drag reduction phenomenon, while doing polymer degradation research, Toms observed that the addition of a long chain polymer (polymethyl methacrylate) in monochlorobenzene dramatically reduced the turbulent skin friction drag by up to 80% and observed that at constant pressure gradient, the flow rate could be increased by the addition of the polymer. Toms reported these results at the First International Rheological Congress. Therefore, it is usually referred to as the "Toms Effect". Later, Savins [8] first used the term "drag reduction". Since the polymer synthesis technology and cost effectiveness have been highly improved, polymer drag reduction has been adopted widely in large pipeline systems for crude oils, water injection and refined petroleum products [9–11]. The first commercial application for high polymer drag reduction was its use in the 48 inches diameter 800 miles long Alaska pipeline carrying crude oil from the North Slope in Alaska to Valdez in the south of Alaska [12,13]. Drag reducing agents (DRA's) were used in the oil and gas producing industries to help lower pressure gradients for the transport untreated crude oil over long distances. DRAs have been very beneficial in reducing frictional losses, allowing a greater production flow rate at an economical cost [14,15]. The present work studies the effect of a commercial type of drag reducing agent on the crude oil production flow lines located in the Egyptian western desert (Fagour field) and owned by Khalda Petroleum Company. Another aim of the present work is to study the rheological behaviors of tested waxy crude oil at different temperatures.

2. Experimental work and theoretical calculations

Field experiments were performed on Khalda Petroleum crude (KPC) oil production line called Fagour pipeline located in western desert of Egypt. The physical properties of this crude oil are listed in Table 1. Fagour pipeline's total length is 28 km from Fagour to Kalabsha facility. The pipeline's length is 16 km from Fagour facility to Bouchis with 6 inches nominal pipeline diameter and 12 km from Bouchis to Kalabsha facility with 8 inches pipeline nominal diameter. At Fagour facility there are two shipping pumps (one pump in operation and the other is a standby) which are used for pumping crude oil from storage tanks to the production line. The discharge of the shipping pump is mixed with the crude oil from Fagour wells production line to give 18,804 bbl/day after mixing point as illustrated in Fig. 1.

2.1. DRA properties and its injection method

The drag reducing agent used in this work is a high molecular weight poly alpha olefin prepared by emulsion polymerization technique and supplied under the commercial name of LP111. Table 2 presents the physical properties for LP111 DRA.

Drag reducing agent (DRA) injection is performed using an injection skid included a texsteam pump (see Fig. 2) with two plungers. The maximum dose for each plunger is 30 gpm (gallon per minute). This injection pump was installed directly at the mixing point of shipping pump discharge and wells production line of Fagour. The DRA injection dose was chosen to be 60 ppm. This choice is attributed to the lower effect of DRA at concentration lower than 60 ppm. This is because of the high water cut in the produced crude oil which is more soluble to the tested DRA (LP 111). The pressure readings are obtained using Parton chart for pressure reading and the DRA dose is adjusted by Kenco gauge. The flow of production line is checked by using an ultrasonic flow meter.

Table 1 Physical properties of KPC crude oil produced at Fagour field.

Property	Test method	Value
API	ASTM-D287-92	40
Viscosity, c pois	Brookfield Viscometer DV + II	3.5:4
Bs and W*, %	ASTM-D96-88	40
Pour point, OC	ASTM-D97-96	65
Cloud point, OC	ASTM-D97-96	68

* Bs and W are the basic sediment and water content as a percent of crude oil.

Table 2 Physical properties of tested DRA (PL111) [16].

Physical property	Characteristic or value
Appearance	White
Physical form	Liquid
Odor	Mild
pH	10–12.3
Density (lbs/gal)	.8
Vapor pressure at 77 °, psi	.46
Freezing point, °F	32
Boiling point, °F	212
Viscosity at 77 °F, c p	375

2.2. Determination of rheological behavior of crude oil

It is important to find the relation between the viscosity and shear rate of crude oil at different temperatures and different DRA concentrations. This relation is investigated in this work to determine the effect of DRA on fanning and Darcy friction factors. It is also important to determine if there is an effect of DRA on crude oil properties or not. So the influences of DRA concentration and temperature on the crude oil viscosity were investigated by the use of a Brookfield Viscometer DV + II. Brookfield Viscometer DV + II type with water bath TC-650 using Rheocalc program as shown in Fig. 3, was used in this research to study the rheological behavior of crude oil under consideration. The Sc4-18 spindle type is used for this viscometer to execute our set of experiments with a sample injected volume of 6.7 ml.

The viscosity of crude oil determined by the use of a Brookfield Viscometer is a measure of the ratio of shearing stress to shear rate. The Brookfield Viscometer measures viscosity by measuring the force required to rotate a spindle in a fluid at specified temperature in relation to its shear rate. On the DV + II viscometer type, the viscosity can be read directly. On other models, the viscosity is obtained by multiplying the reading of shear rate by a constant related to the particular rotational speed used.

The rheological behaviors of crude oil were determined at different concentration of DRA. Crude oil samples for the viscometer were prepared starting by the collection of a blanked sample (treated oil from shipping line) without the DRA. After that, five sani glasses (100 ml) finally, DRA was injected in each sani glass at five different concentrations (10, 20, 30, 40, 50 and 100 ppm).The first set of experiments was performed at constant temperature of 100 °F. The rheological behaviors (shear rate–viscosity relationship) were determined at different concentrations of DRA (10, 20, 30, 40, 50 and 100 ppm). The second set of experiments was performed at different temperatures that varies from 64 to 100 °F and the rheological behavior of samples was investigated for each DRA concentration 10, 20, 30, 40 and 50 ppm).

Figure 2 Texteam pump used for injecting DRA.

2.3. Pipeline friction head loss and pressure drop calculations

There are two factors affecting the friction head loss calculation; namely the Darcy friction factor (f_D) and fanning friction factor. The Darcy–Weisbach friction factor, f_D is 4 times larger than the fanning friction factor, so attention must be paid to note which one of these is meant in any "friction factor" chart or equation being used. Of the two, the Darcy–Weisbach factor, f_D is more commonly used by civil and mechanical engi-

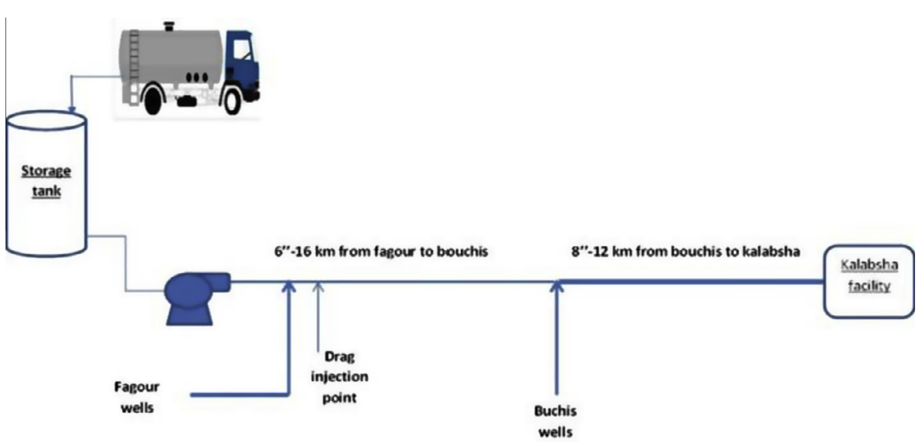

Figure 1 Layout of pipeline network of KPC at Fagour field.

Figure 3 Brookfield Viscometer DV + II type with water bath TC-650.

neers, and the fanning factor, f, by chemical engineers, but care should be taken to identify the correct factor regardless of the source of the chart or formula.

The friction head loss [17] or pressure loss can be calculated using the following equation:

$$h_f = f_D \frac{L}{D} \frac{V^2}{2g} \quad (1)$$

where h_f is the head loss due to friction, L is the length of the pipeline, g is the local acceleration due to gravity, f_D is the Darcy friction factor, V is the liquid velocity, and D is the pipeline diameter.

Fanning friction factor related to the shear stress at the wall can be calculated using the following equation:

$$\tau = \frac{f\rho V^2}{2} \quad (2)$$

where τ is shear stress, ρ is density, V is liquid velocity and f is fanning factor.

The relationship between the friction head losses and the fanning friction factor can be calculated using Eq. (3):

$$h_f = 2f \frac{L}{D} \frac{V^2}{g} \quad (3)$$

where h_f is head loss due to friction, L is the length of the pipe, g is the local acceleration due to gravity, f is a dimensionless coefficient called fanning factor, V is liquid velocity (m/s) and D is pipeline diameter.

The efficiency of DRA under consideration is measured by calculating the pressure drop reduction related to the addition of DRA compared to the pipeline pressure drop with the DRA (see Eq. (4))

$$\mathrm{DR\%} = (\Delta P_{WO/D} - \Delta P_{W/D})/(\Delta P_{WO/D}) \quad (4)$$

where DR% is percent of drag reduction, $\Delta P_{WO/D}$ is pressure drop without drag reducing agent and $\Delta P_{W/D}$ is pressure drop with drag reducing agent.

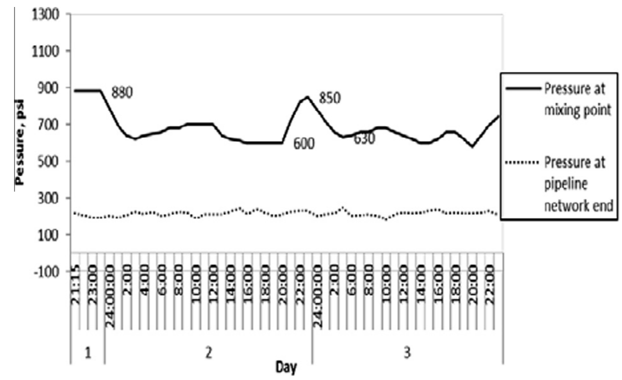

Figure 4 Effect of DRA on Fagour pressures at mixing point and at the line end after different periods of time.

Table 3 Influence of DRA on the shipping rate in relation to periods of time after injection.

With or without DRA treatment	Time, days	Shipping rate, bbl/day
Before injection of DRA	1	4139
	2	4003
	3	4016
	4	3926
	5	4005
After injection of DRA	1	5704
	2	5515
	3	5127
	4	5340
	5	5413
	6	5544
	7	5604

3. Results and discussion

3.1. Effect of DRA on pressure drop

Fig. 4 shows the effect of drag reducing agent on pressure (illustrated by solid line in Fig. 4) directly after the mixing point (illustrated above) of Fagour field. From this figure, it is observed that the pressure decreased from 880 to 600 psi during the first three days at 60 ppm of the tested DRA. On the second day, the pressure was abnormally increased from 600 to 850 psi because of the injection pump plunger which was stuck and the dose decreased from 60 ppm to 30 ppm. This means that any sudden changes in the DRA concentration can lead to bad effects in reducing the pressure drop. This also will lead to reduction in the DRA chemical stream volume (act as shear point). However, the pressure at the end of pipeline does not change (illustrated by the dotted line in Fig. 4).

Table 3 shows that the injection of DRA (60 ppm), increased the shipping pump rate by 37.5% (rate increased from 4000 to 5500 bbl/day). This rate increase is due to the effect of DRA in reducing the pressure drop (included in calculating the pump head) by 36% (pressure decreased from 880 to 650 psi). It is clear that the DRA has an improving effect on lowering the pump energy consumption (at constant capacity) or an increase in the pipeline capacity due to the reduction of the pipeline pressure drop. It noticed that the influence of the tested DRA is highly observed for the 6 inches

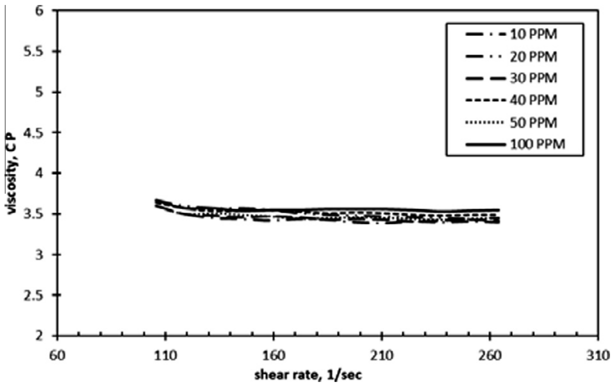

Figure 5 Viscosity–shear rate relationship of crude oil treated with different concentrations of DRA at 100 °F.

pipeline section (16 km from Fagour to Bouchis) compared to 8 inches pipeline section (18 km from Bouchis to Kalabsha). This is can be attributed to the higher value of friction in case of smaller pipeline diameter in which the DRA have the best effect.

The calculated fanning factor decreased from 0.0053 to 0.00281 and shear stress decreased from 5.2748 to 2.7907 lb/(sec^2 ft) after the injection of 60 ppm of the investigated DRA. So it is found that the fanning number and shear stress were decreased by the same percentage of 47%.

3.2. The rheological behaviors of tested waxy crude oil

Fig. 5 shows the viscosity–shear rate relationship for the tested crude oil treated with different concentrations (10, 20, 30, 40, 50 and 100 ppm) of the DRA at a constant temperature of 100 °F. From this figure, it is obvious that there is an insignificant effect of the DRA on crude oil viscosity in relation to shear rate at different DRA concentrations. This means that the influence of the tested DRA in reducing the pipeline pressure drop is not attributed to its effect on viscosity but attributed mainly to its effect by reducing the degree of turbulence energy inside the pipeline network.

Relationship between shear stress and shear rate of KPC crude oil treated with different concentrations of DRA (10, 20, 30, 40, 50 and 100 ppm) is illustrated in Fig. 6. This figure shows that this relationship is a straight line at each concentration of DRA. This rheological behavior indicates that this crude oil type is a Newtonian one at the tested temperature of 100 °F.

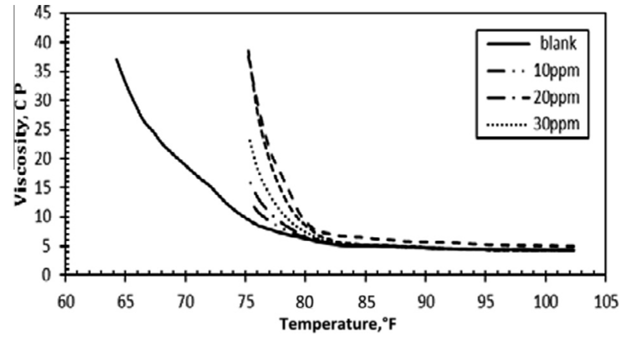

Figure 7 Viscosity–temperature relationship of crude oil treated with different concentrations of DRA.

Fig. 7 depicts the relationship between viscosity of crude oil injected with different concentrations of DRA (0, 10, 20, 30, 40 and 50 ppm) and temperature varied from 67 to 102 °F. Viscosity of the blank sample (without DRA) in the temperature range of 67–85 °F decreased from 37 to 5 c pois respectively. This flow behavior is a non-Newtonian (viscoelastic) in this temperature range and can be expressed in the form of an Arrhenius-type equation indicated in the following:

$$\mu = 20343e^{-0.1T} \quad \text{where } 67\,^\circ\text{F} < T < 85\,^\circ\text{F} \tag{5}$$

However, the viscosity of blank sample changed slightly from 4.9 to 4.3 c pois with increasing temperature from 86 to 102 °F respectively. Subsequently, the tested crude oil showed approximately a Newtonian behavior in this temp range. This flow behavior can be expressed well in a linear equation form as shown in the following:

$$\mu = -0.0458T + 8.873 \quad \text{where } 86\,^\circ\text{F} < T < 102\,^\circ\text{F} \tag{6}$$

For crude oil injected with different concentrations of DRA, it is noted that the working temperature range (67–102 °F) is lower than that of the blank sample. At temperature lower than 77 °F, it is difficult to perform the rheological test on treated crude oil. This can be attributed to the role of the DRA on increasing dramatically the viscosity of the crude which takes approximately the same gummy shape as illustrated in Fig. 8 for crude oil treated with DRA at concentration higher than 60 ppm. This means that the best condition for using this DRA type is at temperature higher than 86 °F.

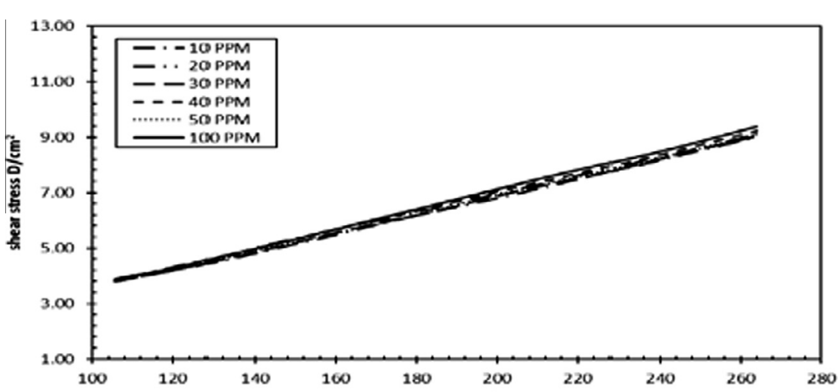

Figure 6 Shear stress–shear rate relationship of crude oil treated with different concentrations of DRA at 100 °F.

Figure 8 The gummy shape of crude oil treated with a high concentration of DRA.

Table 4 Arrhenius and linear fitting equations for the viscosity-temperature relationship of crude oil treated with different concentrations of the investigated DRA.

DRA conc. ppm	Arrhenius equation $67\,°F < T < 85\,°F$	Linear equation $86\,°F < T < 102\,°F$
10	$\mu = 9895e^{-0.092T}$	$\mu = -0.0474T + 9.0156$
20	$\mu = 6.1 * 10^5e^{-0.112T}$	$\mu = -0.0489T + 9.16$
30	$\mu = 10^6e^{-0.146T}$	$\mu = -0.0521T + 9.4475$
40	$\mu = 5 * 10^6e^{-0.193T}$	$\mu = -0.0583T + 10.022$
50	$\mu = 2 * 10^7e^{-0.175T}$	$\mu = -0.0724T + 12.245$

By increasing the DRA concentration, the viscosity is increased at temperatures lower than 80 °F as shown in Fig. 7. This is because the DRA is a high molecular weight polymer which participates in increasing viscosity by increasing its concentration. After 80 °F, the DRA concentration has an insignificant effect on viscosity. So it can be stated that the effect of the investigated does not raise DRA on reducing crude oil viscosity but has an effect on fanning factor and shear stress (reduce turbulent flow energy).

Table 4 lists the two best equations that fit well with the viscosity–temperature relationship for crude oil treated with different concentrations (10, 20, 30, 40 and 50 ppm) of the investigated DRA at two different temperature ranges. These two equations are the Arrhenius equation in the temperature range of 67–85 °F and linear type equation in the temperature range of 86–102 °F with excellent correlation coefficients.

4. Conclusions

This work studied the effect of a commercial type of DRA on the flow characteristics inside a pipeline network of KPC crude at Fagour field. The results showed that that application of 60 ppm of the tested DRA at the field temperature of 100 °F was effective in increasing the wells' production rate by decreasing the pressure drop inside the pipeline network. The capacity of production line can be increased by 38% all over the two pipeline sections of Fagour field due to the great reduction of pressure drop by 36%.

The rheological properties of crude oil treated with varied amounts of DRA at different temperatures were investigated by a Brookfield Viscometer DV + II. The results revealed that at temperatures lower than 80 °F, the viscosity is increased as the DRA concentration is increased. This can be attributed to the polymeric nature of highly molecular weight DRA which participates in increasing viscosity by increasing its concentration. After 80 °F, the DRA concentration has an insignificant effect on viscosity. This behavior interprets somewhat the mechanism of the DRA under consideration in reducing the pressure drop inside the pipeline network. It can be stated that the investigated DRA does not participate in reducing crude oil viscosity but its role may be concentrated in decreasing the degree of turbulence energy. This means that the DRA plays a good job in reducing the fanning factor inside the pipeline network. If the DRA dose increased over 60 ppm, it may lead to the pipeline network plugging due to the polymeric network that can be produced with higher values of viscosity of the treated crude oil.

The efforts done in this present work show the usefulness of using DRA revealed in increasing the capacity of the pipeline network or in improving the power consumption of pumps.

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References

[1] Ferhat Hadri, Sylvain Guillou, Int. J. Eng. Sci. Technol. 2 (12) (2010) 6876–6879.
[2] Yi Wang, Bo You, Jacques L. Zakin, Hafeng Shi, Advanced in Mechanical Engineering 2011 (2011) 17 pages 478749.
[3] Hiroshi Suzuki, Yuta Higughi, Hirofumi Watanabe, Yoshiyuki Komoda, Shogo Ozatna, Takuya Nishimara, Nobuyuki Takenaka, J. Soc. Rheol. Jpn. 40 (2012) 85–90.
[4] Andreea Calin, UPB Sci. Bull. Ser. C 71 (3) (2009).
[5] F. Forrest, G.A. Grierson, Pap. Trade J. 92 (22) (1931) 39–41.
[6] K.J. Mysels, AlChE Chem. Eng. Progress Symp. Ser. III 67 (1971) 45–49.
[7] B.A. Toms, Some observations on the flow of linear polymer solutions through straight tubes at large Reynolds numbers, Proceedings of the 1st International Congress on Rheology, vol. 2, North Holland, 1949, pp. 135–141.
[8] J.G. Savins, Soc. Petrol. Eng. J. 4 (1964) 203.
[9] A.R. Abubakar, T. Al-Hashmi, Y. Al-Wahaibi, A. Al-Wahaibi, M. Al-Ajmi, Eshrati, Adv. Mech. Eng. 2014 (2014) 8 pages 202073.
[10] Serife Zeybek Vural, Goknur Bayram, Yusuf Uludag, Turk. J. Chem. 38 (2014) 142–151.
[11] Pragya Deka, K. Rambhoopal Naida, Tapas Kumar Mandal, Sabrata Kumar Majunder, Int. J. Res. Eng. Technol. 2 (2) (2014).
[12] E.D. Burger, W.R. Munk, H.A. Wahl, J. Petrol. Technol. 34 (2) (1982).
[13] J.F. Motier, L.C. Chou, N.S. Kommareddi, Commercial drag reduction: past, present, and future, in: Proceedings of the ASME Fluids Engineering Division Summer Meeting, ASME, San Diego, Calif, USA, 1996.
[14] G.A.R. Rassoul, Ali.A.A. Hadi, Iraqi J. Chem. Petrol. Eng. 80 (2) (2007) 29–34.
[15] W. Interthal, H. Wilski, Colloid Polym. Sci. 263 (1985) 217–229.
[16] http://www.lubrizolspecialtyproducts.com/Data%20Sheets/lp-111.pdf.
[17] J. Weisbach, Van Nostrand, Mech. Eng. (1872) (translated from German).