

RHEOLOGICAL BEHAVIOR OF WAX DEPOSITED THROUGH PIPELINE TRANSPORTATION

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ABSTRACT

The wax deposit causes flow problems in oil production and transportation. Viscosity's of waxy crude oils in presence and absence of surfactants mixture have been measured at wax content between 9-28%, temperature between 45°C and 65°C and shear rates ranging from 30 to 300 s⁻¹. The behaviors of waxy crude oils before, during and after an application of shear force have been studied. The results of this study reveal that the viscosity of the waxy crude oil decreases as the temperature increases. The results also indicated that the rheological behavior of waxy crude oils has a pronounced effect by the concentration of wax and dispersants. In addition the viscosity of waxy crude oil at low wax concentration behave like Bingham plastic fluid up to 18% wax content, and as pseudoplastic fluids at higher wax content. This implies that it is safe to pumping the waxy crude oil up to 18% wax without causing problem when trying to start up a pipeline after a shutdown. The results reveal by increasing wax concentration up to 23-28%, a significant problems begin to appear induced. On the other hand, the surfactants mixture have been evaluated at 5% and 10% as pour point depressant. Unfortunately, the surfactants mixture give poor results as pour point depressant. For this reasons it was found a major difficulties to measure the rheological dynamic viscosity blew the wax appearance temperature or even at the pour point of waxy crude. Consequently, all data are measured above the wax appearance temperature.

Keywords : Wax deposition, Wax modifier, Wax inhibitors, Wax dispersants, Rheological, Viscosity, Pour point depressant and Pipeline transportation.

INTRODUCTION

The presence of paraffin wax in crude oils presents a host of problems to the producer, transporter, and refiner. The build-up of paraffin's and asphaltenes represents the organic equivalent of scale formation, and their presence in the formation, tubing, transfer lines, storage vessels and pipelines can lead to serious problems. The problems associated with their presence range from minor to severe, and depend on their quantity and composition. However, the paraffin waxes are valuable sources of refined products ranging from motor oil to jet fuel.

Once waxes have deposited in pipelines, storage tanks, well tubing, and formations,

another technique has been used to remove these deposits. Hot-oil from atleast one major drawback a concentration of higher waxes left after treatment. This technique involves the circulation of heated production fluid through the transfer lines, well

Tubing, and formation to dissolve wax deposits. However, since the higher waxes tend to be less soluble at elevated temperatures, these treatments tend to concentrate the higher (harder) waxes in place. Solvent washes are also used, where large amounts of solvents (e.g. xylene) are circulated through the system to remove deposits. These solvent treatments are more effective than the hot oil treatments and cause less damage, but are considerably more expensive. Hot water and hot water plus surfactant treatment can be used very

effectively to remove existing deposits from less water-sensitive areas of production, storage, and transportation (Becker, 1997).

The yield stress concept was first introduced by Bingham, *et al*, 1919 for a class of fluids known as "iscoplastic fluids. The fundamental unit of shear stress is dynes per square centimeter (dynes/cm²) or Newton per square meter (N/m²). Nguyen, and Boger, 1983 and 1992 described the relationship between shear stress and shear rate for different

viscoplastic materials. The yield stress value was measured by extrapolating the dynamic shear stress-shear rate data to the zero shear rate limits (Cheng, *et al*, 1998). Rheological properties of waxy crude oils, from flow properties to yield stresses to time dependent shear thinning behaviours, are strongly dependent on the stress and temperature histories of the sample (Wardhaug and Boger, 1991). The temperature dependent evolution of viscosity at constant shear rate and cooling rate has been studied, it allows to identify the onset temperature for wax crystal formation and to understand the evolution of the fluid velocity profile of a cooling crude being pumped through a pipeline (Ronningsen *et al*, 1991 and Webber, 1999 and Wardhaug and Boger, 1991). Recently, Cheng *et al*, 1998 have used oscillatory, viscoelastic and creep measurements

to characterize the time dependent yield properties of wax crystal structures formed in crude oils. The yield processes has three characteristic regimes with increasing stress: time dependent linear elasticity, creep and time dependent fracture and flow. Webber, Texas, March 1999 has also employed oscillatory measurements to study the evolution of wax crystal structure within lubricating mineral oils, particularly the effects of stress and temperature history on the structure and has observed the yield processes with lubricating oils similar to that observed by Chang *et al*, 1998 with crude oils.

Transport of waxy oil in pipeline often gives rise to wax precipitation. The precipitation commences when the temperature reaches the wax appearance temperature (WAT). Some wax will deposit at the inner side of the wall and some will precipitate in the bulk oil phase as solid particles. The wax particles in the bulk will increase the apparent viscosity of the oil and give rise to an increased pressure drop in the pipeline. This is important in the design of new oil field developments. When present in sufficiently high concentrations, the wax particles will gradually change the flow properties of the oil the oil/wax suspension from Newtonian to non-Newtonian behavior. This transition typically occurs about 10-15°C below the WAT, but the temperature may vary depending on the wax content of the oil. The transition seems to correspond with a solid wax fraction of 1 -2 wt%. Ultimately, when cooled further toward the pour point, the oil turns into a gelled, solid like state exhibiting highly non-Newtonian behavior. This typically occurs when the weight percent of solid wax reaches about 4-5%

Table-1: Novel wax dispersants with different neutralizing agents and solvent

Flash point closed cup	, °C	204
Viscosity at 100°C, c	St	4.2-6
Melting range, °C		45-65
Refractive index at 98.	9 °C	1.430-1.433
Average molecular weight	ight	350-400
Number of carbon atom	m	20-26

Table-2: Specification of separated wax

Flash point closed cup, °C	204
Viscosity at 100°C, cSt	4.2-6
Melting range, °C	45-65
Refractive index at 98.9 °C	1.430-1.433
Average molecular weight	350-400
Number of carbon atom	20-26

Table-3: Wax gram added to the marine Belayim crude oil

Wax % before addition	Wax g added in 100 ml oil	Wax % after addition
9	.	9
9	4	13
9	9	18
9	14	23
9	19	28

(Ronningsen *et al*, 1991).

The precipitation of high molecular weight hydrocarbons from crude oil causes waxy deposits to build up on pipeline walls and leads to a reduction in flow of the oil. Certain chemicals are known to be beneficial in reducing the wax deposition rate but the inhibitor mechanism is poorly understood. Many of the effective inhibitors have a comb-shaped polymer structure and experiments have demonstrated that such polymers increase the meta-stable zone width (MSZW) of wax in a model oil Hennessy *et al*, 1999 and decrease the size of wax crystals grown from solution (Kern and Dassonville 1992). In order to elucidate the inhibitor mechanism on a molecular scale the molecular dynamics (MD) was used to study the interaction of a typical inhibitor (polyoctadecyl acrylate) with the surfaces of paraffin crystal surface. Small polymer units (dimers) were found to interact strongly with the crystal surfaces and introduce local distortion to the growing crystals Duffy and Rodger, 2000.

The present work aim to study the effect of some chemicals as either crystal modifiers, or products that reduce the rate of wax build-up on pipe walls. In this respect, some novel dispersant formulations are prepared and evaluated as pour point depressants. The dispersant formula, which recorded the lowest pour point value, was selected for advanced study. Therefore, a waxy crude oil model was developed from different wax concentration as wax build-up on pipe walls. Moreover, the rheological behavior of such model has been measured with and without wax inhibitor at different temperatures. Finally, the behaviors of wax fluids before during and after an application of shear force have been definitude.

EXPERIMENTAL

Novel formulated wax dispersants

Some wax dispersants that proved to be effective at retarding the deposition were developed and tested. In this respect, a mixture of nonionic surfactant/such as Tween 85 or nonylphenol

Table. 4: Pour point °C waxy crude after addition of 5%, 10% wax dispersants

Pour point °C/Wax %	Dispersan							
	1	2	3	4	ts5	6	7	8
		9%	wax					
At zero dispersant			10	•c				
At 5% dispersant	9	10	9	9	6	7	8	10
At 5% dispersant	8	9	7	8	4	6	6	7
		13%	wax					
At zero dispersant			20	»c				
At 5% dispersant	18	19	17	18	13	14	15	16
At 10% dispersant	13	14	11	15	9	10	10	11
		18%	wax					
At zero dispersant			30	•c				
At 5% dispersant	28	28	26	27	22	24	25	26
At 10% dispersant	25	23	26	22	14	16	15	17
		23%	wax					
At zero dispersant			35	°C				
At 5% dispersant	31	32	30	31	26	28	27	27
At 10% dispersant	26	28	24	20	18	20	19	19
		28%	wax					
At zero dispersant			40	°C				
At 5% dispersant	37	38	35	35	30	31	32	32
At 10% dispersant	33	34	27	26	25	27	27	26

ethoxylate of oleic acid ethoxylate, was blend with dodecyl benzene sulfonic acid, or Turkey red oil, or lauryl alcohol sulfate, and neutralized by different alkali such as alkanol amine or polyamine. The mixed surfactants were dissolved in different solvents such as xylene, decaline or water. The formulated dispersants are given in Table 1.

Dewaxing of crude oil

Separation of wax from crude oil was carried out according to IP standard test method (IP, 1985). In this respect, melt 1 g of wax in a beaker. pipette 15 ml of methyl ethyl ketone into the beaker and place the content in an ice water bath. After cooling, filter the mixture and weight the precipitated crystalline wax. The specification of separated wax is given in Table 2.

Preparation of different concentration of waxy crude oil

Marine Belayiem crude oil was choosen for this study. The specification of crude oil as the

flowing; Specific gravity 0.8731 gm/cm³ at 20°C, API is 30.6, Viscosity 11 cSt at 100°F, Sulfur content 1.7%, 1.5 wt % Asphaltene, Resin/asphaltene ratio is 7.64 and 9 wt % wax. The waxy crude oil model based on the original wax % in Marine Belayiem crude oil were prepared at different wax concentrations as shown in Table 3.

Evaluation of wax dispersants as pour point depressant-

The activities of wax dispersants as pour point depressant were detemined. In this respect, pour point of Marine Belayiem crude oil at 9%, 13%, 18, 23 and 28% wax content were measured in presence and absence of formulated wax dispersants. The wax dispersing formula, which recorded the lowest pour point value, was selected for advanced study. Pour point of waxy crude oil was measured according to the standard test methods (IP, 1986). The results are given in Table 4.

Table-5: Classification of waxy crude oil according with and without dispersant

Wax concentration %	Without dispersant	With dispersant
9		Newtonian
13	Non-Newtonian	Newtonian Newtonian
18	At 45C is Non-Newtonian/ pseudoplastic (or shear thinning) At 55C, 65C is Non-Newtonian/ dilatant (shear thickening)	At 1000ppm pseudoplastic behaviour of Non-Newtonian is disappears.
23	Non-Newtonian (Elastic at low shear rate, creep regions at middle shear rate, and Fracture at high shear rate for all three temperature under study)	At 1000ppm of dispersant the crude began to flow (Non-Newtonain)
28	It is difficult to measure the viscosity at 45C, i.e. the waxy crude is Non-Newtonian (pseudoplastic or shear thinning)	It's easy to measure the viscosity at 2000ppm and at 45C

temperatures, 1) the elastic response up to shear rate of 39.6 sec⁻¹. 2) Creep regions lay at shear rate of 149 sec⁻¹. A clear deviation occurs at shear rates of 188 sec⁻¹ for all temperatures indicated by limited of creep regions and began of fracture point. A dramatic increase of the shear rate following this deviation point is represented by an approximately horizontal segment which ends at shear rates of

Determination of the rheological properties of waxy crude

A Brookfield digital rheometer model LVDV-III+ was used to determine the apparent dynamic viscosity of the prepared samples of the waxy crude oil. The viscometer was connected to a circulating water bath with digital controller model TC-501D. The spindle type and rotational speed were selected according to the dynamic viscosity of the waxy crude oil. The temperature was raised from 45 °C up to 65 °C for heavy waxy crude oil concentration. The results are given in figures (1-20).

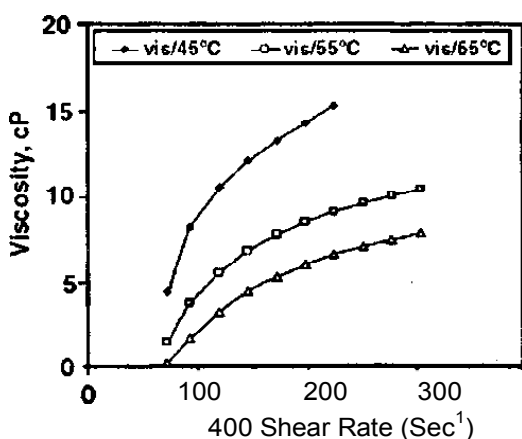


Fig. 1: Shear rate vs. viscosity of 9% wax at different temperature

RESULTS AND DISCUSSION

Wax crystallization and deposition during production can lead to severe pipeline and flow line restrictions. Over time, the build-up of wax will reduce the internal diameter and eventually block the line or well. Remediation performed by mechanical pigging or through solvent washes or hot oiling. All have their advantages and limitations. Wax inhibitors/dispersants and anti-sticking agents are an effective solution to remediate the deposition problem. These chemicals can act as either crystal modifiers, or

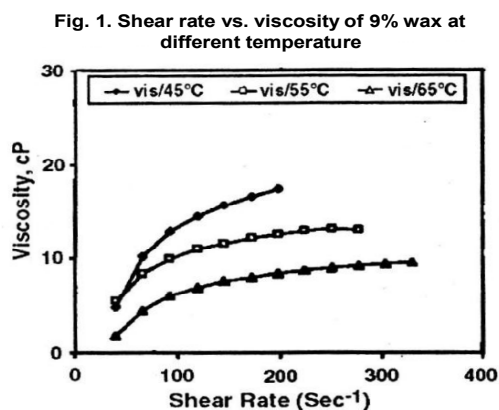


Fig. 3: Shear rate vs. viscosity of 9% wax and 1000ppm of surfactant at different temperature

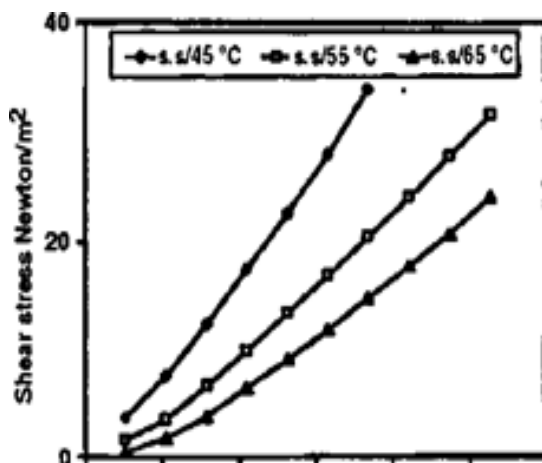


Fig. 2: Shear rate vs. shear stress of 9% wax at different temperature

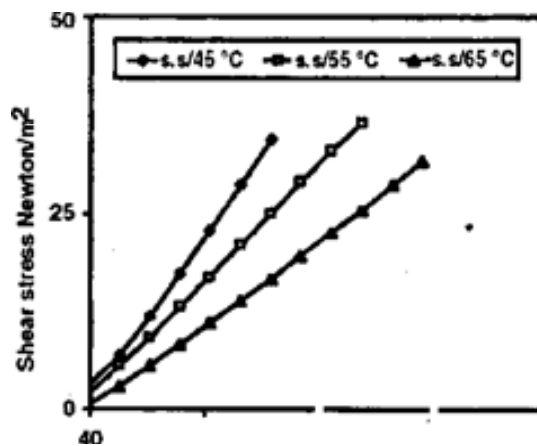


Fig. 4: Shear 1000ppm of surfactant at different temperature

products that reduce the rate of wax build-up on pipe walls.

Pour point depressant- The pour point values of formulated dispersants are given in Table 4. The pour point value measured at 5% and 10% wax dispersants. The pour point of 9%, 13%, 18%, 23% and 28% wax content in absence of dispersants are 10°C, 20°C, 30°C, 35°C and 40°C respectively. The data indicate that the pour point decreases as the concentration of wax dispersants increases. The lowest pour point have been achieved by the formulae number 5. Therefore, the dispersant formula number 5 was selected for advanced test. The results reveals that the pour point of 9%, 13%, 18%, 23% and 28% wax content in presence of 5% dispersants are 6°C, 13°C, 22°C, 26°C and 30°C, respectively. Meanwhile, the corresponding reductions in pour point at 10% wax dispersants are 4°C, 9°C, 14°C, 18°C, 25°C respectively.* It's clear that the wax dispersant give

poor results as pour point depressant, so its difficult to measure the rheological dynamic viscosity blew the wax appearance temperature or even at the pour point of waxy crude. Consequently, all data are measured above the wax appearance temperature. On the other hand, the dispersant formula number 5 was selected to study their effect on the behaviour of the rheological viscosity of crude oil containing different wax concentrations.

Effect of dispersant concentration- A series of dispersant concentrations ranging between of 200-2000 ppm have been added to the waxy crude oil sample to study their effect on the rheological viscosity of the waxy crude oil. The results reveal that, 1000 ppm of dispersant concentrations give an extremely broad change in the viscosity of waxy crude oil having wax concentrations ranging from 13% up to 23% wax. Furthermore, the reduction in the viscosity of crude oil containing 28% wax has been attended when 2000 ppm of dispersant concentration was added. The result indicated that as the wax content increases the corresponding dispersants which led to the flow improvers must be increased up to a certain value, after which no effect have been recorded. This can be attributed to that the adsorption of surfactant on the surface of waxy crude oil reaches sufficient surface coverage.

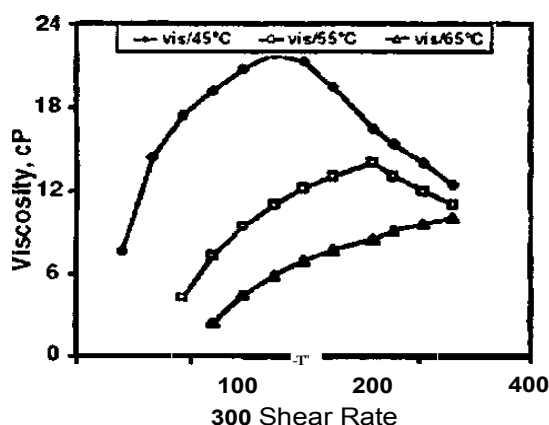


Fig. 5. Shear rate vs. viscosity of 13% wax at different temperature

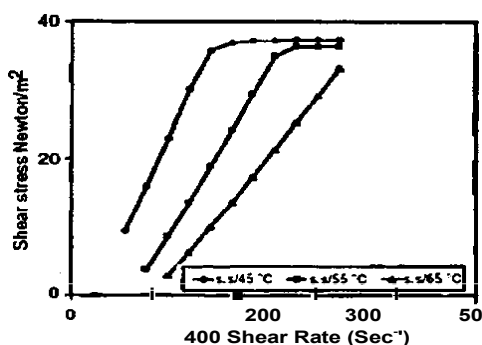


Fig. 6. Shear rate vs. shear stress of 13% wax at

Fig. 6. Shear rate vs. shear stress of 13% wax at different temperature

Viscosity of original crude oil

The viscosity is defined as the ratio of shear stress to shear rate. For a Newtonian fluid the shear stress (σ_{xy}) is directly proportional to the shear rate ($\dot{\gamma}$), or velocity gradient (dv_x/dy). Therefore, the viscosity of a Newtonian fluid is shear rate independent and can be represented by the following equation :

$$(\tau_{xy} = \tau_0 + \mu \eta_p (Y)^n.$$

The relation between viscosity and shear

rate of original crude oil (9% wax) is shown in Figure 1. The graph indicates that the viscosity of the crude exhibits a non linear relationship, i.e. the viscosity increases as the shear rate increases. The original crude oil behaves as Non-Newtonian flow behaviors, typically behaves like pseudoplastic. The shear rate plotted against shear stress exhibit a linear relationship, however, it does not pass through the origin but has a negative y-intercept Figure 2.

The intercept (yield stress) of 9% wax without, surfactant at 45°C,

55°C and 65°C are -9.9 Newtonian/m², -8.3 Newtonian/m² and -7.7 Newtonian/m²,

respectively, whereas, the slope(n) are 0.19, 0.13 and 0.1 respectively. Meanwhile, the viscosity of original crude oil in presence of 1000 ppm of dispersant is increased Figure 3. Such behavior can be explaining by formation of slightly waxy gelled solid like state under static condition. Thereby the negative values of intercept after addition of 1000 ppm of dispersant Figure 4 are varied and reached to -6.07 Newtonian/m², -4.3 Newtonian/m² and -4.3 Newtonian/m² at 45°C, 55°C and 65°C, respectively, i.e., its become approach to the original zero point. Accordingly, the rheological behavior of original

crude in presence of 1000 ppm of dispersant although it still Non-Newtonian (Bingham plastic fluid), it is worthily to know that it is not need any force to pump it. Therefore, by applying the Power law

equation $\tau = \bar{\mu} \dot{\gamma}^n$ where $\bar{\mu}$ is the dynamic viscosity, $\dot{\gamma}$ is the shear rate, m is the intercept, n = slope, when

$n = 1$ the fluid behave as Newtonian, $n < 1$ the fluid behave as pseudoplastic (shear thinning), $n > 1$ the fluid behave as dilatant (shear thickening). The given result are in harmony with the equation, hence slope(n) below than 1, and proved that the rheological behaviors of original crude is Non-Newtonian and are vary between pseudoplastic and Bingham plastic fluid.

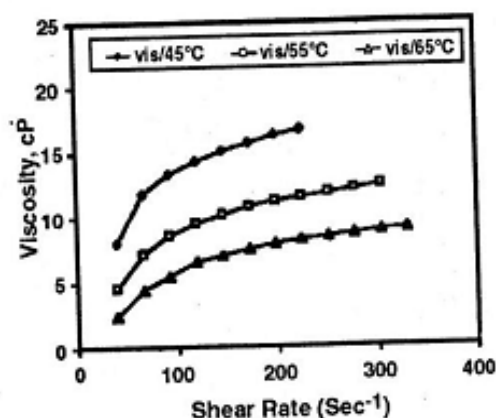


Fig. 7. Shear rate vs. viscosity of 13% wax and 1000ppm of surfactant at different temperature

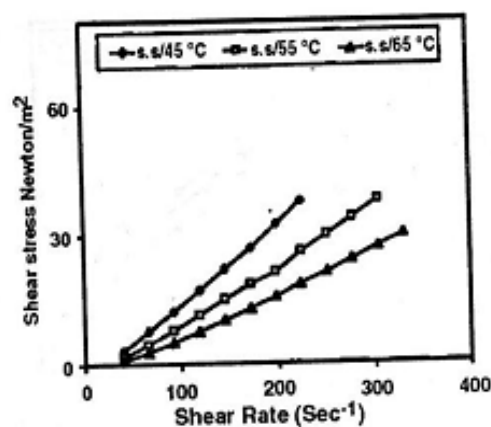


Fig. 8. Shear rate vs. shear stress of 13% wax and 1000ppm of surfactant at different temperature

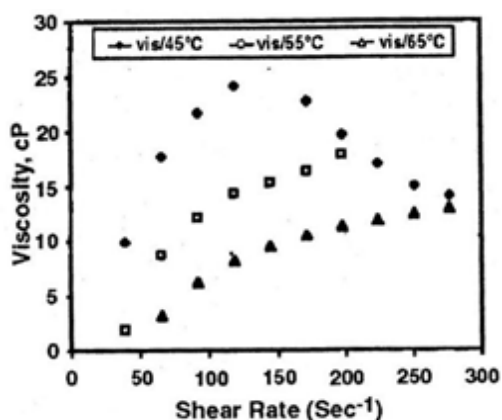


Fig. 9. Shear rate vs. viscosity of 1-8% wax at different temperature

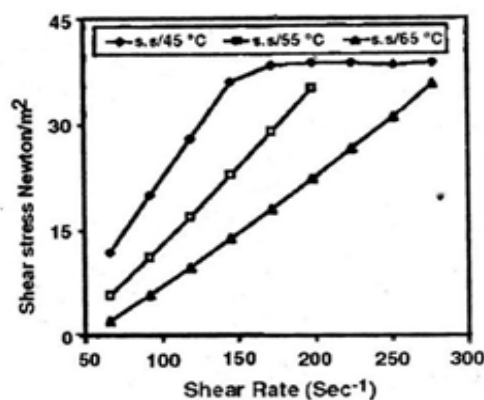


Fig. 10. Shear rate vs. shear stress of 18% wax at different temperature

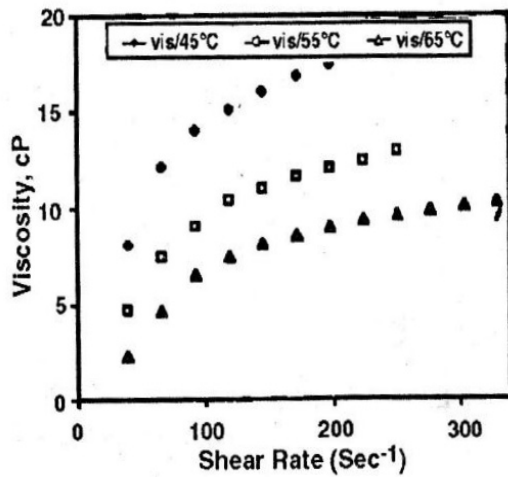


Fig. 11. Shear rate vs. viscosity of 18% wax and 1000ppm of surfactant at different temperature

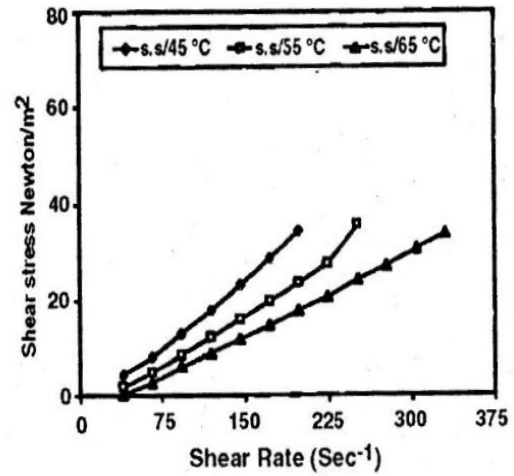


Fig. 12. Shear rate vs. shear stress of 18% wax and 1000ppm of surfactant at different temperature

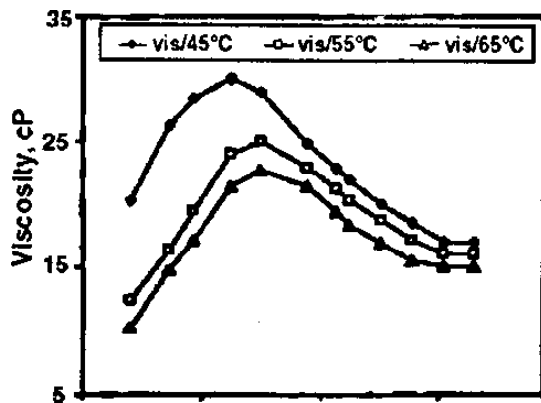


Fig. 13. Shear rate vs. viscosity of 23% wax at different temperature

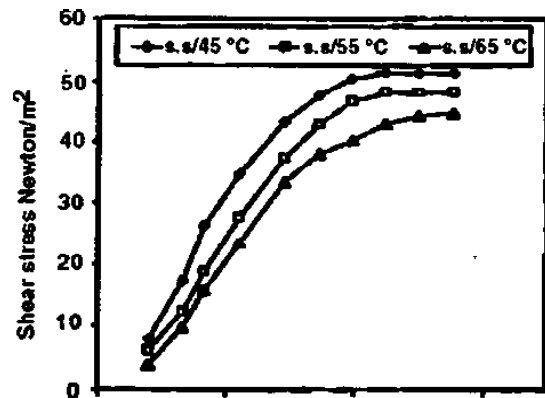


Fig. 14. Shear rate vs. shear stress of 23% wax at different temperature

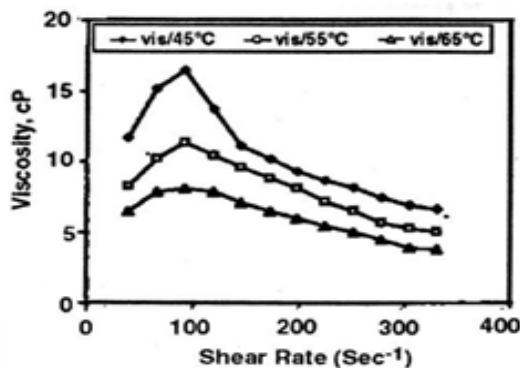


Fig. 15. Shear rate vs. viscosity of 23% wax and 1000ppm surfactant at different temperature

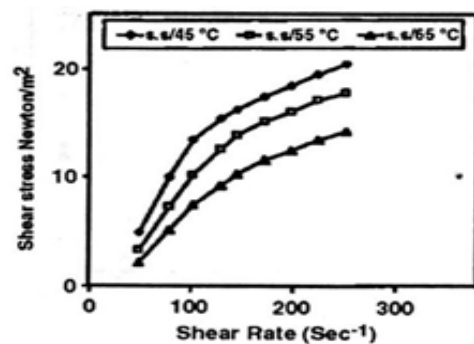


Fig. 16. Shear rate vs. shear stress of 23% wax and 1000ppm surfactant at different temperature

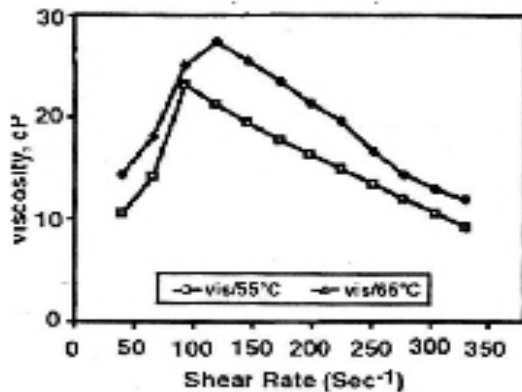


Fig. 17. Shear rate vs. viscosity of 28% wax at different temperature

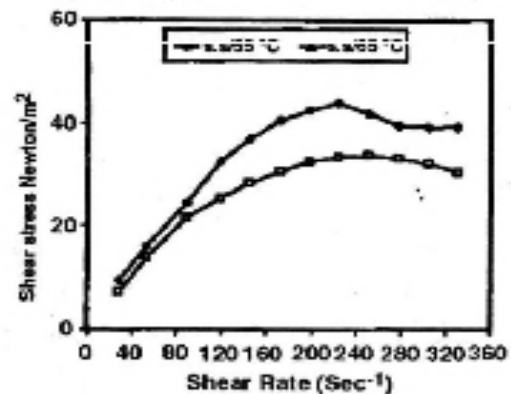


Fig. 18. Shear rate vs. shear stress of 28% wax at different temperature

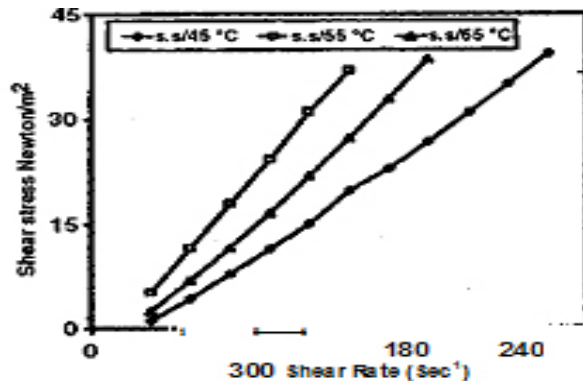
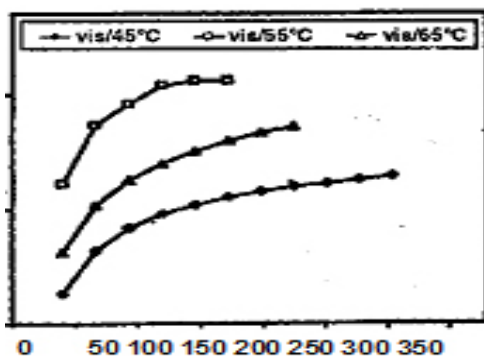


Fig. 19. Shear rate vs. viscosity of 28% wax and 1000ppm surfactant at different temperature

Effect of wax concentration on the viscosity of crude oil

As the concentration of wax increases with respect to the original wax in crude oil under this study, the rheological behavior of the oil also varied. Figure 5 show a significant independence between viscosity and shear rate, it means that 13% wax suspended in crude oil behave like a Bingham plastic fluid at shear rates higher than about 250s⁻¹. Thereby, during a pipeline shut-down, waxy crude oil behave like Bingham plastic fluid, i.e., the pumping pressure is must be applied on the fluid to breakdown of the gelled structure (breakdown of the Bingham yield stress). The force required before addition of dispersant as given in Figure 6, are +11.36 Newtonian/m², -7.4 Newtonian/m² and -14.57 Newtonian/m² at 45°C, 55°C and 65°C, respectively. After dispersant added Figure 8, the forces are decreased to about Newtonian/m², Newtonian/m² and Newtonian/m² at 45°C, 55°C

and 65°C, respectively. Its clear that yield stress of waxy crude oil at 45°C without dispersant having a positive sign, this means that, it must be apply a force to pump the crude after shutdown. Where as, after dispersant added, the yield stress having a negative sign indicate that there is no need to apply any force. On the other hand, a Bingham plastic fluid is similar to a Newtonian fluid in the sense that there is a linear relationship between shear stress and shear rate. However, a Bingham plastic fluid differs by requiring a finite shear stress (pressure) to initiate any yield stress of the fluid. Bingham plastic fluid can be mathematically expressed as : $\dot{\sigma}_{xy} = 5\dot{P}0 + \dot{\mu}p(\bar{a})n$ where, 50= Bingham yield stress, $\dot{\mu}p$ = plastic viscosity, $\dot{\sigma}_{xy}$ = shear stress, 5 = shear rate and n = slop. At 18% wax concentration Figure 9, the viscosity increases as the shear rate increases up to 150 sec⁻¹, 200 sec⁻¹ and 270 sec⁻¹, at 45°C, 55°C and 65°C, respectively, after that the

viscosity decreases as the shear rate increases. This indicated that the waxy crude oil containing 18% wax concentration behave like shear thinning pseudoplastic fluid. The plot of shear stress versus shear rate of 18% wax without dispersant, Figure 10 show the gradually decreasing nonlinearly of the flow curve as the temperature increases from 45°C to 65°C. The plot suggests that the waxy oils behave like pseudoplastic fluids with a yield point +12.21 Newtonian/m² at 45°C, and as Bingham plastic fluid at higher temperature of 55°C and 65°C, respectively.

presence of 1000 ppm dispersants. It is clear that the dispersant reduced the dynamic viscosity at shear rate of 150 sec⁻¹ to about 1.7, 1.5 and 1.2 time a 45°C, 55°C and 65°C, respectively, comparing with the same shear rate without dispersant. Figure 12 indicate that the shear stress versus shear rate of 18% wax in presence of 1000 ppm of dispersant, behave like Bingham plastic fluid for all temperature under study. This another proves that the dispersant change the rheological behavior of solid waxy crude from one case to another.

The behavior of shear rate versus velocity at a wax content of 23% is given in Figure 13. Such figure represents three feature regions for all 304 sec⁻¹ for temperatures. The plots of shear rate versus shear stress given in Figures 14 shows that fluid behave as pseudoplastic (shear thinning). Also the graph exhibit that the initial values of the curve are faraway from zero shear stress axes by +9.828 Newtonian/m², +3.9769 Newtonian/m² and +1.4171 Newtonian/m² at 45°C, 55°C and 65°C, respectively. Therefore, a certain amount of force must be applied to the fluid before any flow is induced. This force is called yield value.

It is clear by increasing the wax concentration, significant problems begin to appear, like, increased drag, wall deposition, and blocked lines. When 1000 ppm of dispersant are added to crude oil containing 23% wax, its viscosity is decreased but still behave as pseudoplastic-shear thinning fluid (Figures 15). Moreover, in figure 16, the initial part of the curve is approximately coincides with the zero after 1000 ppm of dispersant are added, hence the intercept changed to +1.77 Newtonian/m², +2.61 Newtonian/m² and +0.94 Newtonian/m² at 45°C, 55°C and 65°C, respectively. Figure 17, show that

it is difficult to measure the viscosity of crude oil containing 28% wax at 45°C, indicating that the crude oil exhibit a pseudoplastic flow behaviour. Accordingly, figure 18 exhibits high yield value of +16.81 and +13.47 at 55°C and 65°C, respectively, i.e. high amount of force must be applied. In figures 19, it is obvious that the addition of wax dispersants reduce the viscosity from 27.4 cP and 21.3 cP to 14cP and 9.6 cP at a shear rate of 119 sec⁻¹ and at 55°C and 65°C, respectively. It is interesting to notice that the dispersant facilitates the measurement of the viscosity at 45°C. Consequently, the amounts of forces required to flow or pump the waxy crude oil as pronounced from figure 20, are significantly reduced to very low values to reach's to -4.45 Newtonian/m², -6.18 Newtonian/m² and -5.48 Newtonian/m² at 45°C, 55°C and 65°C, respectively. This may be attributed to the presence of the dispersant, which behave as crystal modifier that changes the crystal wax structure, and thereby, lower the sum of its aggregate interactive forces and consequently improving their rheological behavior. This can explain that the wax dispersant acts as either crystal modifier, or products that reduces the rate of wax build-up and increases the homogeneity between wax and oil. The strong dependence of the viscosity on the amount of precipitated wax is clearly illustrated in all figures under this study. Hence, the rheogram plotted between shear rate versus shear stress behave like Bingham plastic fluid up to 18% wax content, and as pseudoplastic fluids at higher wax content. On the other hand, it is clear from the plots of viscosity versus shear rate for all the wax concentrations that the rheological behavior of the waxy crude oil exhibits two different attitudes. The first is non-Newtonian (Bingham plastic fluid) at relatively low wax content. However, at high wax content the crude oil behave as shear thinning fluids (pseudoplastic fluid), i.e., the viscosity decreases by increasing the shear rate. This results are agreement with that in literature (Sherman, 1983, Pal and Rhodes, 1985, Pal et al, 1986, Pal and E J Rhodes, 1989 and Pal and Masliyah, 1990).

It is also clear from all plotted figures that the viscosity of waxy crude oil increases with increasing wax content up to a certain value and then decreases. Such phenomenon can be explained by the following : 1) When particles are introduced into a given flow field, the flow field becomes distorted, and consequently the rate of energy dissipation

increases, which in turn leading to an increase in the viscosity of the system. Einstein (Einstein, 1906, 1911) showed that the increase in the viscosity of the system due to addition of particles is a function of the volume fraction of the dispersed particles. As the volume fraction of the particles increases, the viscosity of the system increases.

Effect of temperature on viscosity

A serious problem in oil production, particularly from deep wells, is deposition of wax on the pipe walls. This occurs when waxes in the crude oil contact the cold pipe walls.

This wax deposit causes flow problems in oil production and transportation. Moreover, the viscosity of waxy oil transported in a pipeline increases with decreasing flow rate, which can give rise to high-pressure drops especially at low flow rates and cause problems when trying to start up a pipeline after a shutdown.

It observed that the viscosity of waxy crude oil decreases as the temperature increases from 45°C-65°C. The decrease in viscosity of waxy crude oil that occurs with raising in temperature is mainly due to a decrease in the viscosity of continuous phase (crude oil). The increase in temperature may also effect the average particle size and particle size distribution. On the other hand, above the wax appearance temperature (WAT) the rheological behaviour of waxy oil are generally exhibit non-Newtonian behavior (viscosity is independent of shear rate).

CONCLUSION

The results reveal that the 1000 ppm of dispersant concentrations give an extremely broad change in the viscosity of waxy crude oil up to 23% wax. The sudden reduction in the viscosity of 28% wax concentrations is attended by 2000 ppm of dispersant concentrations. Crude oil containing 13% wax exhibit independence between viscosity and shear rate, which means that during a pipeline shut-down, the fluid behave as Bingham plastic at relatively low wax content. Thereby, the pumping pressure is must

be applied on the fluid to breakdown of the gelled structure i.e., breakdown of the gelled structure, i.e. breakdown of the Bingham yield stress. Therefore, the force required before addition of dispersant are +11.36 Newtonian/m², -7.4 Newtonian/m² and -14.57 Newtonian/m² at 45°, 55°C and 65°C, respectively. Whereas after dispersant added the forces are decreased to about -4.7 Newtonian/m², -4.6 Newtonian/m² and -4 Newtonian/m² at 45°C, 55°C and 65°C respectively. However, at high wax content the crude oil up to 18% wax concentration the viscosity increases as the shear rate increases up to 150 sec⁻¹, 200 sec⁻¹ and 270 sec⁻¹ at 45°C, 55°C and 65° respectively, after that the viscosity decreases as the shear rate increases. This means that the fluid behave as shear thinning fluids (pseudoplastic fluid). The behavior of shear rate versus viscosity at a wax content of 23% represents three feature regions for all temperatures 1) the elastic response up to shear rate of 39.6 sec⁻¹. 2) Creep regions lay at shear rate of 124 sec⁻¹, and 3) sudden and dramatic failure (fracture) after shear rate of 149 sec⁻¹. A clear deviation occurs at shear rates of 188 sec⁻¹ for all temperatures indicated by limited of creep regions and began of fracture point.

Crude oil containing 28% wax exhibits high yield value of +16.81 and +13.47 at 55°C and 65°C, respectively, i.e., high amount of force must be applied. Consequently, the amounts of forces required to flow or pump the waxy crude oil are significantly reduced to very low values to reach's to -6.18 Newtonian/m² and -5.48 Newtonian/m² 55°C and 65°C, respectively. It implies that it is safe to pumping the waxy crude oil up to 18 wax % without causing problem when trying to start up a pipeline after a shutdown. Meanwhile, by increasing wax concentration up to 23-8%, a significant problem begin to appear thereby, a certain amount of force must be applied to the fluid before any flow is induced. It observed that the viscosity of all waxy crude oil decreases as the temperature increases from 45°C-65°C. The decrease in viscosity of waxy crude oil that occurs with raising in temperature is mainly due to a decrease in the viscosity of continuous phase (crude oil). The increase in temperature may also affect the average particle size and particle size distribution.

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