PRJ, Vol. 3 (January 1991); P. 21-26, 4 FIGS, 6 TABLES.

RHEOLOGICAL PROPERTIES OF SARIR CRUDE OIL

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خواص الدفق لخام نفط السرير

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تم استخدام مقياس اللزوجة ذو الإسطوانتين متحدتي المحور لتعيين خواص الدفق لخام السرير وكذلك استخدام نموذج قانون القوة «المعروف» لتفسير سلوك الإنسياب للخام المذكور. كما تم استخدام علاقة والتر ومعادلة أخرى متعددة الحدود لصياغة تأثير درجة الحرارة على متغيرات قانون القوة السالف الذكر.

أوضحت هذه الدراسة أن إجهاد الخضوع «متغير يستعمل لحساب ضغط إعادة تشغيل خط الأنابيب» شديد الحساسية لمنظومة القياس وظروف التشغيل.

ABSTRACT

The rheological properties of Sarir crude oil have been determined using coaxial cylinder viscometer. Power law model was used to relate the flow behavior. The temperature dependency of the power low parameters were modelled by using Walthers and polynomial type correlations.

The yield stress was shown to be very sensitive to the measurement system and conditions.

INTRODUCTION

Pipelines are the cheapest and the most efficient means for the transportation of crude oils and their distillate and residual products. An important design criterion of the crude oil pipelines is the volume of oil handled at any time during their service life. Considerable uncertainty is often involved in predicting the flow rate on day to day basis due to various operational reasons. Therefore a pipeline system is always designed to handle a wide range of flow rates. Waxy oils may create considerable handling problems in their transport over wide flow rates. For example at low flow rates and during cold season the oil may cool down to temperatures very close to the pour point or even lower as a result of increase in the residence time. At a relatively lower temperature the pipeline may have to handle highly viscous oil at a high pressure drop and there would be large wax deposition requiring more frequent pigging [1]. There is nothing wrong in handling oil at temperatures below the ASTM pour point as long as the pipeline remains continuously operational. In the event of a shutdown with the oil shutin, the oil may form hard three dimensional gel [2]. In order to restart the pumping, the gel structure need to be broken down. Sometimes the restarting pressure may exceed the bursting pressure of the pipeline causing severe problems. A careful evaluation of the rheological and the deposition characteristics of waxy crude oils are required in order to prevent difficulties during the operation. This is not an easy task either. In contrast to the lighter and low waxy oils, the waxy oils do not possess definite and easily predictable rheological properties. The viscosity, for example may change at a given temperature by several hundred percent depending upon the previous thermal and shear history of the oil. The seperation of wax in the form of various sizes and shapes and the intercrystalline forces are responsible for the anamolous behavior of the waxy oils. This paper describes the experimental

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techniques and modelling work carried out to characterize the flow behavior of a waxy crude oil through a pipeline system.

THEORY

Most crude oils contain high molecular weight components [3] typically C_{20+}, which at low temperatures may precipitate out as wax. Wax generally crystallize in orthorhombic structure [3]. The crystals usually form plate like crystals on slow cooling and needle shape crystals upon the conditions of fast cooling or in the presence of additives [5]. The plate type crystals form cages and are responsible for early gelling of oils. The needle shape crystals have higher solubility in oil [5] and gel at relatively lower temperatures. The flow behavior at lower temperatures depend upon several factors, including the type of crystals, size, quantity and intercrystalline forces. The variation of many of the above factors would produce a different rheology. Therefore it is of utmost importance that conditions identical to those occuring in a pipeline be reproduced while measuring the flow characteristics.

Paraffins which have higher freezing points as shown in Table 1, constitute bulk of the wax. Aromatics are also present in traces to very small quantity [3] and influence the crystallization behavior by distorting the crystal lattice.

Wax crystals are mainly responsible in introducing thixotropic (time dependent non-Newtonian behavior) and pseudoplastic behavior into the flow properties of waxy oils. Three important flow related properties required in the design and simulation of pipelines are:

- Relationship between shear stress, shear strain and temperature
- Yield strength
- Deposition rate

The flow behavior of waxy crude oils may be taken as Newtonian over 10 to 20°C above the ASTM pour point. The properties turn towards pseudoplastic at lower temperatures. The change in the behavior may be related to the appearance of wax. Fig. 1 qualitatively sketches different flow behaviors (time independent). The basic behavior in the above case was thixotropic as shown in Fig. 2. The apparent viscosity approaches asymptotic value after the elapse of a definite time. Fortunately it is the asymptotic value which is required in design and simulation work. The apparent viscosity is given as:

$$\mu = \tau / S \quad (1)$$

The yield stress indicated in Fig. 1 is an important

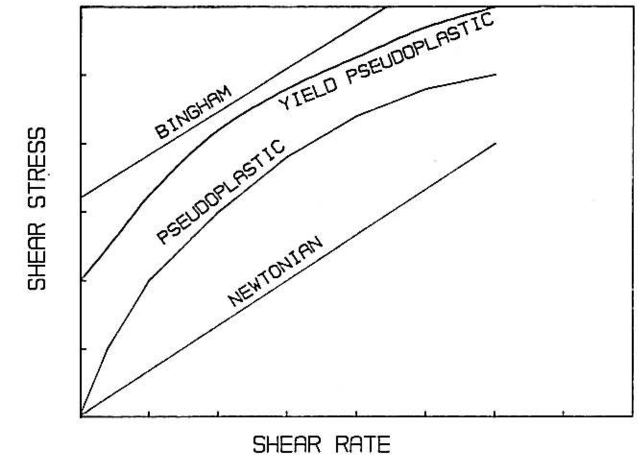

FIG. 1. Flow behavior of different types of fluids.

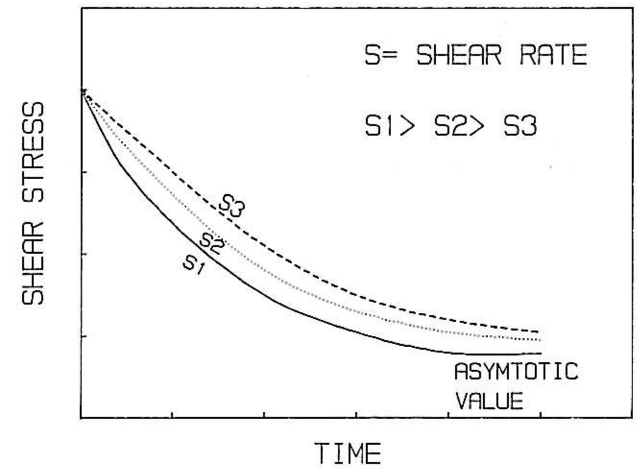

FIG. 2. Thixotropic fluid behavior.

Table 1. Melting and Boiling Points of Some High Boiling Compounds [4]

CN	Lin. Paraffins (In Deg C)		Alky. CYC5			Alky. CYC6			Alky. Ben.		
	B.P.	M.P.	Name	B.P.	M.P.	Name	B.P.	M.P.	Name	B.P.	M.P.
18	317	28	TRDE	326	5	DODE	328	13	DODE	328	3
22	369	44	HEDE	377	27	HEDE	380	34	HEDE	378	27
26	412	56	HCOS	420	42	EICO	422	49	EICO	420	—
30	450	66	PCOS	456	54	TECO	458	60	TECO	454	57

parameter for the yield-pseudoplastic (Bingham plus pseudoplastic) fluids. It is also required in the computation of the restarting pressure as given in the Eq. (2).

$$(\Delta p)_{R.S.} = \int_{x=0}^{x=L} \frac{4\tau_0}{D} dx \qquad (2)$$

The yield stress used in the Eq. (2) depends upon a number of parameters, the most important of them are:

- Final temperature
- Thermal history
- Shear history
- Duration of shutdown time

The yield stress was found by several workers [7, 8] to be very sensitive to the presence of dissolved gases and lighter hydrocarbons as well as to the high molecular weight polymeric additives and natural polymeric materials such as asphalthenes. A careful inclusion of all the factors, no doubt, would lead to more precise measurements.

In order to simulate the actual conditions some companies have used commercial long pipelines [1, 6–8] to measure the yield stress and viscosity. A quick but approximate estimation of the Yield strength [5] can be made by using Rotary viscometer, a method adopted in the present studies.

Wax deposition rate is yet another consideration. It decreases flow area and influences pipe roughness. It can even cause pig blockage. At temperatures above the wax appearance temperature (WAP) the deposition is of lesser significance. The deposition gains importance at lower temperatures. Frequent pigging [8] may keep the surface clean. The quantification of deposition rate in the operating lines is always uncertain. The operators monitor the pump discharge pressure and adjust pigging frequency accordingly. A more detailed treatise of the subject may be found elsewhere in the literature [9–10].

MODELS

A large number of models have been suggested in the literature [1] to relate the flow behavior of time-independent non-Newtonian fluids. The asymptotic behavior of time dependent thixotropic fluids may also be described by the same models. All the models are empirical curve fitting techniques. Selected forms of models are given in Table 2. Isothermal conditions are applicable in each of the relationships given in Table 2.

The model parameters are themselves temperature dependent, therefore other correlations must be used to obtain temperature dependency. The simplest and

Table 2. Rheological Models for the Time Independent Non-Newtonian Fluids

Name	Model		Fluid Type*
Power law	$\tau = k(S)^n$	(3)	
	$n<1$		P/D
	$n>1$		
Eyring	$\tau = A\ \mathrm{ARC\ Sinh}(-1./B\,S)$	(4)	P/D
Ellis	$S = [A + B(\tau)^{m-1}]$	(5)	P/D
Reiner-Philippoff	$S = \tau\left[A + \frac{(B-A)}{1+(\tau/C)^2}\right]^{-1}$	(6)	P/D
Bingham	$\tau = \tau_0 + K(S)^n$	(7)	
	$n=1$		Bingham
	$n<1$		P
	$n>1$		D

*P = Pseudoplastic D = Dilatant

the most widely used model is the Power low model modified to include the yield strength. It is given by Eq. 7.

$$\tau = \tau_0 + K(S)^n \qquad (7)$$

The flow behavior index (n) approaches unity as the flow behavior turns Newtonian. The consistency index (k) could be correlated to the absolute temperature (K) by using Walthers type equation given by Eq. 8:

$$\ln \ln(k + A_1) = B_1 + \ln(T + C_1) \qquad (8)$$

A polynomial type fitting was used for the flow behavior index (n):

$$n = a_0 + a_1 T + a_2 T^2 + a_3 T^3 \qquad (9)$$

EXPERIMENTAL WORK

A modified Fann model 35SA co-axial cylinder rotary viscometer was used to determine the rheological behavior of Sarir crude oil. The viscometer was earlier modified to control the temperature at any predetermined value or vary according to some program. A 6 mm diameter copper tube was tightly wound around the cup and thereafter insulated. A programmable thermostatic circulating bath was used. It was possible to control the temperature to within 0.2°C. The Sarir crude oil used in the present investigations was the pipeline crude, collected from 34 inch Sarir–Tobruk main line. Initial properties and rheological tests indicated that small amount of light components originally present in the crude oil had flashed out during the sampling. The losses were made up prior to the rheological testing. The properties of Sarir main line oil as reported by the Sarir field laboratory were used as reference for the reconstitution. In order to simulate the pipeline conditions as far as possible, the oil sample was taken in viscometer cup at 54.5°C. The oil was then cooled at a rate of 1.0°C/hr until the measuring temperature was reached. Since waxy oils are structurally sensitive, different experiments were planned for different shear rates. The shearing was continued until the asymptotic conditions were reached. The qualitative description of the conditions prior to reaching the asymptotic conditions are given in Fig. 2. Whereas Fig. 3 provides the asymptotic data (actual) in the form of flow curve.

The yield strength or the gel strength was determined by:

- first cooling the sample under dynamic conditions and
- subsequently cooling at static (without shearing) to the final measurement conditions

The gel strength was determined at the lowest possible speed of rotation corresponding to a shearing rate of $5.11\,s^{-1}$. The maximum deflection was taken as the Initial Gel Strength (IGS) and the deflection after one minute and ten minutes were taken to calculate one minute and ten minutes Gel strengths. The difference between different strengths is an indication of the thixotropic nature of the oil.

RESULTS AND DISCUSSION

Equation 10 provides the temperature dependency of the consistency index.

$$\ln \ln(k+5) = 154.829 - 26.981 \ln T \quad (10)$$

The regression constants of the Eq. 9 are given in Table 3.

Table 3. Flow Behavior Index Coefficients (Eq. 9)

a_0	-0.92313583×10^3
a_1	0.88226129×10
a_2	$-0.28116445 \times 10^{-1}$
a_3	$0.29908855 \times 10^{-4}$

The viscosity of oil in the Newtonian range (above

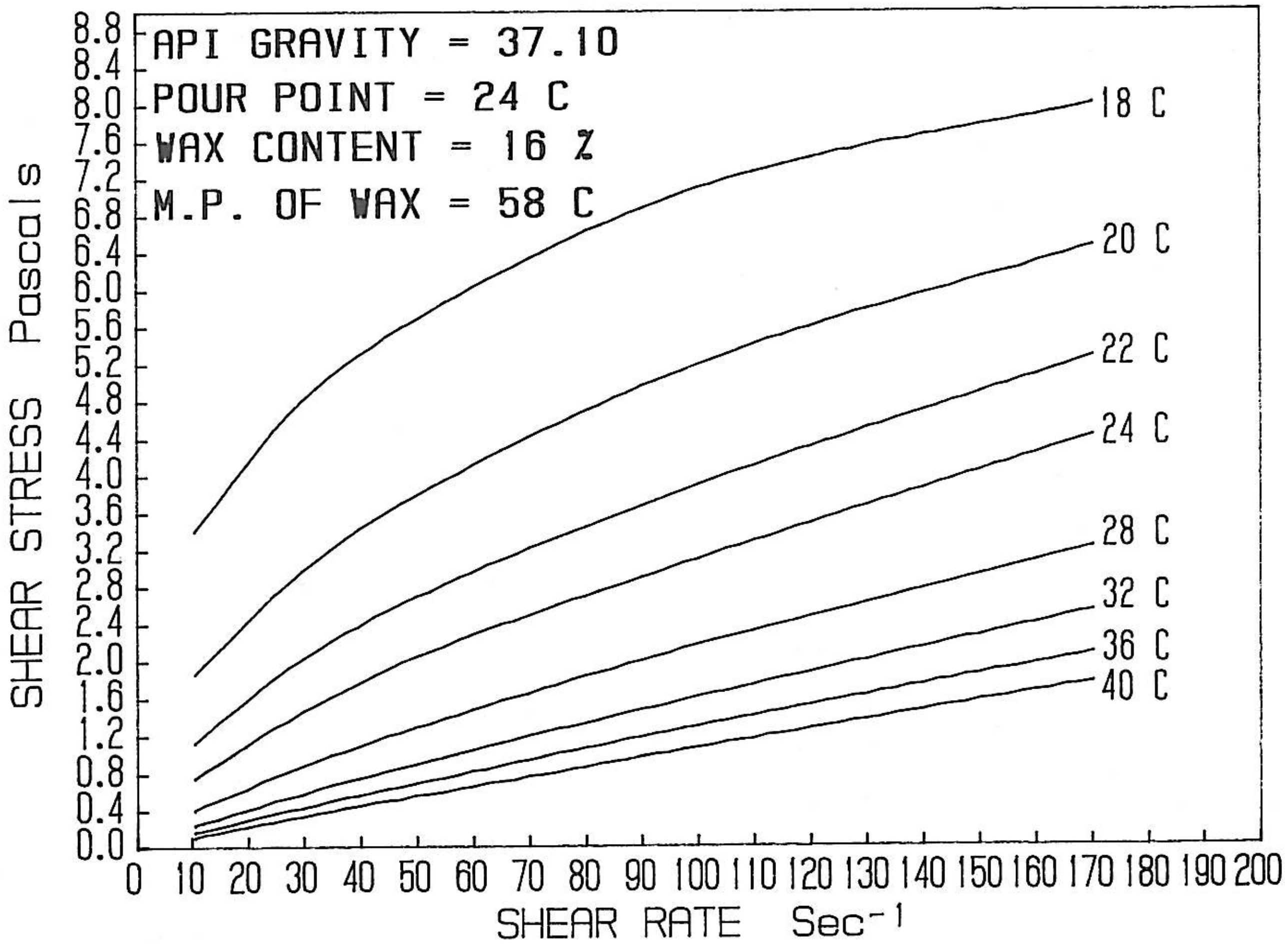

FIG. 3. Flow curves for the waxy oil.

40°C) was correlated by using Eq. 11:

$$\ln \ln \mu = 3.58479 - 0.731745 \ln(T°C) \qquad (11)$$

It is obvious from Fig. 4 that the asymptotic value of the apparent viscosity rises steeply as the pour point (24°C) approaches. This reflects the influence of the formation of the oil cages or traps. The rate of cooling was very slow and therefore only plate shape crystals could grow under these conditions. Figure 3 indicates that the oil is very sensitive to the shear strain at temperatures below above 3 to 4°C of the pour point. For example at 20°C the apparent viscosity decreases by half by increasing the shear rate three times. Similar effect is also seen on the Flow behavior index (n). The value of n (Table 4) departs

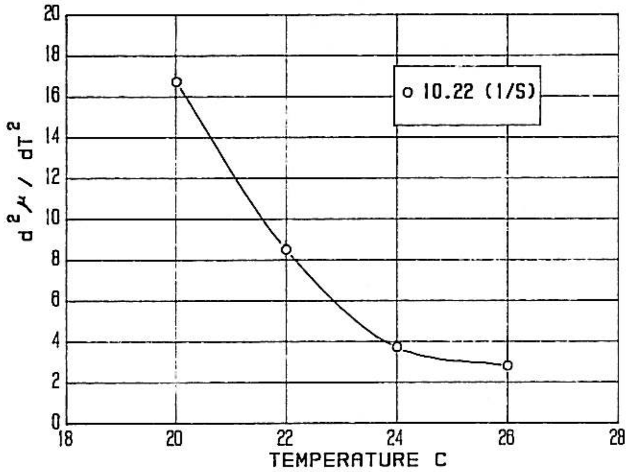

FIG. 4. Viscosity–Temperature relationship.

significantly from unity as the temperature is lower below 24°C, the pour point of the crude.

Similar behavior was also noticed by Fariss [6] and Smith [13].

Table 4. Power Low Parameters for the Waxy Oil

Temperature Deg C	K Pa. S	n
20	0.66098	0.44584
24	0.17591	0.62599
28	0.07622	0.72655
32	0.035732	0.82800
36	0.021605	0.88910
40	0.014362	0.93670

Table 5 gives the yield stress data for a measurement (final) temperature of 29°C. Ford *et al.* [9] used Sarir crude oil in their investigations to determine the yield strength. A model pipeline apparatus initially pioneered by Shell Co. [7] was used by them. Table 6 presents the data collected by Ford *et al.* [9]. A comparison of the data from two different apparatus is provided in this paper. The yield strength was found to be 141.0 Dynes/sq. cm. at 29°C (Table 5). Ford *et al.* [1] reported the yield strength at 29°C to be zero. A different type of apparatus was used by

Table 5. Gel Strength of the Sarir Waxy Oil at 29°C
(Initial temp. = 54.5°C, Static cooling from 30°C)

	Dynes/Sq. Cm.
Initial	141.6
1 Minute	88.5
10 Minute	63.2
(Total cooling time	5.6 Days)

Table 6. Gel Strength of the Sarir Crude Oil from the Reference Ford *et al.* [8]

Initial oil temp.	Final oil temp.	IGS
26.7	23.9	0.0
26.7	22.2	18.0
26.7	21.1	35.0
26.7	18.9	100.0
23.9	22.2	18.0
23.9	18.9	100.0
23.9	21.1	7.0

them. This indicate the importance of the measuring method on the yield value. Similar trend in the yield strength was also noticed by other workers [14]. Different techniques employed to measure the yield strength were:

- Rotary viscometer
- Short capillary tube (Few centimeters)
- Long capillary tube (Few meters)
- Model pipeline apparatus (15 meters)
- Commercial lines

The short capillary tube gave the highest yield strength and the model pipeline gave almost the right value (as compared to actual data). The viscometer also gave higher values and one of the reasons advanced [13] was the loss of light components and gases during the measurement. Perhaps the loss of light components from the oil sample partially explained the high value of yield strength obtained in the present work. Further work would be required to study the influence of the light components on the yield strength.

CONCLUSIONS

- Waxy crude oils behave as thixotropic fluids below 10 to 15°C above the pour point.

- The asymptotic behavior of oil was found to be pseudoplastic with yield pseudoplastic behavior below 5 to 10°C above the pour point.
- Power low model could be used to correlate the flow properties.
- The consistency index was correlated to temperature by using Walthers type equations and the flow behavior index using polynomial fitting.
- The yield stress measurements were found to be very sensitive to the measuring system and the conditions. The coaxial cylinder viscometer gave high yield values.

RECOMMENDATIONS

- The apparent viscosities, measured in the present work need to be compared with the effective viscosity values in the commercial lines.
- The yield strength should be determined using model pipeline apparatus.
- The influence of pipeline deposition on pressure drop, pipeline roughness and finally on the effective viscosities requires further investigations. It is recommended that field scale or pilot scale pipeline set-up should be constructed to study the rheological and deposition properties of the crude oil.

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NOMENCLATURE

$a_0, \ldots a_3$	Constants
A, B, C	Constants
K	Consistency index
m	Constant in Eq. 5
n	Flow behavior index, (dimensionless)
p	Pressure, (pa)
S	Shear rate, (Sec^{-1})
T	Temperature, (Deg K)
X	Distance, (m)
Greek	
μ	Viscosity, (Pa S)
τ	Shear stress, (Pa)
τ_0	Yield stress, (Pa)

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