

PETROLEUM ENGINEERING

Rheological Behavior of Saudi Crude Oils

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Abstract. The wide changes in temperature during summer and winter in Saudi Arabia may cause changes in Saudi crude oil properties. Since crude oil behavior has a significant importance for pipeline design calculations and storage, rheological behavior of Arab light, Arab Berri and Arab heavy crudes were determined at different temperatures (10-70°C). Viscosity-temperature relationships were also studied. The results indicated that crude oil properties were changed from Newtonian to non-Newtonian at low temperatures while Arab Berri crude behaved non-Newtonian at both low and high temperatures.

Nomenclature

A, B, C	=	Constants
K	=	Consistency index, Pa. (sec) ⁿ
n	=	Flow behavior index, Dimensionless
$\dot{\gamma}$	=	Absolute value of shear rate, (sec) ⁻¹
T	=	Absolute temperature °R
t	=	Temperature °C
ζ	=	Kinematic viscosity, Cst.
μ	=	Viscosity of fluid, cp
τ	=	Shear stress, Pa
r	=	Correlation coefficient
r ²	=	Coefficient of determination

1. Introduction

Identification of the rheological behavior of crude oil is needed for proper design of pipelines, storage and handling. Crude oil behavior may be changed from Newtonian at high temperatures, above room temperature to non-Newtonian at low temperatures, due to the existence of suspended solid particles such as paraffins, asphalt and other compounds [1]. Fluids are classified according to their rheological properties into Newtonian and non-Newtonian fluids as presented by the following equation [1,2]:

$$\tau = K \dot{\gamma}^n \quad (1)$$

With pressure and temperature held constant, a Newtonian fluid will exhibit a direct proportionality between applied shear stress and shear rate. The logarithmically plotting of shear stress-shear rate relationship shows straight line of unity slope, its intercepts at shear rate equal unity is the viscosity. All fluids which do not exhibit a direct proportionality between shear stress and shear rate at constant temperature and pressure are classified as non-Newtonian. The most common non-Newtonian crude types are pseudo-plastic, dilatant, Bingham plastics and thixotropic [1,2,3,4,5].

Pseudo-plastic are fluids whose apparent viscosity decreases with increasing values of shear stress, power-law equation is used for calculations [2,3] as presented in equation (1). When shear stress-shear rate relationship is plotted on logarithmic coordinates, the slope of the straight line is the value of n which is less than unity. Dilatant fluids behavior [4] is opposite to that of a pseudo-plastic. The apparent viscosity increases as the deformation rate increases. With reference to the power law, the flow behavior index, n , is greater than unity. The dilatancy is observed at very high concentrations of ultrafine particles in liquids [1].

Bingham plastics [2] will not deform continuously until the applied stress exceeds the yield point. After that the shear rate will be proportional the shear stress.

Some previous studies has been published in similar area using different types of crude oils. No definite conclusion have been obtained due to the different nature of the crudes studied [6,7,8].

The aim of this work was to identify the rheological behavior of three types of crude oil at different temperatures. Different correlations were also applied to investigate the variation in viscosity with temperatures.

2. Experimental Work

Rheological behavior of crude oil is determined by measuring the viscosity of the liquid using Brookfield Viscometer [9,10] (LVT model). Measurements made using different speeds to detect and evaluate the rheological properties of the test material.

Sixteen milliliters of the sample of the crude oil to be tested was poured into the UL adapter tube. Next, the spindle was attached to the viscometer spindle coupling. The UL adapter tube was fixed into the viscometer locating slot provided. The tube was gently tapped to remove any air bubbles which might have gotten trapped in the oil when pouring the oil into the tube. The adapter tube assembly was then placed in a water bath at different temperatures. The viscometer was levelled using levelling screws and the bubble level. The speed with a control knob was turned to the desired value and the motor was then switched on. When the pointer on the dial showed a

constant reading, the clutch was depressed to hold the pointer and the motor was shut-off, the reading on the dial was then noted and this reading was multiplied by the relevant factor in centipoise. Viscosities were measured using spindle 1 at lower temperatures 10, 15 and 20°C while the adapter was used to measure liquid viscosities at higher temperatures because it prevents turbulent flow from occurring by having a narrow clearance between the spindle and fluid container.

3. Results and Discussions

The behavior of three Saudi Arabian crude oils, namely, Arab light, Arab Berri and Arab heavy has been carried out at temperatures 10, 15, 25, 38, 55 and 70°C. Their API gravities were 36.50, 32.90 and 27.40° API respectively at 60°F. Their viscosities were measured at different temperatures and shear rates. In this study power law equation was used to study the rheological properties of the Saudi crude oils.

3.1. Determination of Rheological Behavior Parameters

On logarithmic coordinates, shear stress is plotted as a linear function of shear rate. The slope of the straight line (n) and the intercept value of the line on the shear stress axis where shear rate equals unity, K , determine the rheological behavior of the Saudi crude oils. The values of the rheological parameters n and K were found and tabulated in Table 1. These results show that the Arab light crude behavior was non-Newtonian (pseudo-plastic) at low temperatures (below 25°C) where n was less than unity and Newtonian at temperatures higher than room temperature (25°C or above). Berri crude behavior was non-Newtonian (pseudo-plastic) at low and high temperatures where n varied from 0.792 to 0.914. Arab heavy crudes were behaved as non-Newtonian (dilatant) at low temperatures where n was larger than unity and Newtonian at high temperatures. Also the behavior of crude oil could be investigated by plotting the change in viscosity with shear rate. A change in viscosity with a change

Table 1. Rheological parameters and viscosity correlation coefficient r for Saudi crude oils

Temperature °C	Arab light crude			Arab Berri crude			Arab heavy crude		
	K	n	r	K	n	r	K	n	r
10	0.380	0.990	0.995	0.222	0.876	0.999	2.200	1.0480	9.999
15	0.290	0.958	0.999	0.176	0.862	0.998	1.580	1.0285	0.999
20	0.210	0.997	0.999	0.134	0.914	0.999	1.140	1.0260	0.999
25	0.095	1.000	0.999	0.094	0.845	0.999	0.420	1.0000	0.999
38	0.601	1.000	0.999	0.083	0.806	0.999	0.265	1.0000	0.999
55	0.044	1.000	0.999	0.064	0.792	0.999	0.150	1.0000	0.999
70	0.038	1.000	0.999	0.047	0.816	0.999	0.110	1.0000	0.999

in shear rate shows a non-Newtonian fluid behavior while Newtonian fluid shows constant viscosity as the rate of shear is changed.

Figure 1 shows a decreasing viscosity with an increasing in shear rate at low temperatures for Arab light crude oil, this is a pseudo-plastic behavior. While at high temperatures Figure 2 shows Newtonian behavior where the viscosity remains constant as the rate of shear is changed.

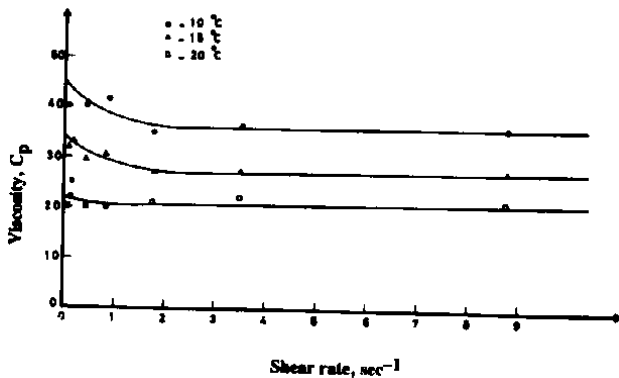


Fig. 1. Effect of Shear rate on the viscosity of the Arab light crude oil at various temperatures

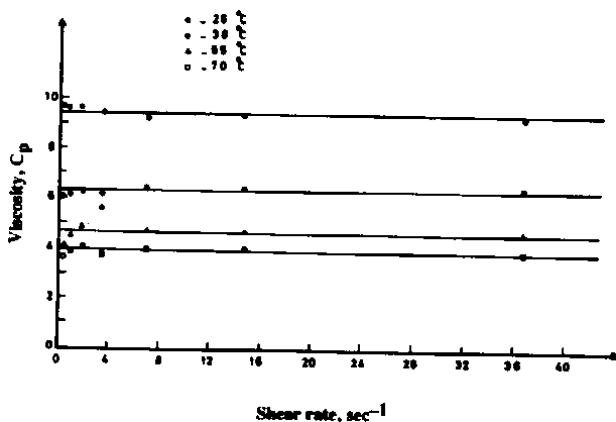


Fig. 2. Effect of Shear rate on the viscosity of the Arab light crude oil at various temperatures

Figures 3 and 4 show non-Newtonian behavior for Arab Berri crude oil at both low and high temperatures where the viscosity decreases with the increase in shear rate.

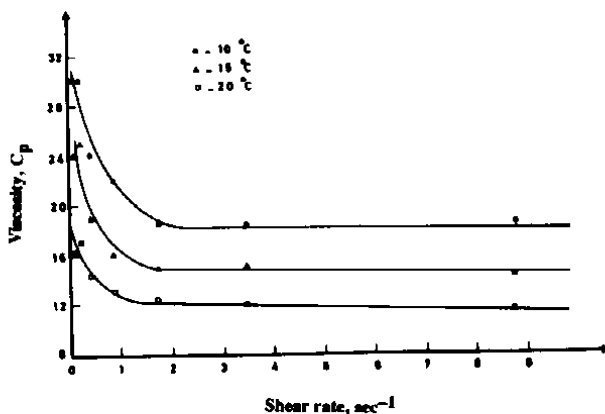


Fig. 3. Effect of Shear rate on the viscosity of the Arab berri crude oil at various temperatures

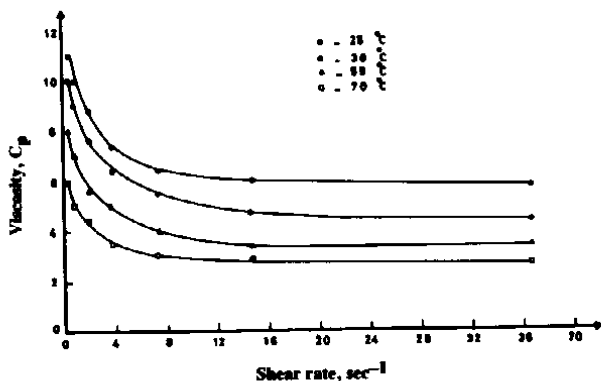


Fig. 4. Effect of Shear rate on the viscosity of the Arab berri crude oil at various temperatures

Figure 5 shows a sharp increase in viscosity with increase in rate of shear up to 1 sec^{-1} for heavy crude oil at low temperatures, this increase in viscosity became slight at higher rate of shear, this is a dilatant fluid. The fluid behavior became Newtonian at temperature of 25°C or above as it is shown in Figure 6. Pseudo-plastic or dilatant behavior is due to a solid dispersed of asymmetric particles such as paraffins, asphalted and resinous components [1]. Suspensions of ultrafine or fine particles in liquids at low concentrations may show Newtonian or pseudo-plastic, and dilatant at a very high concentrations.

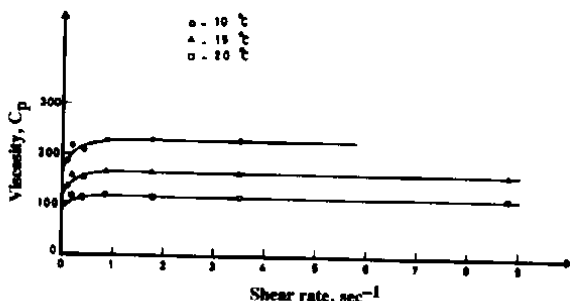


Fig. 5. Effect of Shear rate on the viscosity of the Arab heavy crude oil at various temperatures

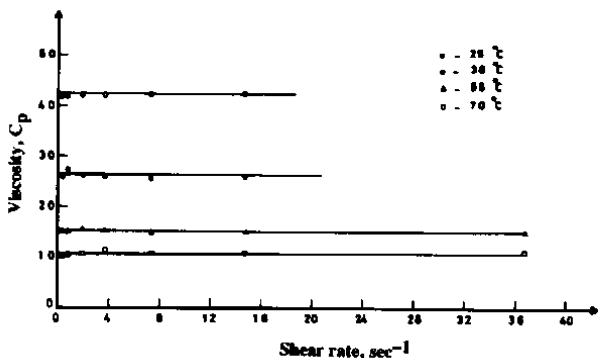


Fig. 6. Effect of Shear rate on the viscosity of the Arab heavy crude oil at various temperatures

3.2. Effect of Temperature on the Viscosity of Saudi Arabian Crude Oils

For correlating the variation of viscosity with temperature, several relationships were considered. Those were Andrade [11], Herchel [12], and Dean and Lane [13] correlations. Due to the change in crude behavior from non-Newtonian to Newtonian at temperatures higher than 25°C, for Arab light and Arab heavy crude oils, and for more accuracy viscosity temperature correlations were applied for two regions: i) Region of low temperatures below 25°C and ii) region of temperatures of 25°C or above.

Figure 7 shows the variation in viscosity with temperature using Herchel correlation [12] for Berri light and heavy crudes.

$$\mu = A \cdot t^B \quad (2)$$

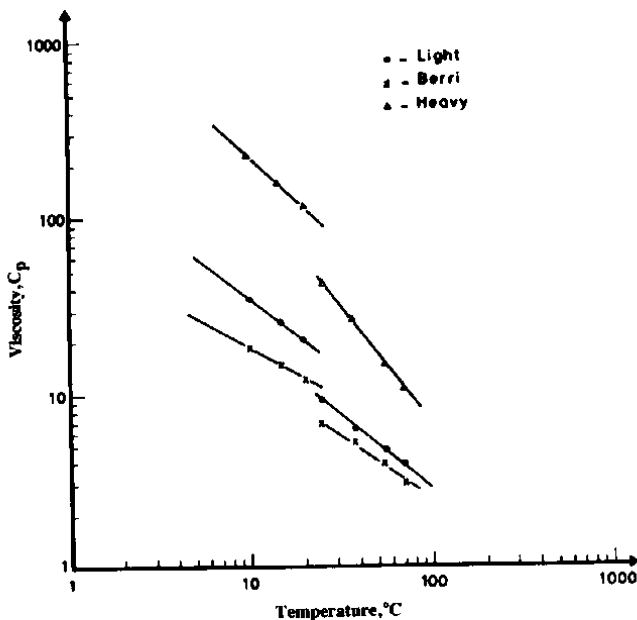


Fig. 7. Variation of the viscosity of Arab light, Arab berri and Arab heavy crude oils with temperature, using Herchel correlation at 6 rpm

when plotting $\log \mu$ versus $\log t$, a linear correlation was obtained for all the crudes and the following correlations between μ and t were obtained:

For light crude:

At $t < 25^\circ\text{C}$

$$\mu = 190.2518 \quad t^{-0.706}$$

At $t \geq 25^\circ\text{C}$

$$\mu = 125.9282 \quad t^{-0.8161}$$

For Berri crude:

At $t < 25^\circ\text{C}$

$$\mu = 69.71312 \quad t^{-0.57325}$$

At $t \geq 25^\circ\text{C}$

$$\mu = 75.8863 \quad t^{-0.7448}$$

For heavy crude:

At $t < 25^\circ\text{C}$

$$\mu = 2000.572 \quad t^{-0.9394}$$

At $t \geq 25^\circ\text{C}$

$$\mu = 3174.708 \quad t^{1.3343}$$

Figure 8 shows the variation in viscosity with temperature using Andrade correlation [11] for Berri, light, and heavy crudes:

$$\mu = A \cdot e^{B/T} \quad (3)$$

when plotting $\log \mu$ versus $1/T$, a linear correlation was obtained for all three crudes and the correlation between μ and T were obtained.

For light crude:

At $t < 25^\circ\text{C}$

$$\mu = 7.0627 \times 10^{-6} \exp(4366.563/T)$$

At $t \geq 25^\circ\text{C}$

$$\mu = 1.5438 \times 10^{-2} \exp(1890.085/T)$$

For Berri crude:

At $t < 25^\circ\text{C}$

$$\mu = 1.0546 \times 10^{-4} \exp(3419.594/T)$$

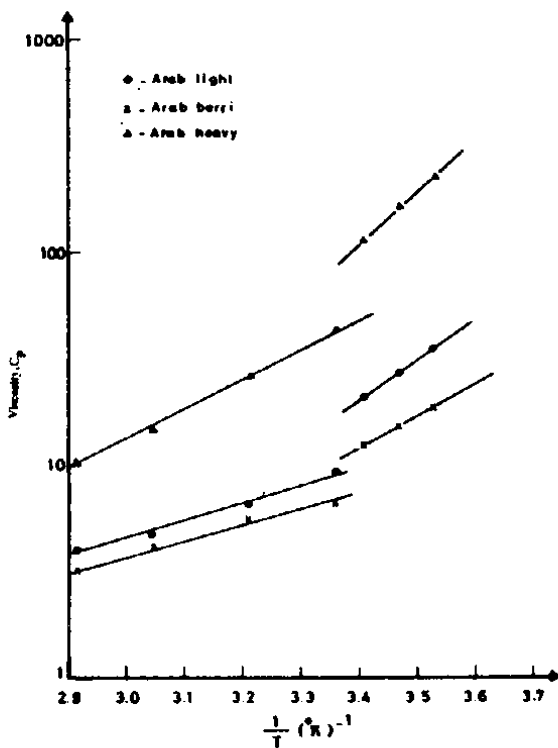


Fig. 8. The variation of the viscosity of Arab crude oils with the reciprocal of temperature, using Andrade correlation at 6 rpm

At $t \geq 25^{\circ}\text{C}$

$$\mu = 1.8310 \times 10^{-2} \exp(1759.313/T)$$

For heavy crude:

At $t < 25^{\circ}\text{C}$

$$\mu = 5.3135 \times 10^{-7} \exp(5629.006/T)$$

At $t \geq 25^{\circ}\text{C}$

$$\mu = 1.1857 \times 10^{-3} \exp(3114.156/T)$$

Another empirical equation was obtained by Dean and Lane [13] from a study on different cuts of three crude oil for up to 100°C and found that:

$$\zeta = (A + Bt + Ct^2)^{-1} \quad (4)$$

When plotting the reciprocal of the measured viscosities versus temperature in °C as shown in Figure 9, the correlation holds and the following equations were obtained:

For light crude:

At $t < 25^\circ\text{C}$

$$\zeta = (1.533752 \times 10^{-2} + 5.973524 \times 10^{-4} t + 7.38838 \times 10^{-5} t^2)^{-1}$$

At $t \geq 25^\circ\text{C}$

$$\zeta = (-7.90745 \times 10^{-4} + 4.141254 \times 10^{-3} t - 1.705952 \times 10^{-5} t^2)^{-1}$$

For Berri crude:

At $t < 25^\circ\text{C}$

$$\zeta = (2.7701 \times 10^{-2} + 1.5999 \times 10^{-3} t + 2.0005 \times 10^{-5} t^2)^{-1}$$

At $t \geq 25^\circ\text{C}$

$$\zeta = (0.12433 - 8.8374 \times 10^{-4} t + 4.20282 \times 10^{-5} t^2)^{-1}$$

For heavy crude:

At $t < 25^\circ\text{C}$

$$\zeta = (2.983113 \times 10^{-3} - 3.451636 \times 10^{-5} t + 1.322055 \times 10^{-5} t^2)^{-1}$$

At $t \geq 25^\circ\text{C}$

$$\zeta = (-3.028993 \times 10^{-3} + 8.0670979 \times 10^{-4} t + 5.128566 \times 10^{-6} t^2)^{-1}$$

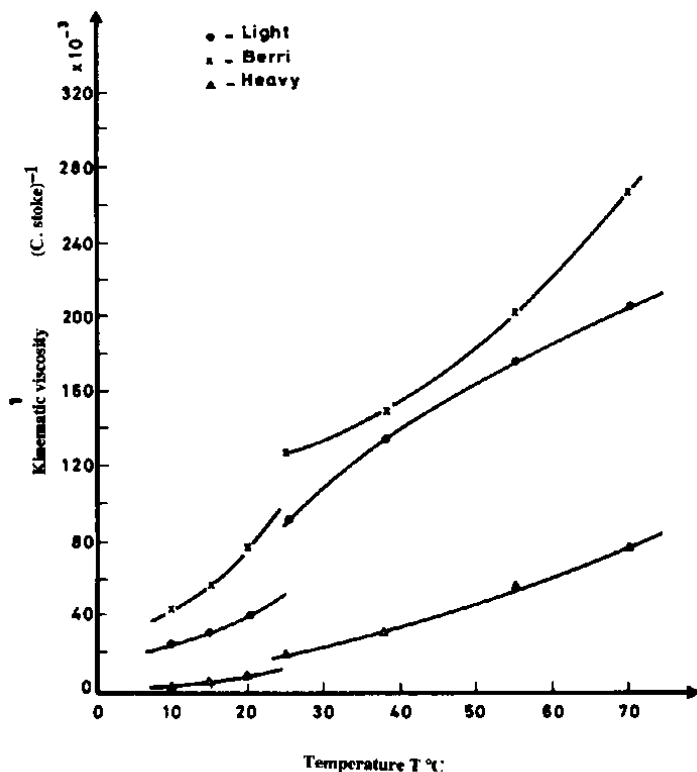


Fig. 9. Variation of the reciprocal of kinematic viscosity of crude oils with temperature, using Dean and Lane correlation at 6 rpm

Kinematic viscosity was calculated by dividing the absolute viscosity by the density of crude oil at different temperature using capillary stoppered Pycnometer [14].

When computing the correlation coefficient for the representation of experimental data by Herchel [12], Andrade [11], and Dean and Lane [13] was obtained. Dean and Lane [13] correlation was in an excellent match to the data with a very good degree of confidence.

The correlation coefficient r for input data compared using the following formula:

$$r = \frac{n \sum xy - \sum x \cdot \sum y}{\left[[n \cdot \sum x^2 - (\sum x)^2] [n \sum y^2 - (\sum y)^2] \right]^{1/2}} \quad (5)$$

where r^2 = coefficient of determination.

The coefficient of determination should not be less than 0.9.

4. Conclusions

The main objective of this study was to identify the rheological properties of different Saudi crude oils; Arab light, Arab Berri, and Arab heavy crude at different temperatures ranging from 10 to 70°C.

Based on the experimental results of this investigation, the following conclusions were made:

- i) Saudi crude oils tested have shown non-Newtonian behavior at low temperatures and Newtonian behavior at temperatures equal to or higher than 25°C, except Arab Berri crude which has shown non-Newtonian behavior at high and low temperatures.
- ii) The viscosity of the crudes is inversely proportional to the API gravity and decreased with temperature.
- iii) Dean and Lane correlation was representative of the data obtained experimentally at high and low temperatures.
- iv) High accuracy matching between the power law model and the experimental results of this study was obtained.

References

- [1] Govier, G.W. and Aziz, K. *The Flow of Complex Mixtures in Pipes*. Florida: Robert E. Krieger Publishing Company, 1982.
- [2] Longwell, P.A. *Mechanics of Fluid Flow*. New York: McGraw-Hill, Book Co. Inc., 1966.
- [3] Metzner, A.B. "Non-Newtonian Flow." *J. Industrial and Engineering Chemistry*, 49, No. 1429 (1957).
- [4] Govier, G.W. and Ritter, R.A. Pipeline Flow Characteristics of Crude Oils." *Proc. Sixth World Petroleum Congress*, Section VII/1, Venezuela, Caracas (1963).
- [5] Ritter, R.A. and Baticky, J.P. "Numerical Prediction of the Flow Characteristics of Thixotropic Liquids." *Society of Petroleum Engineers Journal*, 7, No. 369 (1967).
- [6] Melton, L.L. and Saunders, C.D. "Rheological Measurements of Non-Newtonian Fluids." *Trans. AIME*, 210, No. 196 (1957).
- [7] Govier, G.W. and Fogarasi, M. "The Interpretation of Data on the Rheological Behavior of Thixotropic Crude Oils." *Journal of Canadian Petroleum Technology*, 4 (1972).
- [8] Szilas, A.P. "Determining the Flow Curves Permitting Head Loss Calculation for Thixotropic-Pseudoplastic Crudes." *Koolaj es Foldgaz*, 4 (1971).
- [9] BEL. *Solution to Sticky Problems*. U.S.A.: Brookfield Engineering Laboratories, Inc., 1981.
- [10] BEL. *Brookfield Viscometer Instruction Manual*. U.S.A.: Brookfield Engineering Laboratories, Inc. 1980.

- [11] Andrade, E.N. Da. C. "A Theory of the Viscosity of Liquids." Part 1, *Phil-Mag.*, 17, No. 497 (1934).
- [12] Herchel, W.H. "The Change in Viscosity of Oils with Temperatures." *J. Ind. Eng. Chem.* 14, No. 715 (1922).
- [13] Dean, F. W. and Lane, F.W. "Viscosity-temperatures of Fractions of Typical American Crude Oil." *J. Ind. Eng. Chem.*, 13, No. 9 (1921).
- [14] IP Standards for Petroleum and Its Products. Part 1, *Methods for Analysis and Testing*. Vol. 1, London: The Institute of Petroleum, 1980.

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السلوك السرياني للزيت الخام السعودي عادل محمد حميدة

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ملخص البحث: يتغير السلوك السرياني للزيت الخام السعودي نتيجة للاختلاف الكبير في درجات الحرارة صيفاً وشتاءً. وحيث أن سلوك الزيت الخام له أهمية كبيرة في حسابات تصميم الأنابيب وتخزينه، النفط الخام فقد تم تحديد السلوك السرياني للخامات: العربي الخفيف، ويربي والثقيل عند درجات حرارة تتراوح بين (١٠ - ٧٠ متوية). وقد تم أيضاً دراسة العلاقة بين التغير في لزوجة الزيت الخام مع الحرارة. وقد أوضحت نتائج التجارب أن سلوك الزيت الخام السعودي قد تحول من السريان النيوتوني إلى اللانيوتوني عند درجات الحرارة المنخفضة في حين كان سلوك الخام ويربي لانيوتوني عند كلا من درجات الحرارة العالية والمنخفضة.