CHEMISTRY & CHEMICAL TECHNOLOGY

Chem. Chem. Technol., 2020,
Vol. 14, No. 3, pp. 412–419

Chemical Technology

STUDY ON RHEOLOGICAL PROPERTIES OF EXTRA-HEAVY CRUDE OIL FROM FIELDS OF UKRAINE

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https://doi.org/10.23939/chcht14.03.412

Abstract. The rheological properties of oils from 3 wells of Yablunivske field (Poltava region, Ukraine) were investigated using a rotational viscometer. According to the dynamic viscosity and shear stress dependence on the shear velocity, the nature of the oil flow has been determined, which is of practical importance for evaluating the effectiveness of different modes of action on the rheological behavior of oils during their extraction and transportation.

Keywords: extra-heavy oil, oil transportation, oil rheological properties.

1. Introduction

To date, due to the steady depletion of light, low-viscosity oil reserves, the need for the developing of high-viscosity oil and natural bitumen fields [1, 2] is increasingly important. As a rule, such fields are characterized by high concentration of metals and sulfur compounds, high values of density and viscosity, increased coking ability [3, 4] due to the high content of asphaltenes and resins. Taking into account the latter fact, such oils are extremely difficult to dehydrate [5]. The oils can also corrode the equipment, which in turn will result in the emergency shutdown of the entire refinery [6, 7].

Very often, high-viscosity crude oil fields are a complex multilayer system in which different "floors" have not only different filtration-capacity properties, but also different properties of the reservoir fluid [8]. The most important condition for the formation of extra-heavy crude oil is the loss of light fractions in the areas of tectonic disturbances, as well as hydrogeochemical and biochemical oxidation of oil in the zones of paleo- and modern hypergenesis. The reservoir waters in these zones oxidize oil by transferring chemical oxidizers and various reactive microorganisms resulting in increase of oil viscosity and decrease of oil mobility. Due to these factors, the secondary transformations of oil and its enrichment with heavy fractions occur.

All mentioned above leads to a higher production costs, increased cost of transportation by existing oil pipelines and difficulties in oil refining according to classical schemes [9, 10]. While attempting to develop the field under natural mode, the high viscosity of such oil under reservoir conditions is the reason of low well yields, and sometimes even their absence. Since high-viscosity oil has a low content of gasoline and diesel fractions and a high content of heavy fuel oil with high pour point, such oil is not desirable to be processed under a traditional refinery scheme. However, it is a good raw material for the production of bitumen which has not to be modified further, compared with bitumen produced from conventional oil [11-14]. Usually the modification increases the bitumen cost and complicates the production scheme.

Oil rheological properties are important parameters allowing to substantiate and implement effective complex technologies for the oil recovery increase [15-17]. The peculiarity of extra-heavy oil rheological properties is variability of theirdynamic viscosity, which depends on the applied shear stress and shear rate . Oil flow is non-Newtonian fluid and is determined by its colloid-chemical state (composition of the dispersed phase and the dispersion medium), the nature of intermolecular interactions and structure formation [2]. The regularities of non-Newtonian fluids motion have a series of peculiarities.

For ordinary or Newtonian fluids, the relation between the shear stress τ and the shear rate $\frac{dw}{dn}$ is expressed as a straight line passing through the point of origin with a slope equal to viscosity value. The viscosity of non-Newtonian fluids at given temperatures and pressures does not remain constant, but varies depending on the shear rate, its duration, or the "previous history" of the fluid, as well as the design of the apparatus. Therefore, the dependence of τ on $\frac{dw}{dn}$ is nonlinear.

Non-Newtonian fluids can be divided into three groups. The first group includes viscous or stationary non-

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Newtonian fluids. For these liquids, the function $\frac{dw}{dn} = f(\tau)$ is independent on time. There are Bingam plastic fluids, pseudoplastic fluids and dilatant fluids depending on the function type.

The second group includes non-Newtonian fluids, in which the dependence between $\frac{dw}{dn}$ and τ changes over time. The structure of thixotropic fluids is destroyed and their fluidity increases with the increase in duration of the certain shear stress. But when the stress is removed, the fluid structure is gradually restored, and its flow is discontinued. The fluidity of rheopectant fluids decreases with the increase in shear stress duration.

The third group includes viscoelastic fluids, which flow under the stress τ, but after removing the stress they partially restore their shape, like elastic solids.

According to experts' evaluation, the largest reserves of extra-heavy crude oil are located in Canada, Venezuela, and the Russian Federation. Many other countries in the world, such as China, the USA, Brazil, Iran, Mexico also have high-viscosity oil fields. Approximately 2 % of the world's heavy oil reserves are concentrated in Ukraine. However, due to the complexity of oil sampling and insufficient production of such oil, there are practically no publications on their exploration [1]. A number of extra-heavy oil deposits have been found at the oil and gas condensate fields of the Dnieper-Donetsk Basin, for example the Yablunivske gas and condensate field, located in the Poltava region at a distance of 17 km from Lokhvitsa. Successful experience in the development of this field demonstrates the feasibility of "connecting" this additional source of hydrocarbons for the production of oil, gas and condensate [18].

The aim of this work is the investigation of rheological properties of oil from Yablunivske field to determine the efficient method of its extraction and suitability for transportation.

2. Experimental

To study the properties of extra-heavy oil from the Yablunivske field, the samples from three wells were taken:

Sample 1 – oil from well 88 with a density of 959 kg/m^3 at 323 K;

Sample 2 – oil from well 94 with a density of 969 kg/m^3 at 323 K;

Sample 3 – oil from well 337 with a density of 953 kg/m^3 at 323 K.

The most important physico-chemical properties of oil from the Yablonivske field were investigated by us previously [8], and are presented in Table 1.

The degassed crude oil from the Yablonivske field with abnormally high viscosity belongs to heavy, high-viscosity and sour oil.

The coking ability and pour point for all samples are extremely high, indicating a high content of asphalt-resin hydrocarbons in oil. This will cause difficulties in the transportation of oil, especially at low temperatures, and will require additional measures to reduce the pour point. The chlorides and water content of the samples under study are also extremely high because the oil did not undergo desalination and dehydration, which are obligatory before refining. The kinematic viscosity of investigated oil at 323 K is quite high. The viscosity value is used to determine and calculate the following technological parameters: the mobility of oil in the reservoir during its production, the rate of filtration in the reservoir, the type of displacement agent, the capacity of the pump, the conditions of transportation through the pipeline, *etc*.

To improve oil recovery and to determine the method of oil viscosity reduction during transportation, their rheological properties were studied depending on temperature and shear rate. A modern high-precision rotational viscometer Rheomat-30 (Contraves AG, Switzerland) was used. Viscometer was equipped with a rotary-type adapter with coaxial cylinders. The CM409.484 measuring system consisted of a cylinder with 25 mm diameter and a chamber with 23.8 mm inner diameter and volume of 40 cm^3. The range of shear rate was from 0 to 452 s^{-1}; the temperature range was 293–343 K. The required temperature was provided by a circulating thermostat UH-8 (MLW, Germany) equipped with a special flow cell. Demineralized water was used as a heat carrier.

Table 1

Physico-chemical properties of oil

Property	Sample 1	Sample 2	Sample 3
Density at 293 K, kg/m^3	975	985	970
Kinematic viscosity at 323 K, mm^2/s	324	486	400
Coking ability, %	10.1	10.6	7.1
Pour point, K	290	317	282
Water content, %	5.0	25.0	5.5
Chlorides content, mg/dm^3	2890	5400	7351
Sulfuric-acid resins content, vol%	17.8	24.5	15.9

The procedure was based on the determination of the dynamic (effective) viscosity of the fluids in the range of 0.1–4·10^5 Pa·s. We registered the resistance moment of the inner cone of the measuring device with the test material at different strain-rate gradients, and calculated the shear stress and dynamic viscosity.

Dynamic viscosity (η, Pa·s) was determined according to Eq. (1):

$$\eta = \eta_{rep} \cdot \alpha \qquad (1)$$

where η_{rep} is the viscosity, which corresponds to the position of the device switch at the shear stress for the corresponding measuring system, Pa·s; α is the device readings, %.

The shear stress (τ, Pa) is determined according to Eq. (2):

$$\tau = \eta \cdot D_{rep} \qquad (2)$$

where D_{rep} is the shear rate, which corresponds to the position of the device switch at the shear stress for the corresponding measuring system, s^{-1}.

3. Results and Discussion

To construct rheological flow curves in the τ-η-D coordinates, we used experimental results obtained for all three samples at 293 K (Tables 2-4) and at the temperatures of 303, 313, 323, 333 and 343 K (Figs. 1-6).

Table 2

Dynamic viscosity of Sample 1 at 293 K

Shear rate D_{rep}, s^{-1}	Viscosity, which corresponds to the position of the device switch at the shear stress for the corresponding measuring system η_{rep}, Pa·s	Device readings α, %	Dynamic viscosity η, Pa·s	Shear stress τ, Pa
3.32	0.337	0.5	0.1685	0.5594
4.52	0.248	19	4.712	21.2982
6.15	0.182	20.5	3.7310	22.9456
8.35	0.134	29	3.8860	32.4481
11.35	0.0987	36.5	3.6025	40.8883
15.4	0.0727	46	3.3442	51.5006
21.0	0.0533	58	3.0914	64.9194
28.5	0.0393	73	2.8689	81.7636
38.7	0.0289	92.5	2.6732	103.4528
52.7	0.0213	108	2.3004	121.2310
71.7	0.0156	145	2.2620	162.1854
97.3	0.0115	195	2.2425	218.195
132	0.00848	266	2.2557	297.750
180	0.00622	354	2.2019	396.338
245	0.00457	480	2.1936	537.432
332	0.00337	635	2.1400	710.463
452	0.00248	835	2.0708	936.002

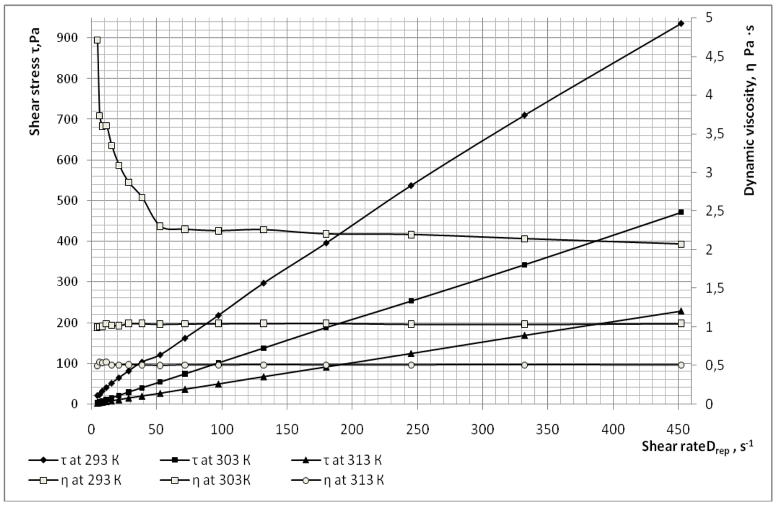

Fig. 1. Rheological properties of Sample 1 at 293, 303 and 313 K

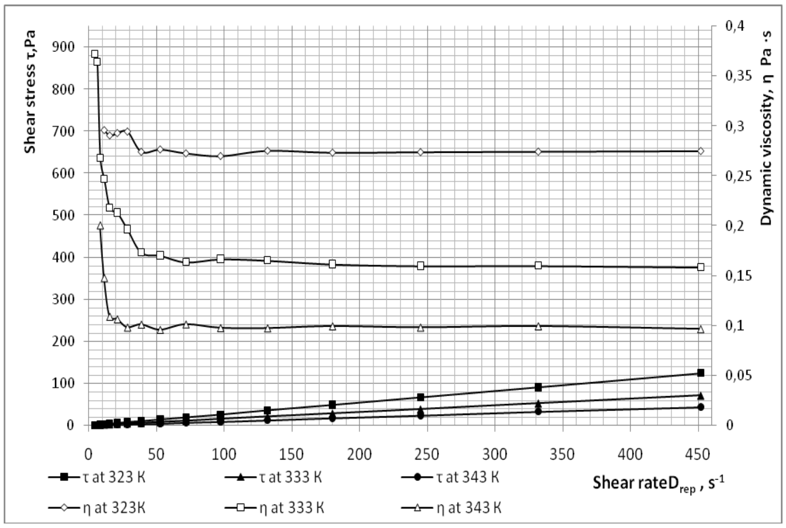

Fig. 2. Rheological properties of Sample 1 at 323, 333 and 343 K

Table 3

Dynamic viscosity of Sample 2 at 293 K

Shear rate D_{rep}, s^{-1}	Viscosity, which corresponds to the position of the device switch at the shear stress for the corresponding measuring system η_{rep}, Pa·s	Device readings α, %	Dynamic viscosity η, Pa·s	Shear stress τ, Pa
0.0615	18.211	7.5	136.582	8.3998
0.0835	13.413	10	134.130	11.1998
0.1135	9.868	13	128.284	14.5602
0.154	7.273	17.5	127.2775	19.6007
0.210	5.333	22.5	119.992	25.198
0.285	3.930	30	117.900	33.6015
0.387	2.894	41	118.6540	45.9190
0.527	2.125	52	110.500	58.2335
0.717	1.562	74	115.588	82.8765
0.973	1.151	98	112.798	102.752
1.32	0.848	123	104.304	137.6812
1.80	0.622	161	100.142	180.2556
2.45	0.457	206	94.1420	230.6479
3.32	0.337	264	88.9680	295.3737
4.52	0.248	340	84.32	381.126
6.15	0.182	430	78.26	481.299
8.35	0.134	555	74.37	620.990
11.35	0.0987	695	68.60	778.570
15.4	0.0727	865	62.89	968.437

Analysis of Sample 1 shows that at 293 K the oil viscosity decreases from 4.71 to 2.30 Pa·s with a slight change in shear rate from 4.52 to 52.7 s^{-1} (Table 2). Further increase in shear rate from 52.7 to 452 s^{-1} decreases the dynamic viscosity to 2.07 Pa·s. Under the same conditions, the dependence of shear stress on the shear rate is nonlinear and the shear stress varies from 936 to 21.3 Pa. Thus, at 293 K Sample 1 behaves as a non-Newtonian pseudoplastic fluid.

With the increase in temperature from 293 to 343 K, it is another nature of the dynamic viscosity changes. Thus, when the shear rate is increased from 4.52 to 452 s^{-1}, the dynamic viscosity of Sample 1 changes slightly: from 0.99 to 1.04 Pa·s at 303 K, from 0.496 to 0.506 Pa·s at 313 K, from 0.37 to 0.27 Pa·s at 323 K, from 037 to 0.16 Pa·s at 333 K and from 0.20 to 0.10 Pa·s at 343 K. The dependence of the shear stress on the shear rate is linear and at the shear rate of 452 s^{-1}, in the temperature range of 303–343 K Sample 1 behaves already as a Newtonian fluid.

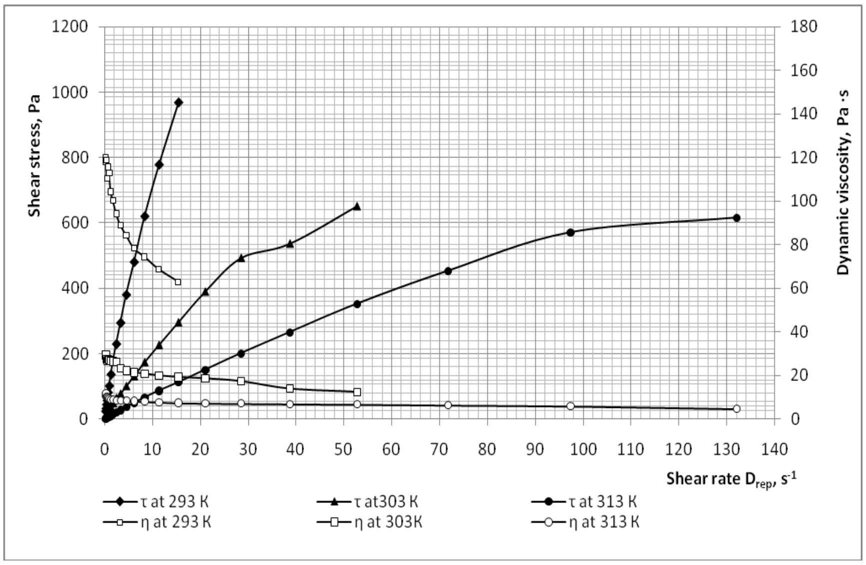

Fig. 3. Rheological properties of Sample 2 at 293, 303 and 313 K

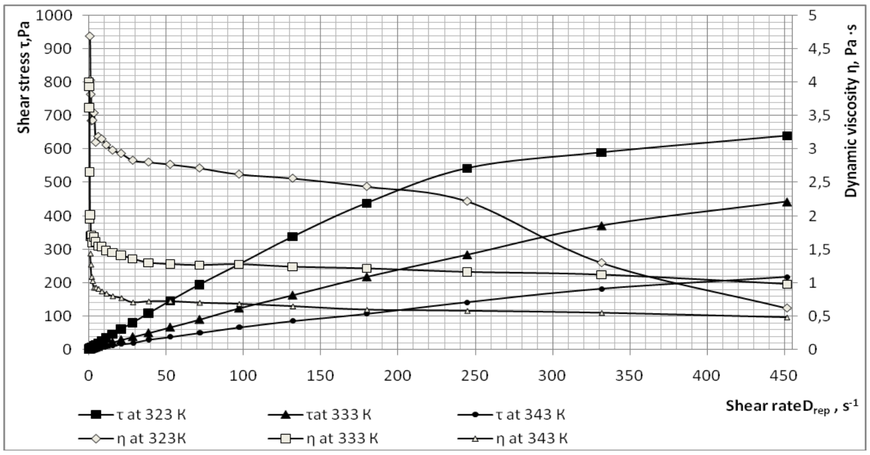

Fig. 4. Rheological properties of Sample 2 at 323, 333 and 343 K

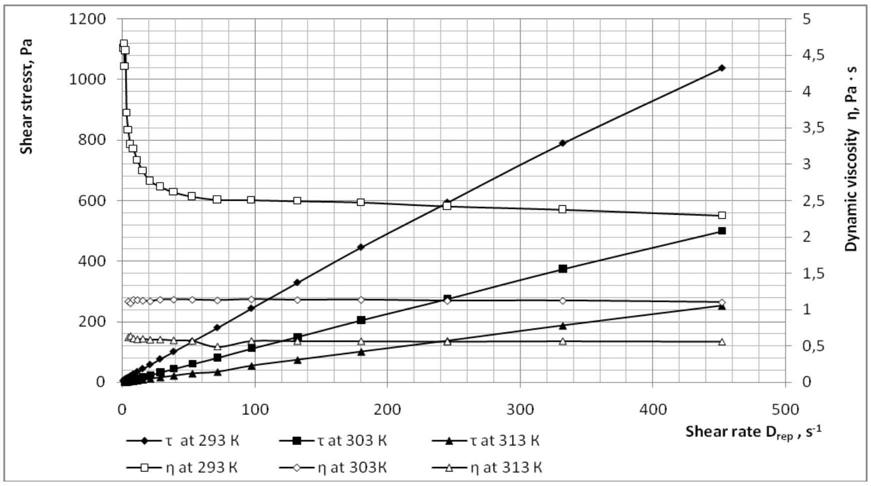

Fig. 5. Rheological properties of Sample 3 at 293, 303 and 313 K

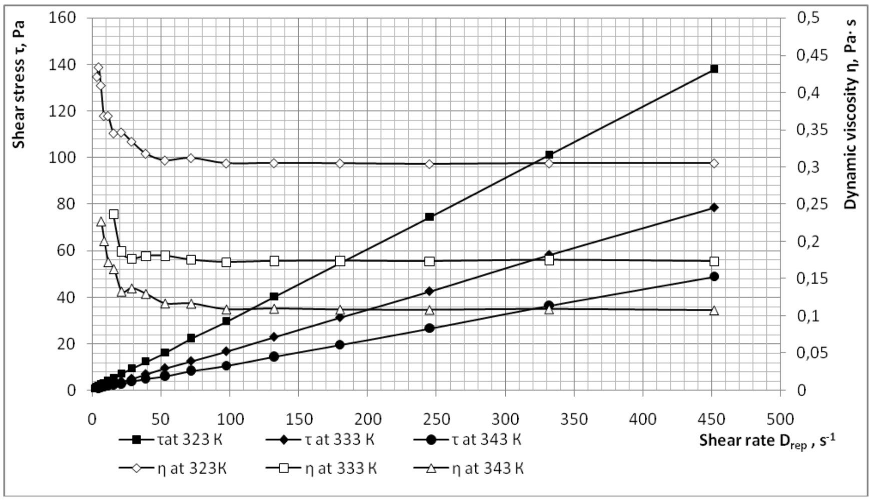

Fig. 6. Rheological properties of Sample 3 at 323, 333 and 343 K

Table 4

Dynamic viscosity of Sample 3 at 293 K

Shear rate D_{rep}, s^{-1}	Viscosity, which corresponds to the position of the device switch at the shear stress for the corresponding measuring system η_{rep}, Pa·s	Device readings α, %	Dynamic viscosity η, Pa·s	Shear stress τ, Pa
0.527	2.125	0.5	1.0625	0.5600
0.717	1.562	2.5	3.905	2.7998
0.973	1.151	4.0	4.604	4.4797
1.32	0.848	5.5	4.664	6.1564
1.80	0.622	7.0	4.354	7.8372
2.45	0.457	10	4.570	11.1965
3.32	0.337	11	3.707	12.3072
4.52	0.248	14	3.472	15.693
6.15	0.182	18	3.276	20.1474
8.35	0.134	24	3.2160	26.8536
11.35	0.0987	31	3.0597	34.7275
15.4	0.0727	40	2.908	44.7832
21.0	0.0533	52	2.7716	58.204
28.5	0.0393	68.5	2.692	76.722
38.7	0.0289	90.5	2.6154	101.2159
52.7	0.0213	120	2.556	134.7012
71.7	0.0156	161	2.5116	180.0817
97.3	0.0115	218	2.507	243.931
132	0.00848	294	2.4931	329.0892
180	0.00622	398	2.4755	445.590
245	0.00457	530	2.4221	593.4145
332	0.00337	705	2.3758	788.7656
452	0.00248	925	2.294	1036.89

Sample 2 has a substantially higher value of dynamic viscosity. At the shear rate of 0.06 s^{-1} the dynamic viscosity is 136.58 Pa·s. With the increase in shear rate to 4.52 s^{-1} the viscosity decreases to 62.89 Pa·s. The shear stress with increasing shear rate increases sharply from 8.40 to 968.44 Pa, *i.e.* by 115 times. The increase in temperature from 303 to 343 K decreases viscosity far less dramatically, but the values of shear stress at all temperatures are significant (651–217 Pa). At the values of shear rate higher than 21 s^{-1}, the dynamic viscosity dependence is nonlinear, so it can be concluded that Sample 2 behaves as a non-Newtonian pseudoplastic fluid in the whole temperature range from 293 to 343 K.

For Sample 3 the dynamic viscosity is 4.60 Pa·s at the shear rate of 0.97 s^{-1}, and even with its increase to 21 s^{-1}, the viscosity decreases to 2.77 Pa·s. Further increase in shear rate by 21.5 times decreases the dynamic viscosity to only 2.29 Pa·s. In this case, the shear stress increased from 4.48 to 1036.89 Pa, *i.e.* by 230 times. Unambiguously, Sample 3 at the temperature of 293 K refers to non-Newtonian pseudoplastic fluids.

When the temperature is increased by only 10 K, the oil viscosity decreases by 3.4 times. However, with increasing temperature from 303 to 343 K and the shear rate from 0.97 to 452 s^{-1} the change in viscosity is negligible – only 10–30 %. The shear stress increases from 48.76 to 498.83 Pa with the decrease in temperature from 343 to 303 K. The dependence of the shear stress on the shear rate is linear and at the value of 452 s^{-1} the Sample 3 behaves as a Newtonian fluid in the temperature range of 303–343 K.

Graphic example of the dynamic viscosity and shear stress dependence on the temperature is given in Figs. 7 and 8 (obtained on the data of Figs. 1-3 at the shear rate of 4.52 s^{-1}).

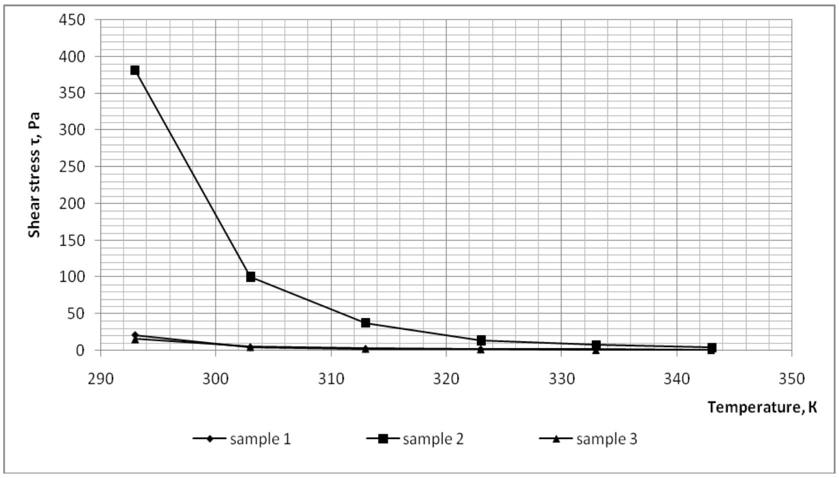

Fig. 7. Shear stress *vs.* temperature at the shear rate of 4.52 s^{-1}

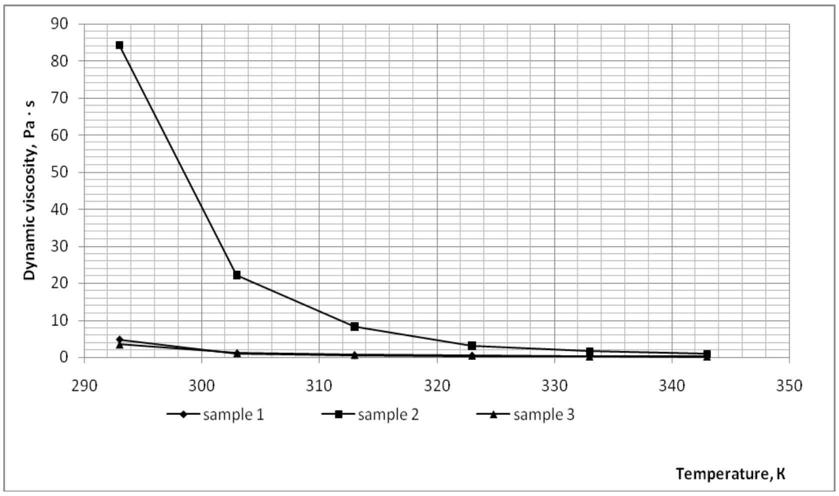

Fig. 8. Dynamic viscosity *vs.* temperature at the shear rate of 4.52 s^{-1}

The shear stress of the Samples 1 and 3 linearly decreases with the increase in temperature from 293 to 343 K. A sharp decrease is observed only in the region of 293–303 K (from 21.3 Pa for the Sample 1 and 15.7 Pa for the Sample 3 to 5.04 Pa). Then the curve becomes linear, which confirms that under 303 K the Samples 1 and 3 behave as non-Newtonian fluids. With increasing temperature to 343 K the flow character becomes linear, and therefore the oils become Newtonian.

The shear stress and dynamic viscosity of Sample 2 are significantly higher than those of Samples 1 and 3. The viscosity changes especially dramatically as the temperature increases from 293 to 303 K; it decreases by more than 3.9 times. The same is observed for the shear stress which is changed by 3.8 times. Further increase in temperature results in the decrease in both shear stress and dynamic viscosity, but without sharp drop.

4. Conclusions

The rheological properties of extra-heavy crude oil from three wells of the Yablunivske field have been investigated. At the temperature of 293 K and within the shear rate range of 0.7–452 s^{-1} the shear stress of Samples 1 and 3 nonlinearly depends on the shear rate. The samples behave as non-Newtonian fluids but at the temperatures above 303 K they become Newtonian ones. Thus, for this type of oil the transfer with heating is advisable.

The dependence of shear stress on shear rate is nonlinear for sample 2 in the temperature range of 293–343 K at a shear rate higher than 21 s^{-1}. Thus, it can be concluded that in the whole range of temperatures Sample 2 behaves as a non-Newtonian pseudoplastic fluid.

The investigated rheological properties are of practical importance for evaluating the effectiveness of different modes of action on the rheological behavior of crude oil during its extraction and transportation. When heating Samples 1 and 3 to the temperatures above 293 K, their non-Newtonian properties are smoothed and the dependence of the dynamic viscosity on the shear rate decreases. Sample 2 requires more heating or other methods of reducing the viscosity (adding anti-viscosity modifiers or even depressants).

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Received: May 15, 2019 /Revised: May 22, 2019 / Accepted: July 02, 2019

ДОСЛІДЖЕННЯ РЕОЛОГІЧНИХ ВЛАСТИВОСТЕЙ ВАЖКИХ ВИСОКОВ'ЯЗКИХ НАФТ РОДОВИЩ УКРАЇНИ

Анотація*. Досліджено реологічні властивості високов'язких нафт з 3-х свердловин Яблунівського родовища (Полтавська обл., Україна) за допомогою ротаційного віскозиметра. За характером кривих залежності динамічної в'язкості та напруження зсуву від швидкості зсуву встановлено характер течії даних нафт, що має практичне значення для оцінки ефективності різних способів дії на реологічну поведінку цих нафт при їх видобутку та транспортуванні.*

Ключові слова*: важка нафта, транспортування нафти, реологічні властивості нафти.*