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Effect of Ultrasonic Oscillations on the Fluidity of Heavy Oil Products at Low Temperatures

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Abstract—We develop a laboratory setup to estimate the force of rotation of a metal branch pipe in a viscoelastic medium. We show that 2-min action of shearing ultrasonic oscillations (frequency, 32.5 kHz; specific power, no more than 0.008 W/cm^2) reduces by 17% the static limit of fluidity brought to an initial temperature of Ì-100 fuel oil cooled to -15°C in the wall layer of a rotating branch pipe. We obtain a linear regression dependence between the ratio of the threshold force of the onset of branch pipe motion to the consumption current of the ultrasonic transducer and the fuel temperature.

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INTRODUCTION

Heavy oil products, in particular, furnace fuel oil, are transported in the technological pipelines of tank farms and thermal power stations. A problem is weak fluidity of heavy oil products, especially at decreased ambient temperatures, when they become jellylike [1]. Basic complications arise when the medium begins to move (starting modes), when oil products, at least in the wall layer of the pipe, undergo transition from an elastic to a fluid state [2]. Usually, steam heating is applied to decrease resistance of oil products to movement through technological pipelines (increase in fluidity). However, the given technology is rather power-intensive, expensive, and, owing to high heat-insulating properties of heavy oil products, not very efficient.

A large number of studies are devoted to how mechanical oscillations affect the fluidity of oil products (see, for example, [3, 4]). In particular, in [4], a decrease in gel formation with an increase in the intensity of ultrasonic oscillations has been revealed. In [5], the effect of a dual decrease in oil current resistance has been shown at temperatures near -7°C in the main oil pipelines by the creation of shearing or torsion ultrasonic oscillations in pipe walls. Thus, the effect of acoustic control via the fluidity of oil products with a melting temperature of up to 29°C has been proved experimentally. The purpose of the given work is to study the application of an acoustic method to decrease the current resistance of especially heavy and viscous oil products (melting temperature near 40°C) at lower ambient temperatures.

LABORATORY SETUP

To conduct experimental investigations, a laboratory setup was developed [6]. It contains (*1*) a vessel for the studied medium (*2*) (Fig. 1). On axis (*3*) of the external support a rotating acoustic node is suspended containing Π-shaped bracket (*4*) of the investigated metal branch pipe (*5*) with piezoceramic cylinder (*6*) glued to its top end face, excited in the longitudinal mode of oscillations. The piezoceramic cylinder and the branch pipe constitute a half-wave transducer of

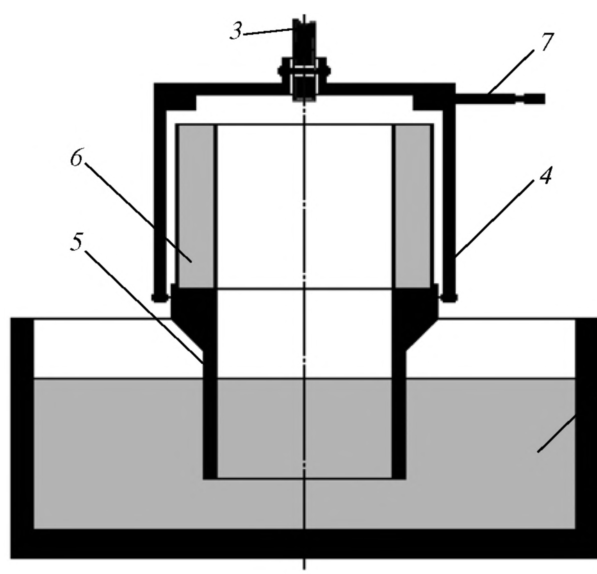

Fig. 1. Scheme of laboratory setup: (*1*) capacity, (*2*) investigated medium, (*3*) axis of rotation of external support; (*4*) Π-shaped bracket, (*5*) metal branch pipe, (*6*) piezoceramic cylinder, (*7*) lever.

the system for exciting ultrasonic oscillations; this fastens pointwise to the edge of the Π-shaped bracket in the zone of the oscillatory speed node, which results in acoustic decoupling of the system for exciting ultrasonic oscillations from the other part of the construction. The laboratory setup is equipped with temperature gauges in the volume of the investigated medium and on the wall of the branch pipe.

The vessel is filled with the investigated medium at room temperature. The acoustic node is fixed in the volume with the investigated medium by means of auxiliary fastenings. Then the setup is cooled to the required temperature. After extraction from the refrigerator, the rotating part of the setup is connected to the axis of rotation of external support (*3*) and the auxiliary fastenings are removed. Lever (*7*), to which the force gauge is attached at a fixed distance from the axis of rotation of the setup, is turned to the lateral wall of the Π-shaped bracket. An electric signal is fed from the generator to the piezoceramic cylinder within a regulated time, which causes shearing oscillations to develop in the investigated medium in the wall layer of the branch pipe. On the lever, through the force gauge, force is created at which the branch pipe, together with the rotating acoustic node, shifts and begins to rotate in the working medium (in the horizontal plane). This force is recorded by the force gauge.

Note that the scheme of the setup is based on inversion to the geometry of the problem on movement of a working medium in a pipe [5]. Indeed, an increase in fluidity not in the full volume of the working medium, but only in its wall layer, is critical to decrease the resistance of oil pumped through the pipeline. This effect is also supposed to be recorded when there is a decrease in force as the branch pipe begins to rotate. The given approach has certain analogies to the way of measuring viscoelastic properties of liquid media based on torsion oscillations [6].

MATERIALS AND METHODS

For preliminary study of the capabilities of the laboratory setup, a control accelerometer based on a console bimorph piezoelectric transducer with a 2-mm console shoulder was glued to the bottom end face of the investigated branch pipe [6]. Analysis of the input electric resistance achieved on the given flexural transformer of the control accelerometer did not reveal eigenresonances at frequencies of up to 50 kHz. Sensitivity of the control accelerometer in preresonance areas is measured on a vibraton exciter in the frequency range below 200 Hz in comparison to a standard accelerometer and was 1.1 mV/ms^2.

The setup was filled with M-100 fuel oil. Analysis of the control accelerometer's response to excitation of the half-wave transformer in the retuning frequency mode (excitation amplitude, 2 V) has made it possible to establish the resonance frequency, which varied from 32 to 34 kHz depending on the fuel oil temperature (a range of −15° to 12°C) at the maximum developed amplitude. The fuel oil temperature in the volume was controlled by a thermoresistor (−15°C, 86 kΩ; to +12°C, 22.5 kΩ). Since the resonance frequency of the acoustic node changes with the temperature of the medium, the generator frequency was chosen at 32.5 kHz. As well, according to the indications of the control accelerometer, oscillatory accelerations of 750 m/s^2 developed at the end face of the branch pipe submerged in the working medium at room temperature with a generator working output voltage of 50 V.

To conduct the basic experiment, the control accelerometer was removed. The bilateral area of the part of the branch pipe submerged in fuel oil (external diameter, 25 mm; internal, 24 mm; depth of submersion, 10 mm) was $S = 9.43$ cm^2.

The force of the onset of branch pipe motion was measured by an SBA-100L force gauge (CAS Corporation) connected through a bridge amplifier to a PowerLab-8/30 electronic recorder (ADInstruments). The force gauge, fixed horizontally on the lever (shoulder of 25 mm relative to the rotation axis of the system) through the draught was set in motion tangential to the circular trajectory of the rotating node of the setup after the electronic recorder was turned on. After the branch pipe began to rotate (displacement, 3–10 mm), the force decreased. The typical response of the force gauge is shown in Fig. 2. As an estimate of the force of the onset of motion, the maximum force value F_{max} is taken.

The force gauge was calibrated by suspension of known loads, and its sensitivity was 0.2 μV/g. We determined the orders of the signal level of this gauge determining the forces of the onset of motion in fuel oil at room temperature—near 3 μV, and at −15°C, near 300 μV. It is obvious that such a substantial difference in force gauge indications makes it possible to reliably fix changes in the state of the medium in the branch pipe wall layer.

The oil-filled setup was cooled in the freezer of a refrigerator for no less than 5 h. The attained temperature values were near −15°C (86 kΩ); however, statistical scatter was observed (see table).

In addition to the force corresponding to the onset of motion of a branch pipe (F_{max}, μV), the initial fuel oil temperature in the volume (T_V, kΩ), initial branch pipe temperature (T_t, Ω), and initial consumption current of the piezoelectric transducer (I, mA) were also controlled.

RESULTS

Eleven measurements were performed directly after 2-min ultrasound, and seven without ultrasound (table).

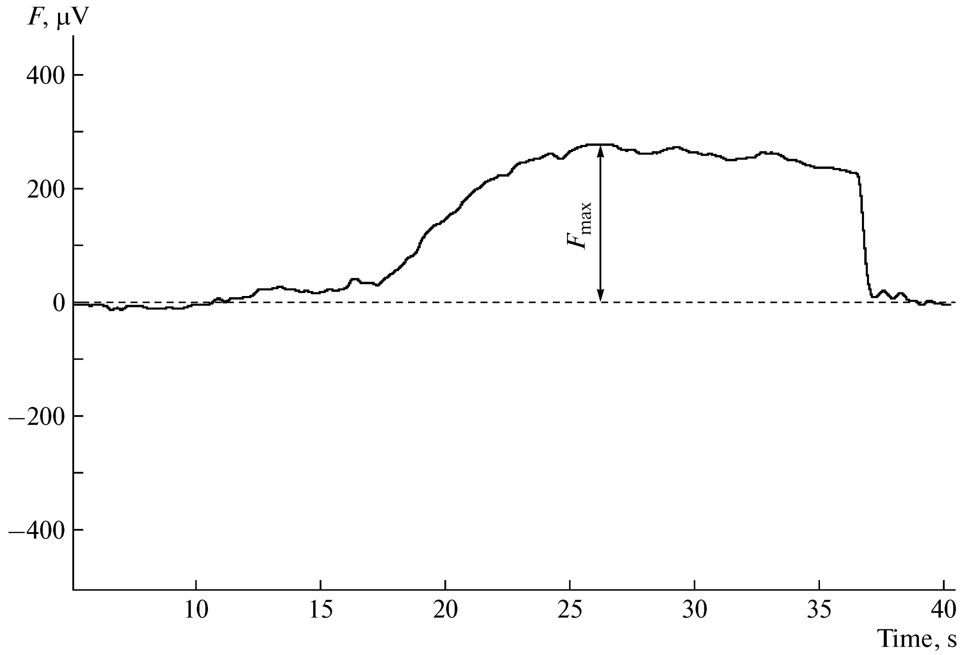

Fig. 2. Dependence of response of force gauge at onset of rotation of branch pipe of laboratory setup in cooled M-100 fuel oil: F_{max} is maximum force.

In estimating the reliability of variations between cases with and without ultrasound, no statistically significant variations were revealed in the size of the force corresponding to the onset of motion, the initial fuel oil temperature in the volume, the initial branch pipe temperature, and the ratio of the force of onset of motion to the initial branch pipe temperature. However, statistically significant variations have been revealed for the ratio of the force of onset of motion to the initial fuel oil temperature in the volume (F_{max}/T_v) with and without ultrasound. We introduce p—a quantitative characteristic of the statistical significance of distinctions (the probability that the opposite hypothesis is true). With allowance for the smallness of the sample, a value $p < 0.1$ can be considered an indicator of statistical reliability. A magnitude of F_{max}/T_v averaged over sample appeared on average ($n = 11$) to be 17% less with ultrasound than without ($n = 7$).

In estimating the Spearman correlation coefficient (r) over the group of measurements with ultrasound ($n = 11$), the following was revealed: a statistically significant direct interrelation between the force corresponding to the onset of branch pipe motion and the initial fuel oil temperature in the volume $r = 0.79$ (statistical significance of correlation coefficient $p = 0.004$), a statistically significant direct interrelation between the initial fuel oil temperature in the volume and the initial branch pipe temperature $r = 0.68$ ($p = 0.022$), and a statistically significant reverse interrelation between the initial fuel oil temperature in the volume and the consumption current of the piezoelectric transducer $r = -0.64$ ($p = 0.035$).

Analysis has shown that a consumption current value of 65 mA (line 11, table) is a power surge. When this line is removed ($n = 10$), the correlation coefficient between the initial fuel oil temperature in the volume and the consumption current of the piezoelectric transducer increases to $r = -0.85$ ($p = 0.002$), which makes it possible to construct an informative linear regression model (normality of distributions was checked by the Shapiro–Wilk criterion):

$$T_v = (9.4 \pm 2.3) - (0.36 \pm 0.07)I; \qquad (1)$$

coefficient of determining the linear regression model $r^2 = 0.73$; statistical significance of linear regression model $p = 0.001$; regression members are determined with a statistical significance of $p < 0.001$ (standard error of mean in parentheses).

In the absence of ultrasound ($n = 7$), no statistically significant correlation between the parameters in the table is observed.

According to the experimental data (table), it was also possible to construct the following informative linear regression models:

—Between the initial fuel oil temperature (kΩ) and the magnitude of the force corresponding to the onset of motion (μV),

$$T_v = (-489.3 \pm 201.0) - (8.2 \pm 2.4)F_{max}; \qquad (2)$$

$r^2 = 0.52$, $p = 0.007$, $n = 11$, regression members determined with significance $p < 0.01$.

Characteristics of force of onset of branch pipe motion of laboratory setup in cooled M-100 fuel oil

No.	F_{max}, μV	T_t, Ω	T_v, kΩ	Ultrasound (2 min)	I, mA	F_{max}/T_t	F_{max}/T_v
1	300	–	86.2	–	–	–	3.48
2	340	563	86.6	–	–	0.60	3.93
3	268	615	82.5	–	–	0.44	3.25
4	185	730	86.3	+	17	0.25	2.14
5	178	610	80.4	+	40	0.29	2.21
6	193	590	86.4	–	–	0.33	2.23
7	145	509	76	+	50	0.28	1.91
8	200	618	84.8	+	32	0.32	2.36
9	165	610	83.5	+	25	0.27	1.98
10	277	580	85.8	+	30	0.48	3.23
11	185	620	86	+	65	0.30	2.15
12	260	737	91	+	21	0.35	2.86
13	249	610	86.7	+	19	0.41	2.87
14	161	599	79.8	+	35	0.27	2.02
15	235	650	85.2	+	29	0.36	2.76
16	210	648	83.4	–	–	0.32	2.52
17	183	695	83.3	–	–	0.26	2.20
18	230	544	85.2	–	–	0.42	2.70

—Between the force of onset of motion normalized to the consumption current (mA), and the initial fuel oil temperature in the volume ($n = 10$),

$$F_{max}/I = -(54.7 \pm 10.5) + (0.75 \pm 0.13)T_v; \quad (3)$$

$r^2 = 0.79$, $p = 0.0003$, regression members are determined with significance $p < 0.001$.

DISCUSSION

The force measured in experiment necessary for the onset of branch pipe motion in fuel oil in our laboratory setup is obviously proportional to the magnitude of the static limit of fluidity of the viscoelastic medium [2] and characterizes the effect of ultrasonic oscillations on the transition of fuel oil from an elastic to a fluid state. From the results of experiment, it follows that it is possible for ultrasonic oscillations to stimulate a decrease in the static limit of fluidity relative to the initial temperature for M-100 fuel oil at a temperature near –15°C; however, the magnitude of the effect does not yet exceed 17%.

As well, an electric power of about 0.75 W (voltage, 50 V; average consumption current, 29.4 mA; cos(φ ≈ 0.5) is fed to the piezoelectric transducer of the laboratory setup. The electroacoustic efficiency coefficient of the acoustic node with the piezoceramic cylinder working in the longitudinal oscillation mode (latitudinal piezoeffect) barely exceeds 10%. Then, with allowance for EC, the specific acoustic power (normalized to contact area S) from the laboratory setup in cooled fuel oil can constitute about 0.008 W/cm^2, which is rather far from the maximum capabilities of modern ultrasonic equipment.

The dependence of consumption current on temperature (1) testifies to the correctness of choosing the oscillation mode of the acoustic node, whose amplitude depends on the change in the pliability of the investigated medium with a rise in temperature. From regression equation (2), it follows that the static limit of fluidity, as supposed, increases with decreasing fuel oil temperature. Note that the work limits of obtained regression dependences (1–3) lie in the temperature of approximately –11°C (75 kΩ) to –18°C (92 kΩ) and have been determined, strictly speaking, only for the given laboratory setup.

As for the mechanisms of decrease in the static limit of fluidity of heavy oil products, according to [7], one of them is deformation of the cubic structure of paraffin deposits and extraction from them of liquid fractions under the action of static force. Possibly, shearing ultrasonic oscillations can intensify this process. On the other hand, we cannot exclude the intramolecular influence of shearing ultrasonic oscillations on conformational restructuring of long hydrocarbon molecules or their partial rupture [8].

CONCLUSIONS

It is experimentally shown that 2-min action of shearing ultrasonic oscillations (frequency, 32.5 kHz; specific power, 0.008 W/cm^2) reduces by 17% the static limit of fluidity brought to the initial temperature of M-100 fuel oil cooled to −15°C in the wall layer of the rotating branch pipe of the laboratory setup. Regression dependence (3) between the specific force of the onset of branch pipe rotation, the consumption current of the ultrasonic transformer, and the initial fuel oil temperature has been established. Further studies are necessary to evaluate the possibilities of enhancing the discovered effect.

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