Experimental Studies of the Effect of Plasma-Pulse Treatment on Rheological Properties of Oil

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Abstract. The paper presents the results of experimental studies of the effectiveness and duration of the pulse-plasma treatment of oil. The aim of this work is to assess the effect of plasma-pulse treatment of oil (PPT) on its viscosity and pour point (solidification). The relevance of the work results is due to the need to improve the efficiency of oil transportation through main and industrial pipelines. The research work carried out relates to the field of physicochemical and mechanical methods of processing heavy and bituminous oils during their transportation through pipelines without the use of heating and thinners.

1. Introduction

According to all available forecasts, the production of hard-to-recover reserves, including high-viscosity oils, will steadily increase in the near future and will require widespread introduction of new technologies, both in the production process and in the process of their transportation to consumers. In this regard, the research problem on studying the effect of plasma-pulse treatment on the rheological properties of high-viscosity oil with the aim of further developing and substantiating new effective integrated technologies that reduce resource costs for pumping oil and oil products through various types of pipelines are very relevant and in demand.

The basic principles of plasma-pulse treatment technology have been described, for example, in [1 - 3]. The physical basis of the plasma-pulse treatment (PPT) is periodic pulses of equal strength, spaced at equal time intervals, due to the passage of the discharge current through a calibrated metal conductor (wire), which after explosion turns into vapor with high density, temperature and pressure. The shock wave formed during the explosion, radially propagating at supersonic speed, causes an elastic compressive and tensile effect on the environment. In this case, the liquid serves as a medium that transfers the pressure, created as a result of the explosion of the wire. The use of the mechanism of plasma-pulse treatment inside the pipeline can cause an oscillatory process in the system, the result of which will be, on the one hand, cleaning of the inner surface of the pipe from accumulating deposits, and on the other hand, a permanent harmonic influence on the fluid moving inside the pipeline.

2. Effect of pulse impact on the rheological characteristics of oil

Like all structured media, oil has the property of thixotropy, which means that when the medium is shaken, its viscosity sharply decreases due to the destruction of the structural framework. Viscosity anomalies, i.e. dependence of effective oil viscosity on shear stress or velocity gradient have been observed.
studied by many authors [4 - 6]. Filtration of anomalous oils in a porous medium deviates from the Darcy and Newton laws. It has been found that high-viscosity oil (HVO) is characterized by a high content of high-molecular heteroatomic compounds (asphaltenes, resins) and paraffin [7]. According to the degree of dispersion, HVO belongs to colloidal systems. In this case, the dispersed phase is composed of solid components, and the dispersed medium is liquid hydrocarbons with dissolved gases [8 - 9].

In order to determine the prospects of plasma-pulse technology introduction for the extraction of heavy and high-viscosity oil, in Saint-Petersburg Mining University in 2009 laboratory measurements of the properties of high-viscosity oil from Tatarstan (ρ = 0.874 g / cm3, μ = 40.9 mPa · s) and Komi Republic (ρ = 0.94-0.97 g / cm3, μ = 710 mPa · s; asphaltenes -23%, paraffin -12%), treated by series of PPT pulses were carried out. The purpose of these studies was to study the possibilities of reducing the viscosity anomalies of high-viscosity oil (HVO) under plasma-pulse treatment. Detailed research results are presented in [10]. Briefly, the application of plasma-pulse treatment in the amount of 10 ... 40 pulses made it possible to reduce the effective oil viscosity up to 30%, and the signs of thixotropic properties up to 48%, depending on the processed oil. Based on the results of the studies, it was suggested that the use of PPT causes a dispersing effect on the major structure-forming components of oil - asphaltenes, resulting to decrease of the intensity of the thixotropic properties of oil.

In 2017, experts of the Novas group of companies and the Scientific Center for Nonlinear Wave Mechanics and Technology of the Russian Academy of Sciences carried out experimental research named “Intensity of pressure pulsations in the treated medium, changes in the rheological properties of oil as a result of PPT application” [11]. The treatment was carried out on 3 types of oil. Each type of oil under study was subjected to 100 PPT pulses, successively following each other. Samples of the studied oil were taken every 10 pulses to measure the rheological characteristics. The dynamic viscosity was measured at temperatures of 20°C, 40°C, 60°C.

The research results confirmed some decrease in the viscosity of the treated oil (4 to 8%), while it was noted that the effectiveness of the treatment of some samples becomes higher with an increase of their temperature. However, the quantitative effect of treatment applied to different oil samples can vary significantly. Apparently, the effectiveness of the impact is highly determined by the initial physical and chemical characteristics of the oil samples.

3. Research objects and methods of the experiment

During current experiment, three samples of commercial oil were selected for research. All samples were preconditioned in accordance with GOST R 51858-2002 “Oil. General technical conditions”.

Sample No. 1 is characterized by the following main indicators: oil density at 20°C - 942.3 kg/m³; mass fraction of water - 0.30%; mass fraction of mechanical impurities - 0.0126%; mass fraction of sulfur - 1.23%; mass fraction of paraffin - 1.5%; the bubble point - 77.2°C.

Sample No. 2 with the main parameters: oil density at 20°C - 823.9 kg/m³; mass fraction of water - 0.05%; mass fraction of mechanical impurities - 0.0036%; mass fraction of sulfur - 0.26%; mass fraction of paraffin - 21.9%; the bubble point - 46.4°C.

Sample No. 3: oil density at 20°C - 874.8 kg/m³; mass fraction of water - 0.03%; mass fraction of mechanical impurities - 0.0085%; mass fraction of sulfur - 0.84%; mass fraction of paraffin - 6.8%; the bubble point - 53.8°C.

All samples belong to the category of sulfur oils, samples No. 1 and No. 3 are heavy oils, sample No. 2 is highly paraffinic oil, which can also be classified as heavy. While preparing for the tests, it was noted that sample No. 2, upon contact with air in an open container, solidifies at room temperature and completely loses its mobility.

During the research work, reference samples of all oil samples were taken and subjected to the following studies:
- investigation of the oil flow curve at three temperature rates (5°C, 20°C and 40°C). The flow curve was compiled according to the results of measurements at 10 shear rates in the range of 0 ... 50 s⁻¹ during the forward and reverse motion;
- determination of oil density;
- investigation of the pour point;
- investigation of mechanical impurities;
- investigation of water content;
- investigation of the content of asphaltenes, resins and paraffins.

At the next stage, the oil samples were treated with plasma-pulse equipment with varying degrees of intensity. The treatment of the oil samples was carried out using a plasma-pulse generator "Plasma Streamer 102". The treatment was carried out in a cylindrical metal tank, positioned vertically and filled with oil to a level approximately 100 mm below the upper level. The tank has a volume of 40 liters and is made of aluminum with a wall thickness of 2.4 mm. The plasma-pulse generator was hanged vertically above the tank in such a way that its lower part was immersed into the oil being processed to a depth of 150-200 mm above the center of plasma emitter.

Initially, sample No. 1 was treated sequentially with 100 PPT pulses. Samples were taken from the vessel after 2, 10, 20, 40, 60, 80, and 100 pulses. The samples taken in this way in opaque sealed containers were numbered and sent to the laboratory for analysis.

Laboratory analysis was carried out using the following equipment:
- Anton Paar Rheometer MCR 302;
- Anton Paar DMA™ 4200M density meter;
- Mettler Toledo T5 automatic titrator;
- LECO Corporation CHN628 analyzer of carbon / hydrogen / nitrogen with an attachment for the determination of sulfur;
- Liquid cryothermostat LOIP FT-311-25.

A similar procedure was carried out for oil sample No. 3. The sample was exposed to plasma-pulse treatment in the range of 2 ... 80 pulses, samples were taken after 2, 10, 20, 40, 60, 80 pulses.

The results of laboratory analysis of samples No. 1 and No. 3 showed that the most noticeable changes in the rheological properties of the studied samples occur in the range of 0 ... 40 pulses. In this regard, the further research program was adjusted in such a way as to expose the samples in the range of 0 - 40 pulses with sampling after 1, 3, 5, 8, 14, 23 and 40 pulses. According to this program, oil sample No. 2 was also processed.

All treated oil samples were investigated with the same procedure as described above for reference samples, determining the major rheological parameters of oil.

At the final stage of the work, based on the results of the studies carried out on the change in the flow characteristics of the test samples, the parameters of PPT impact were determined, at which the greatest changes in such parameters were achieved. For each oil sample, the required number of PPT pulses was determined, most optimal in terms of changing their rheological parameters. After that all samples were re-processed with the selected intensity.

Further, the selected samples were examined for
- determination of the mechanical impurities content;
- determination of water content;
- determination of sulfur content;
- determination of asphaltenes, resins and paraffins content.

One of the oil samples, namely sample No. 2, which showed the greatest response to the PPT influence in previous studies, was also selected for studying the relaxation time by determining the flow curve at ambient temperature daily for 7 days, as well as determining pour point.

4. Laboratory studies results
Figures 1 shows the graphs of the viscosity dependence on the shear rate for oil sample No 1 at 5°C, 20°C and 40°C. Each curve corresponds to a certain number of PPT pulses. For comparison, a curve is provided that corresponds to the reference sample (before PPT). Based on the results of measuring the viscosity, density and pour point of oil, 5 PPT pulses were taken as the optimal impact for Sample No. 1.
Figure 1. Oil sample No.1 viscosity dependence on shear rate before and after PPT (5 pulses).

(a – at 5°C; b – at 20°C; c – at 40°C)

Figure 2 presents the graphs of the viscosity dependence on the shear rate for oil sample No 2 at 5°C, 20°C and 40°C. Based on the results of measuring the viscosity, density and pour point of oil, 8 PPT pulses were determined as the optimal impact for Sample No. 2.

Figure 2. Oil sample No.2 viscosity dependence on shear rate before and after PPT (8 pulses).

(a – at 5°C; b – at 20°C; c – at 40°C)

Figure 3 shows the graphs of the viscosity dependence on the shear rate for oil sample No. 3 at 5°C, 20°C and 40°C. Based on the results of measuring the viscosity, density and pour point of oil, 20 PPT pulses were determined as the optimal impact for Sample No. 3.
Table 1 presents the comparative results of measurements of water, sulfur, asphalt-resin-paraffin (ARP) substances content and the mass fraction of mechanical impurities in oil samples before and after PPT treatment.

**Table 1.** The results of measuring the content of water, sulfur, ARP and the mass fraction of mechanical impurities in the studied samples before and after PPT treatment.

| Sample No. | Water content, % | Sulfur content, % | ARP content | Mass fraction of mechanical impurities, % |
|------------|------------------|-------------------|-------------|------------------------------------------|
|            |                  |                   | asphaltenes, % | resins, % | paraffins, % |                                      |
| №1 before PPT | 0,34             | 1,23              | 6,9          | 15,3      | 0,1         | 0,03                                    |
| №1 after 5 PPT | 0,28             | 1,24              | 6,8          | 15,24     | 0,14        | 0,01                                    |
| №2 before PPT | 0,04             | 0,28              | 3,2          | 9,40      | 15,80       | 0,32                                    |
| №2 after 8 PPT | 0,06             | 0,33              | 3,15         | 9,23      | 15,56       | 0,24                                    |
| №3 before PPT | 0,11             | 0,86              | 5,0          | 13,3      | 4,9         | 0,03                                    |
| №3 after 20 PPT | 0,18             | 0,89              | 4,93         | 13,21     | 4,91        | 0,03                                    |

Oil sample No. 2, subjected to treatment with 8 PPT pulses was selected to assess the stability of the rheological properties of oil (viscosity and pour point) after plasma-pulse treatment in time. The study was carried out over seven days with the measurement of the viscosity and pour point values once a day. Figures 4 - 5 show the results of the relative measurements.
Figure 5. Oil sample No. 2 viscosity change after 8 PPT pulses, depending on the relaxation time at a maximum shear rate of 50 s\(^{-1}\).
(a – at 5°C; b – at 20°C; c – at 40°C)

5. Summary of the experimental results

The results of the studies allow us to conclude the possibility of using the technology of plasma-pulse treatment to increase efficiency and reduce costs when transporting oil through pipelines and the need for further, more detailed study of the ranges and mechanisms of treatment in order to achieve the optimal effect. The difference in the effect of PPT treatment on different types of oil is associated with the different content of ARP components and volatile components.

Following the research results oil sample No. 1 has a general trend of viscosity decrease after plasma-pulse treatment with a local minimum of viscosity when exposed to 3-14 pulses. The maximum efficiency was shown by treatment with 5 pulses, while there was a decrease of viscosity by 5.3%, 4.7% and 4.8% at temperatures of 5°C, 20°C and 40°C respectively.

Oil sample No.2 has shown also a general trend of viscosity decrease after plasma-pulse treatment with a local minimum of viscosity in the range of 5-15 pulses. The sample demonstrates the best tendency to decrease in viscosity after exposure to 8 pulses. It should be noted that the nature of the decrease of viscosity in the temperature range varies. At 5°C, a change in the structural state of oil was observed, a thickening caused by a transition to a coherent-dispersed state, which, with an increase in shear rate and temperature, becomes a free-dispersed state, that contributes to a decrease in viscosity. At 5°C, a decrease in viscosity characteristics is particularly noticeable on the reverse motion (up to 30%), at 20°C, oil has reduced its viscosity to the maximum rate (more than 40%), and at 40°C, the changes are not so notable (15%).

When studying the stability of the rheological properties of oil Sample No. 2 after 8 PPT pulses during the first seven days after oil treatment, it is observed the following:

- preservation of the oil viscosity parameter during the first three days and its further increase achieving of viscosity value as before PPT after 4-6 days;
- a decrease in the pour point of oil during the first three days and its further increase achieving the pour point values as before PPT on the 4-th day;

Thus, it is possible to take the relaxation time for oil sample No. 2 in this experiment equal to 4-6 days.

Evaluating the results of Oil sample No. 3 studies, there is also a general trend of viscosity decrease after PPT treatment with a local minimum of viscosity after 20 pulses, at which a decrease in viscosity
by 10%, 12% and 14% has been achieved at temperature of 5°C, 20°C and 40°C respectively. In this case, the dependence of viscosity on the number of pulses demonstrates a highly nonlinear and non-monotonic character.

For all tested samples, within the margin of error, no influence of PPT on the density and pour point of the tested oil was revealed.

In general, the results of the studies carried out have shown that the plasma-pulse effect is capable to affect the mobility of oil without deteriorating its consumer quality. The considered technology allows to reduce the viscosity of oil (depending on the initial characteristics) up to 40%, provided that the optimal treatment mode is selected.

At the same time, oil processing using the PPT technology showed high economic efficiency. Considering the technical characteristics of PPT equipment (each pulse consumes 1125 J) provided in [12], we can calculate amount of energy required for treatment of oil samples. Dividing it by volume of oil in each test we obtain an average energy consumption for oil processing during the experiment - 0.075 kWh/m³, which indicates a significant energy efficiency of the investigated technology. Moreover, by scaling up the experiment to large volumes of treated oil, the unit rate of energy consumption shall become significantly lower.

6. References

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