Applying the technology of hydrodynamic cavitation treatment of high-viscosity oils to increase the efficiency of transportation

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Abstract. The article investigates the possibility of applying hydrodynamic cavitation treatment to reduce oil viscosity in Russian pipeline transportation system and increase its performance. The result of laboratory tests and suggestions on technology application are given.

1. Introduction
Modern oil industry of the Russian Federation is characterized by the growth of viscous (further VO) and high-viscosity (further HVO) oils in a total structure of hydrocarbon reserves. Developing fields with prevalence of VO and HVO is a perspective direction from the point of view of their high quality and special rheological characteristics. According to data of 2014, the HVO fraction from the total makes up almost 30 % or 7.5 billion ton, and over the last years, since 1992, this fraction has been constantly growing [1].

The conducted analysis of economic efficiency of VO and HVO extraction and transportation is characterized by their unprofitability or small profitability. Large Russian companies, such as OJSC “NK Rosneft” and OJSC “AK Transneft”, annually invest sufficient financial resources in perfecting the transportation process and modifying VO and HVO rheological characteristics. The most common ways of treating raw materials in order to achieve large transportation rates are:

• Thermal heating
• Adding dopants and diluents
• Applying electromagnetic radiation

Thermal heating is the most common and effective, but at the same time the most expensive method of treatment, performed by means of oil heaters. According to JSC “Transneft – Siberia”, along the entire route of the oil main Zapolyarye – Purpe there will be constructed eight points of oil heating to treat northern VO under low temperature conditions [1]. Currently, for oil preheating tubular sectionalized furnaces (PTB-10/TSF-10) are used. Their basic characteristics are presented in Table 1.

Fuel used for operation of such furnaces is gas distillate. Taking into account that the cost of gas for large industrial enterprises of Yamal-Nenets autonomous region and Tyumen region is on average 2848 rbl./m³, approximate losses on oil heating per 1°C account for 280 000 roubles a year at pumping volume of 1 million ton [2]. Over the year, the expenditure on heating will account for 252 million roubles.

Unfortunately, thermal oil heating is dependent on economic conditions in the country. If we assume that on average the price for 1000m³ of gas rises annually by 15 % for the needs of industrial
enterprises, and the minimum gas consumption at heating points (based on the throughput capacity of the oil main “Zapolyarye – Purpe” of 30 million ton) will comprise 2.8 million m³ a year, application of more power-intensive and energy resource effective technologies of transportation is of vital importance[3].

| Parameter                  | Value                  |
|----------------------------|------------------------|
| Output by product          | 900 m³/hour            |
| Fuel power                 | 4.2 GJ/hour            |
| Operating pressure         | To 6.4 MPa             |
| Oil temperature at the output | Not above 70 °C       |
| Consumable fuel            | Gas distillate         |
| Number of burners          | 4 pieces KC-400        |
| Performance efficiency, %  | 71                     |
| Heat losses at operation, %| 8                      |

2. Research

According to foreign scientists, such as Hemmit F. and Dejli J., from the American Society of Mechanical Engineers, the most perspective is the hydrodynamic cavitation treatment characterized by its performance, profitability and possibility to use internal reserves of the material to change rheological characteristics of oil (plastic viscosity, pour point, etc.). Within the framework of realization of the grant given by OJSC “AK Transneft” the authors have investigated the cavitation phenomenon and the possibility of combining cavitation with pour point depressants to improve the efficiency, and the hydrodynamic equipment has been designed.

The cavitation phenomenon arises at the moment when the fluid pressure and the fluid saturated vapor pressure become close. At close values the fluid emanates plentiful bubbles (caverns) filled up with dissolved gas[4]. The collapse of the bubble is characterized by sharp jumps of temperature and pressure, and propagation of the energy wave facilitates breaking down of nearby carbonaceous chains and molecular compounds. The quantity of bubbles can vary from $10^4$ to $10^6$.

Figure 1 shows simulation of the hydrodynamic cavitation process due to pipeline section change by means of ANSYS/FLUENT software. The obtained data and dependences have been taken into consideration when conducting laboratory tests.

Figure 1. Distribution of a thermal field during cavitation
Zone 1 – a preheat zone, zone 2 – a zone of cold boiling, zone 3 – flow and thermal field stabilization.
Simulation has demonstrated that when high-viscosity oil passes through a narrowed section there is a local rise in temperature on the working chamber – diffuser boundary, which is a precondition for economic profit.

Figure 2 shows a laboratory unit; cavitation equipment is in the bottom left-hand corner and Figure 3. Tests involved such equipment as the centrifugal pump and cylindrical tubes of 3 cm² in diameter. Pour point depressant DPN-1R (produced in Russia) was tested; about 200 liters of high-viscosity Usinsk oil $\rho = 945$ kg/m³ and $\nu = 150$ mPa·s have been treated.

The minimum oil flow rate in the module required for cavitation to emerge is determined by the formula (1):

$$V_{kav} = \frac{64 \cdot P_n}{g \cdot P_{nv}} \left( \frac{29 \cdot \rho \cdot g}{P_n} \right)^{1.9}$$

(1)

$P_{nv}$ – critical cavitation pressure (Pa)
$P_n$ – saturated vapor pressure (Pa)

Required pump head for cavitation to emerge:
\[ N_{to} = \frac{V^2_{To}}{2g} + h_M, \]  

(2)

where \( h_M \) – total head loss in the module, m;

Total head loss in the module is made up of head losses in the confuser, diffuser and cylindrical part of the module and is calculated by the formula:

\[ h_M = \left( \frac{\lambda}{8\sin\frac{\alpha}{2}} \left(1 - \frac{1}{n_1^2}\right) + \frac{\lambda}{8\sin\frac{\beta}{2}} \left(1 - \frac{1}{n_1^2}\right) + \sin\beta \left(1 - \frac{1}{n_1^2}\right) \right) \frac{V^2_{To}}{2g}, \]  

(3)

where \( \beta \) – expansion angle of a diffuser, degree; \( n_1 \) - expansion ratio of a diffuser, \( \alpha \) – expansion angle of a confuser, degree; \( n \) – contraction ratio.

During laboratory tests it has been revealed that the least pressure loss is observed in confusers with the expansion angle of up to 40° and the contraction ratio of 1.2 – 3.0 and in diffusers with the expansion angle of less than 50°.

The final form of the formula of head looks as follows:

\[ N_{to} = \frac{V^2_{To}}{2g} \left( \xi_r + \xi_f + 1 \right), \]  

(4)

The conducted studies have demonstrated that complex oil treatment is a perspective direction Table 2 and Figure 4.

**Table 2.** Comparative analysis of efficiency of oil viscosity reduction methods.

| Characteristics                  | DPN-1R | Cavitation treatment | Complex treatment |
|----------------------------------|--------|----------------------|-------------------|
| Depression T, °C                 | 10–14  | 5–7                  | 17–20             |
| Viscosity reduction, %           | 42-57  | 32-40                | 66-70             |
| Dynamic stress reduction         | 2–3    | 4                    | 6-7               |
| Static stress reduction          | 4-5    | 3-4                  | 5-7               |
| Time to restore rheological      | 1      | 5                    | 4                 |
| characteristics, days            |        |                      | 7                 |

**Figure 4.** Storage Age-Dependence of Dynamic Viscosity.
Due to local pressure changes and, thereof, emergence of conditions for cavitation and breaking of fluid continuity, energy is released. The released energy is equivalent to oil temperature changes at an average density of 945 kg/m$^3$ and viscosity of 150 mPa·s by 2-3 °C. Both computer and real models have demonstrated a 94.6 % convergence. Because initial oil heating temperature can be changed, financial expenditures [5, 6] also change.

3. Conclusion
The analysis and calculations carried out by the authors demonstrate that application of cavitation treatment to reduce economic load is substantiated and leads to economic benefits [7]. The expediency and efficiency of applying complex oil treatment consists in the following:

- Increase of initial heating temperature of a high-viscosity oil by 2-3°C due to cavitation treatment;
- Reduction of oil viscosity due to a complex method that in turn will lead to reduction of the power and fuel consumption by heaters;
- Improvement in rheological characteristics of oil due to breaking down of carbonaceous connections that will positively affect further petroleum transportation and refining, allowing for increase in the yield of light cuts during atmospheric rectification.

The applied technology can be used on field or technological pipeline systems with diameters up to 300 mm and viscosity values of transported oil 150-200 mPa·s.

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