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Improvement of hydro-transport of highly viscous heavy oil in a two-phase annular flow

Rinat M. Karimov · Jing Jiaqiang · Guo Yuyin · Radmir R. Tashbulatov · Anvar R. Valeev · Alexander V. Kolchin

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Abstract. *The results of experimental studies focused on the developing effective special pumping methods for collecting and long-distance transportation of highly viscous extra-heavy oils extracted from hard-to-recover deposits of natural bitumen and kerogen shale are presented. To eliminate the widely used "hot methods" of pumping, which are associated with the risks of thawing permafrost and high greenhouse gas emissions, new methods have been proposed for practical implementation and improving the efficiency of an underutilized hydro-transport technique.*

A concept and devices have been developed to create a stable annular flow of water and foam. A specially designed mixer ensures the tangential injection of water into the oil flow, forming the required streamlines for creating a water ring. In certain cases, the hydraulic resistance reduction effect can exceed 80%, and the pressure drop during hydro-transport of heavy oil within the water ring is comparable to that of water pumping.

Based on the research results, the maximum achievable hydraulic effect of the proposed method was evaluated, and key research directions were formulated to enhance the stability of the structured annular "oil-in-water" flow in long-distance horizontal pipelines, including the use of ultrasonic and magnetic treatment methods.

Keywords. annular two-phase flow · near-wall water-foam layer · extra-heavy viscous oils · hydraulic resistance reduction agents · hydro-transport.

Mathematics Subject Classification (2010): 76T10

Rinat M. Karimov, Radmir R. Tashbulatov, Anvar R. Valeev, Alexander V. Kolchin
Ufa State Petroleum Technological University, Ufa, Russian Federation
E-mail: karimov_rinat@mail.ru

Jing Jiaqiang, Guo Yuyin
Southwest Petroleum University, Chengdu, People's Republic of China
E-mail: jjq@swpu.edu.cn

1 Introduction

According to ExxonMobil [11] (Fig. 1), global energy demand is expected to increase by 15% by 2050. It is projected that oil and natural gas will continue to account for more than 50% of the world's energy supply. As oil production declines by 5-7% per year [11], the reserves of more accessible "light" oil will also be depleted. Consequently, the profitability of future projects will largely depend on the efficiency of new technologies for developing hard-to-recover reserves (HRR).

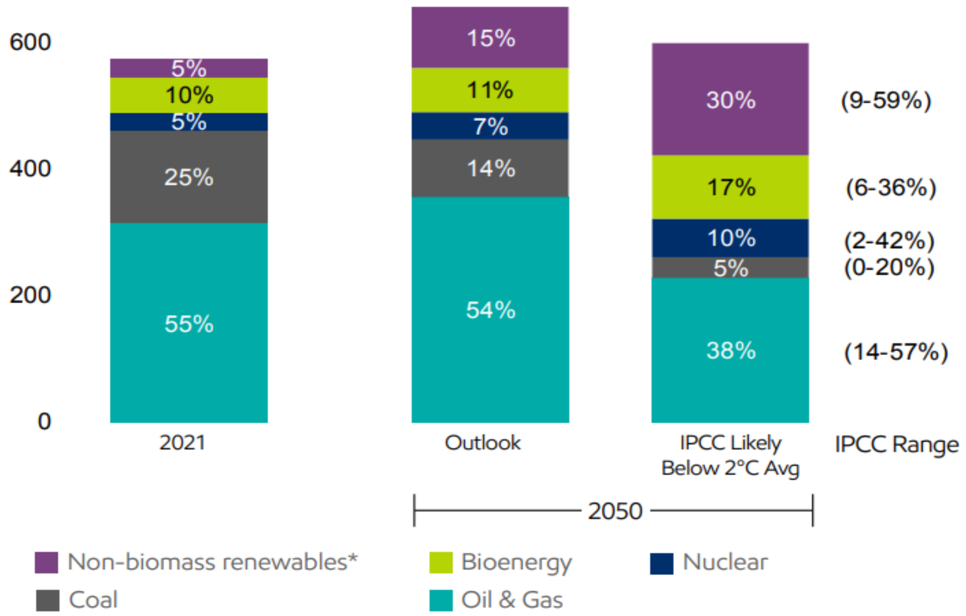


Fig. 1. Global energy mix

The extensive long-term practical experience in developing heavy oil resources (including heavy oil, natural bitumen, and kerogen-rich oil shales) leaves no doubt that such deposits, which are widespread in major oil-producing countries, could become the primary resource base in the medium term.

At the same time, since pipeline transportation—both field and trunk pipelines—is the most cost-effective method for delivering crude oil over long distances [10], the feasibility of developing hard-to-recover reserves will largely depend on the advancement of more efficient specialized pumping methods. For instance, hot oil transportation helps address flowability issues; however, it is associated with significant direct thermal energy costs and substantial indirect expenses, such as increased greenhouse gas emissions from boiler fuel combustion and the risk of permafrost thawing in areas with permanently frozen or seasonally thawing soils [24].

Given the current industry landscape and the global environmental agenda emphasizing decarbonization, there is a growing need for more efficient solutions for the development, transportation, and processing of ultra-heavy, high-viscosity crude oil that minimize thermal and chemical impacts.

2 Methods

Years of experimental and theoretical research have led to the development of various flow assurance (FA) methods for stabilizing the transportation of high-viscosity crude oil. One such method, rooted in earlier hydraulic transport technologies, involves creating and maintaining a boundary smoothing/wetting annular layer of a less viscous phase along the inner pipeline surface, within which the highly viscous heavy oil core is transported.

By injecting and swirling a low-viscosity medium (such as water, gas, or foam) along the pipeline walls, this approach reduces hydraulic resistance [14]. This method not only minimizes friction but also helps prevent paraffin deposition on pipeline walls by flushing away accumulating residues.

The origins of these techniques trace back to the early development of hydraulic transport technologies for high-viscosity crude oil. However, progress was initially hindered by challenges in separating ultra-viscous stable emulsions (due to the high content of resins and asphaltenes in crude oil) and the complexity of designing internal helical surfaces within steel pipes to maintain the annular layer.

Today, with advancements in specialty oilfield chemicals and pipeline engineering, the industry has made significant strides in optimizing chemical formulations and developing specialized polymer coatings for steel pipelines-solutions that now make it possible to handle even more complex transportation scenarios.

In certain cases, the reduction in hydraulic resistance can exceed 80%, and the pressure drop during the hydraulic transport of heavy oil within a water annular layer is comparable to that of water alone [1].

A study in [6] illustrates the experimental results using crude oil with a viscosity of 5 Pa·s (5000 cP). The authors found that by optimizing the parameters of annular flow, the hydraulic resistance could be reduced by more than 90% (Fig. 2).

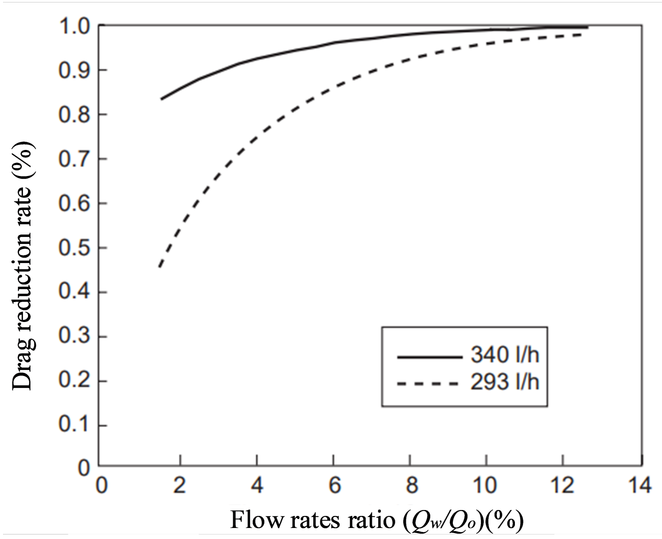


Fig. 2. Effect of oil-water flow ratio on DR rate under fixed total flow rate

To quantify the effectiveness of this method, the Frictional Pressure Gradient Reduction Factor (RF) [20] is used. This factor characterizes the ratio of pressure drops between a single-phase crude oil flow and a two-phase annular oil-water flow at the same oil volumetric flow rate.

Additionally, measurements were taken for extra-heavy crude oil with a viscosity of approximately 37 Pa·s (37,000 cP), which was transported through glass and steel pipelines. The results showed that the hydraulic efficiency factor reached a value of 156.

Nevertheless, despite advancements in science and technology within the industry, the challenge of maintaining a stable annular layer under changing flow conditions in long-distance pipelines remains a pressing issue.

For example, an experiment on a heavy oil pipeline operating with an annular water layer at a flow velocity of 1.5 m/s showed that deposits formed on the inner pipe wall, leading to a significant increase in pressure drop from 0.207 MPa to 1.172 MPa [3].

To implement the hydraulic transport method for high-viscosity heavy oil in a water-foam annular layer, a special chamber-generator was developed to create the annular boundary layer in the oil-water flow. Its design ensures the required flow path directions and streamlining patterns (Fig. 3) [16].

As the oil-water mixture flows through the chamber, it forms a vortex-shaped annular flow, which remains stable across a wide flow rate range. To achieve this, the device includes a special vortex generator, a cyclone tube, and an outlet for excess water phase removal.

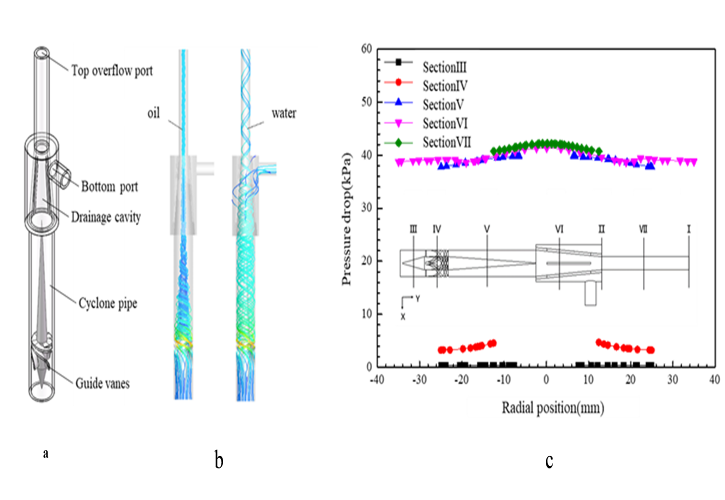


Fig. 3. Lubricating elements - (a) structure; (b) streamline distribution; (c) resistance characteristics

Results

Hydrotransport in a water ring with additives. In order to improve the efficiency of two-phase hydraulic transport to create a smoothing ring around the flow of high-viscosity oil, a series of experimental studies have been conducted to investigate the effect of water properties on the stability of the annular two-phase oil-water flow. It is known that aqueous solutions of polymers and surfactants (surfactants) have viscoelastic properties that can dampen turbulence in the near-wall layer, as well as prevent the destruction of the structure of the annular flow. It has been found that the addition of a certain volume of non-ionogenic polyacrylamide (PAM) to the aqueous phase forming a smoothing film near the pipe wall can increase the stability of the oil-water annular flow [18]. The value of hydraulic resistance when adding polymer additive is significantly reduced simultaneously due to stabilization of two-phase annular flow and damping of turbulence in the near-wall layer. Fig. 4 shows the results of research on the effect of PAM addition on the pressure drop when pumping high-viscosity oil in the water ring. The results confirmed that hydraulic resistance can be significantly reduced by adding water-soluble antiturbulence additives to the water phase.

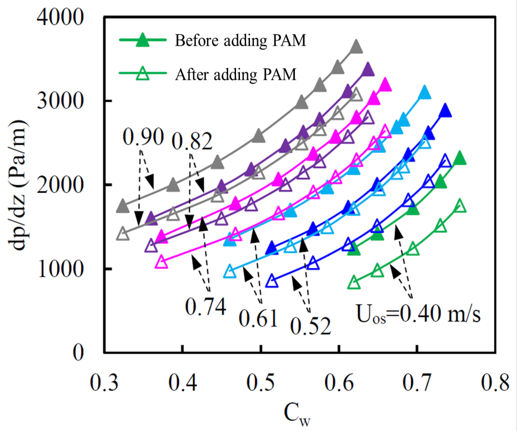


Fig. 4. Effect of adding polyacrylamide (PAM) to the aqueous phase on specific pressure drop under the annular mode of oil flow in water

Hydrotransportation in a water-foam ring layer. Despite the fact that the technology of hydrotransportation of high-viscosity oil in a water ring has an insignificant level of energy consumption and is, with a closed cycle of water use, environmentally friendly, the stability of the ring structure during pumping over long distances through horizontal pipelines is difficult to ensure in practice, which limits the process of its implementation. It has been proved that gas microbubbles in the boundary layer of the outer water flow ring can further reduce the hydraulic resistance [12, 13, 19, 26]. In addition, it is already known that water-foam flooding can provide enhanced oil recovery - the fluidity of foamed oil (high-viscosity oil containing a large number of microbubbles) increases several times [22].

Based on the above-mentioned studies, a new concept of hydrotransport using a water foam ring instead of water has been proposed [15]. In this case, although the water foam disintegrates during the pumping process, the method remains effective due to the fact that the microbubbles migrate to the upper pipe formation due to the density difference, while the water or water solution released from the foam migrates to the lower part of the pipe, as shown in Fig. 5. Furthermore, when the oil flow in the core is surrounded by water foam, the risks of oil bubbles sticking to the walls are reduced, and the flow structure becomes more stable than that of the heavy oil-water annular flow structure. In addition, the water-foam ring technology can significantly reduce the amount of water required, improving environmental friendliness and reducing the cost of separation in the treatment facilities.

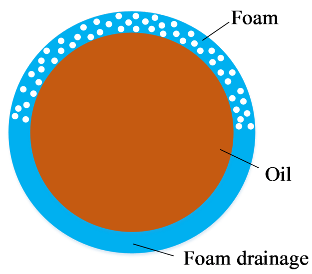
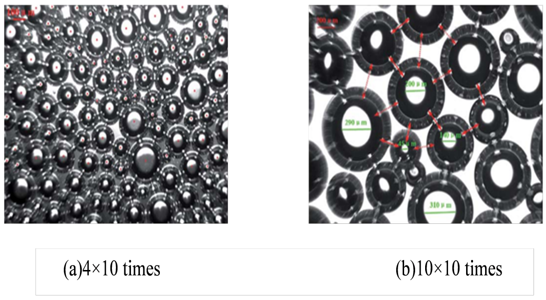


Fig. 5. Degradation of oil ring flow in a water-foam ring

Experimental results showed that when the ratio of oil and water flow rates is greater than 0.1, a sliding layer of two components can be formed between the oil and the wall of the pipe, consisting of foam in the upper formation and water released from the solution on the lower formation of the pipe, and the effect of reducing hydraulic resistance can reach more than 70% [25]. Experimental studies in vertical pipes have confirmed the efficiency of the water-foam ring layer obtained with the use of AFS-2 foaming agent, which isolates the oil flow from the pipe wall - the value of the effect of hydraulic resistance reduction exceeded 50% at the value of the ratio of mass flow rates of foam to oil from 0.18 to 0.24.

The efficiency of the considered methods is primarily influenced by the composition and ratio of phases, the design of mixing and foaming chambers, on which the stability of the annular layer depends [18]. Studies of the foam microstructure obtained by the orthogonal method showed that the water-foam layer retains stability at high oil and salt content and collapses, flowing to the lower-forming pipe, at high oil temperatures.



(A) magnification 4×10 **(B) magnification** 10×10
Fig. 6. Microstructures of foam under different magnifications at 20°C

Discussion

The exact prediction of the magnitude of pressure drop and flow structure are the main tasks for practical realization of hydraulic conveying in two-phase annular flow regime. By now, a rich theoretical and experimental experience of such studies has already been accumulated. The model obtained by Brauner allows to calculate quite accurately the pressure drop and conditions of oil retention in two-phase annular flow [8]. This study contributed to the development of the theory of annular flow in liquid-liquid systems. Later, Amery and Tirandaz [2] developed a wave model describing the pressure drop in annular flow (WCAF). In this model, factors such as boundary layer perturbation, wave surface shape and slip coefficient were taken into account. Salin and Talon [21] proposed a model to describe the pressure drop in annular flow of two-phase flow based on a linear theory that simultaneously accounts for differences in viscosity, density and inertia force. Strazza et al [23] studied the characteristics of annular two-phase flow of oil-water system in horizontal and inclined pipelines (at small inclination angles) to determine the transition region and pressure drop distribution along the pipe. The experimentally measured pressure gradients were compared with the calculated ones obtained by Brauner [7], Arney [4] and Bannwarth [5] and it was concluded that all these models are in agreement with the experimental data.

3 Conclusion

Stability of the annular foam layer on longer horizontal pipelines can be achieved by chemical agents and special additives. Adjusting the density difference between the aqueous and oil phases, using ionogenic surfactants (surfactants) to control the degree of emulsification of the mixture can increase the efficiency of the methods. The presence of natural surfactants and particles in oil - paraffins, asphaltenes and resins on the contrary - promotes sedimentation and accumulation of oil droplets on the wall. Influence of the latter factor can be reduced by adding sodium silicate to the aqueous phase. Increase in the roughness of the wall and the presence of corrosion marks on it can increase both hydrophilicity and lyophilicity, which weakens the forces of adhesion of the inner surface with liquid droplets.

It is worth noting that the achieved results of increasing hydraulic efficiency in pumping heavy extra-viscous oils in a water-foam ring are not the limit. In the development of this direction it is supposed to study the influence of magnetic and ultrasonic treatment, based on their application together with surfactant methods of creating stable fine dispersed inverse and reverse-inverted emulsions of both water-hydrocarbon and bi-oil types [28, 29], addition of low-boiling agents to the cold oil flow, which form a boiling layer of gas bubbles in the near-wall area at the pipes, creating the slippage effect [9, 27, 30].

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