Improving the Efficiency and Transportation of High-Viscosity Oils by Emulsification and Creating a Coaxial Flow

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Abstract. Currently, high-viscosity oil fields are actively developed in the world. This is due to the depletion of world reserves of light oils and a significant resource of heavy high-viscosity oils. The viscous oil production requires a solution to the issue of its transportation, which becomes much more complicated. This is determined by greatly increasing pressure loss due to hydraulic resistance when pumping heavy oil. To reduce the loss of the head, the pumped oil viscosity should be decreased. Viscosity can be reduced through heating, dilution with a less viscous petroleum product, emulsification, and creating a coaxial flow. The heating and dilution techniques are very widely used in world practice, however, other ones, i.e. emulsification and creating a coaxial flow are also very promising; the essence of these techniques is a different way of introducing additional fluid and creating a two-phase system that facilitates the oil transportation.

1. Introduction

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1.1. Relevance. Literature review

The relevance of the topic under consideration is primarily determined by the constant global demand for hydrocarbon feedstock; the light oil reserves are gradually depleting, therefore, the need for the transportation of high-viscosity petroleum products is growing.

1.2. Formulation of the problem

The transportation of high-viscosity oil is complicated by significant hydraulic resistance. The research objective is reducing the pumped oil viscosity by emulsification and creating a coaxial flow.
2. Theoretical experimental research

2.1. Reducing viscosity by emulsification

Emulsification is one of the newest ways of transporting heavy oil through a pipeline as an oil-in-water (O/W) or a double water-in-oil-in-water (W/O/W) emulsion with a droplet size of about a micron. Preparing an oil-water emulsion is an alternative technology to increase the heavy oil fluidity when pumping through a pipeline. In this case, heavy oil is transformed into an oil-water emulsion and stabilized using surfactants. Oil is dispersed in water in the form of small droplets using surfactants, and we get a stable low-viscosity oil-water emulsion [1, 3]. The ways of forming droplets to prepare an emulsion require the use of such equipment as dispersants, stirring rotor-stator mechanisms, colloid mills, high-pressure and high-shear stress homogenizers, as well as obtaining an emulsion using membranes and ultrasonic waves [1]. Possible emulsion types are shown in Figure 1.

![Figure 1. Different Emulsion Types.](image)

The use of surfactants and water to create a stable oil-water emulsion with heavy oil to improve the efficiency of its pipeline transportation has become the subject of several studies and numerous patents. When pumping heavy high-viscosity oil as an oil-water emulsion, heavy high-viscosity oil does not contact with the pipeline surface; thereby, the risk of oil adsorption on the pipeline walls is significantly reduced. As a result, the oil-in-water structure has significantly less hydrodynamic friction compared to anhydrous oil flow.

A monomolecular surfactant layer is formed at the oil and water interface, Figure 2, preventing the growth of droplets and the stratification of the emulsion into individual oil and water phases during transportation. Water is the hydrophilic part of the mixture, while oil is the hydrophobic one. In the monomolecular layer at the oil-water interface in the composition of the emulsion, the near-polar area (the hydrophilic ‘head’) of the surfactant contacts water, and the non-polar ‘tail’ (the hydrophobic area) contacts oil, as shown in Figure 2. Due to the properties of this adsorbed layer, the water-oil surface stabilizes, and the emulsion behavior is controlled [4].

![Figure 2. Surfactant-Stabilized Emulsion.](image)

It should be considered that heavy high-viscosity oil is a complex mixture of hundreds of thousands of different components. Asphaltenes act as natural emulsifiers. Other active surfactants in oil are naphthenic acid, resins, porphyrins, etc. [4]. The presence of these components increases the oil emulsion composition complexity since their molecules can interact with each other and regroup at the oil-water interface. In this case, the transportation of heavy oil as an emulsion requires three processing stages, i.e. preparing an oil-water emulsion, transporting the emulsion prepared, and
separating the oil and water phases. Separating oil-water emulsion into phases is required to extract oil. To do this, the technologies have been developed, including thermal, electrical, and chemical demulsification, freezing and thawing, pH change, solvent addition, and demulsification using membranes [5, 6].

Another important criterion for improving pipeline transport efficiency is the rheological properties of the emulsion prepared. The rheological properties of the emulsion depend mainly on the dispersed oil volume and the droplet size distribution [7]. The droplet size distribution depends on surfactant type, mixing energy, and pressure. As a rule, non-ionic surfactants such as Triton X-114 are used due to their ability to withstand the salinity of the water obtained; also, they are cheap, and the emulsion prepared on their basis is easily separated; they also do not form unwanted organic residues negatively affecting the oil properties [9]. Thereat, the heavy oil emulsion demonstrates either Newtonian behavior at a high shear rate or that characterized by a decrease in shear viscosity at a low shear rate [3, 10]. The resulting emulsion fluidity depends on the properties of the polar hydrophilic ‘head’ and the non-polar hydrophobic ‘tail’ of the surfactants used. It is interesting to use biological surfactants to obtain an emulsion, which significantly reduces the negative impact on humans and the environment due to much less activity and easier processing.

The main emulsion characteristic is dispersity, i.e. the degree of the dispersed phase fragmentation in a dispersion medium. Many other emulsions properties depend on dispersion.

The dispersion measure is the specific interfacial surface \( S_{SP} \), m\(^2\), i.e. the ratio of the total surface of droplets to their total volume, determined by the formula:

\[
S_{SP} = \frac{S}{V},
\]

where: \( S \) is the surface area, m\(^2\), \( V \) is the system volume, m\(^3\).

Dispersion is the reciprocal of the droplet diameter: \( D = \frac{1}{d} \), where \( d \) is the droplet diameter.

There are a huge number of techniques to create an emulsion: simple agitation, stirring using a rotor-stator system, injecting fluid through a porous membrane or using high-pressure units, etc.

When using the above-listed heavy high-viscosity oil emulsion demulsifying procedures, such factors as the close heavy oil and water density values, a large amount of asphaltenes in heavy oil, or, more commonly, amphiphilic molecules leading to creating stable emulsions should be considered.

The use of oil-in-water emulsions to reduce the heavy crude oil and bitumen viscosity is being actively studied to provide an alternative to using diluents or heating to reduce the heavy oil viscosity in pipelines. Moreover, the emulsion viscosity is much less sensitive to temperature than other heavy oil transportation techniques.

From the practical use point of view, for this technique, the convenience of obtaining, transporting, and storing the emulsion, a sufficiently high decrease in the viscosity of heavy high-viscosity oil and stability under dynamic transportation conditions like in static ones in the case of the pipeline shutdown, and the possibility of separating oil and water after transportation can be emphasized.

The main issues of the heavy oil transportation include the cost of surfactants and the choice of their type, the surfactant ability to maintain the emulsion stability when pumping it through the pipeline, the complexity of separating water from oil at the final stage given that the heavy oil density is close to that of water, and the need to consider the emulsion properties such as rheological characteristics and stability, which depend on several parameters, including droplet size distribution, temperature, salinity and pH of water, the heavy oil composition, mixing energy, and volume ratio of oil and water [11]. Also, the presence of natural hydrophilic particles such as clay and silica in the composition of oil may cause emulsion instability [4]. Various mechanisms that may lead to destabilizing an oil-water emulsion include Ostwald ripening, sedimentation, or foam formation due to different densities of products, and coalescence of droplets. The main task of the surfactant is stabilizing the emulsion under the effect of the shear force and reducing the surface tension at the
interface. Sometimes an oil-water emulsion contains solid particles and gases, which further complicate the process. In general, the smaller the droplet size, i.e. 10 μm or less, the higher the emulsion stability [4]. As a rule, the heavy oil-in-water emulsion behavior is complicated due to the interaction of various components in this system and other above-listed factors.

A decrease in the volume of water in the mixture impairs the emulsion stability. An increase in the transported water volume improves the emulsion stability, but the energy consumption to pump ballast (water) grows. Experiments have shown that the minimum amount of water should be about 30 % of the total volume of the transported mixture. The disadvantage of this pumping method is the risk of phase inversion, i.e. transformation of an oil-in-water emulsion into a water-in-oil one when the pumping speed or temperature changes. Transporting oil-water emulsions through pipelines with intermediate pumping stations is also undesirable since phases are dispersed in the pumps, and such emulsions are then difficult to destroy.

The standard emulsion consists of 70 % oil and 30 % water with a surfactant content of 500-2,000 ppm. The emulsion prepared in this way has a density within 50–200 cP under the pipeline operating conditions (Figure 3) and is also especially stable. The emulsification technique for pumping heavy high-viscosity oil is most widely used in Venezuela to sell ORIMULSION [14]. The extraction of oil from the emulsion for further processing requires its separation into phases, and such technology is still not available in Venezuela. The issues associated with the water reuse remain unresolved.

![Figure 3. Reducing the Heavy Oil and Bitumen Viscosity by Transforming Them into an Oil-Water Emulsion [3].](image)

3. Reducing the oil viscosity using coaxial flow

The high viscosity of bitumen and heavy oil leads to a significant drop in the head during their transportation through the pipeline, which does not allow simply pumping oil as a single-phase flow. A way to reduce the pressure drop in the pipeline under the friction force effect during the transportation of bitumen and heavy high-viscosity oil is creating a coaxial flow. The basic principle of this technology is that the central heavy oil flow in the pipeline is surrounded by a thin layer of water or solvent near the pipe walls, which acts as a lubricant maintaining the pressure required to pump water or solvent inside the pipe. In this case, water, or solvent flows through the pipe in the form of an annular stream, while heavy oil is the flow core inside the pipeline (Figure 4).
The technique for transportation of heavy high-viscosity oil by creating a coaxial flow is based on the natural physical property of less viscous fluids to flow to the pipeline surface and form an intermediate layer separating the heavy high-viscosity oil and the pipeline wall.

The coaxial flow can be created in various ways: using factory-made screw threads or spiral-welded metal strips (wires) of the required size and with a given pitch (Figure 5 a), water supply through ring couplings with tangential holes located perpendicular to the oil flow (Figure 5 b), or laying an oil pipeline with perforated walls inside the pipeline of a larger diameter and pumping water between them (Figure 5 c). Only the first two techniques of creating an annular water layer have become somewhat widespread.

Figure 4. An Example of a Coaxial Flow Injector Configuration.

![Coaxial Flow Injector Configuration](image)

Figure 5. Pumping Heavy High-Viscosity Oil Inside an Annular Water Layer: a - Creating an Annular Water Layer Using Screw Thread; b - Creating an Annular Water Layer Using Ring Couplings; c - Creating an Annular Water Layer Using a Perforated Pipeline.

![Pumping Heavy High-Viscosity Oil](image)

The required amount of water is 10–30% of the coaxial flow volume [1]. As a result, the pressure drop along the pipeline length depends insignificantly on the heavy oil viscosity and turns out to be very close to that when pumping water. Also, Benzakharia et al. [15] have discovered that if heavy oil is in the pipe center, and water flows near the surface of its walls, the head drop is reduced by more than 90% as compared to flow without water lubrication.

Coaxial flow refers to the two-phase flow of a fluid inside a pipeline. In this mode, water or solvent is near the pipe wall and serves as a lubricant for the central heavy oil flow. In this case, the core heavy oil flow moves virtually in a piston mode (flow mode with a structural core). However, pumping water and oil through a pipeline as a two-phase flow allows the creating of several flow regimes, depending on the oil properties such as density, surface tension, flow shear rate, and the fluid pumping rate.

This technique allows for reducing the pressure drop to a level close to that of pumping water. Pressure surges and drops are reduced throughout the entire pipeline length. Another advantage of this technique is the comparative availability and low cost of water.

However, it has serious limitations. E.g., an ideal coaxial flow can be achieved in very rare cases of fluids with the same density [15]. A group of scholars [16] has found that waves are formed at the water and oil interface, which leads to the creation of a wavy coaxial flow. Also, if the density difference between oil and water is significant, the buoyancy force creates a radial motion of the
central oil flow. As a result, the central flow part is displaced towards the upper pipeline wall, as shown in Figure 6, i.e. a feature of this technique is an unstable annular flow regime, at which the desired transportation efficiency is achieved. The flow rate and capillary instability caused by surface tension lead to the disturbance of the flow core. Thereat, an increase in the flow rate leads to the growing stability of its core. Studies have shown that it is quite difficult to ensure the stability of all transportation parameters. Thus, at a stable ratio of heavy oil and water volumes, the annular flow regime is unstable at a low flow rate. With a growing flow rate, friction between the fluids increases. Stabilizing the configuration requires special observations and periodic system adjustments.

![Figure 6](image)

**Figure 6.** Radial Oil Position in the Central Flow Part: a – ideal coaxial flow; b – flow at different densities. C is the perimeter of contact between the oil phase (flow core) and the pipe wall.

An unstable annular flow regime at the commercial application of this technique requires a special design of the entire pipeline system (particularly, a special calculation of the pumping station capacity, geometry, etc.), and the development of special procedures for the system startup and shutdown. It seems that the issue of developing special procedures for the system startup and shutdown is a significant limitation of the technique since it requires the use of special additional management approaches.

Also, the flow stability is still a subject of research [16, 17]. With an increase in the pumping distance, gravitational stratification of oil and water inevitably occurs, which leads to a sharp increase in the pressure drop in the pipeline. To ensure the stability of the near-wall water layer, a surfactant is added to it. The surfactants used are organic compounds, the molecules of which have a polar (hydrophilic) group and a non-polar (hydrophobic) chain. The hydrophilic part of the molecule can be nitrogen-containing groups. The hydrophobic part consists of a paraffinic chain or aromatics. Surfactant molecules are oriented in such a way that their polar part faces the water, and hydrocarbon radicals face oil. At the phase interface, surfactants form a thin film preventing the mixing of fluids. On the other hand, the surfactant layer adsorbed on the pipe surface prevents its wetting with oil and ensures the stability of the near-wall water layer. However, even in the presence of surfactants, the near-wall water layer gradually destroys, and the stratification of oil and water occurs.

Another issue of this technique is that oil tends to stick to the pipeline wall, which leads to partial or complete blockage. This issue can be exacerbated during the shutdown, which leads to the formation of water and oil layers, and a significant initial head is required to restart.

4. Conclusions

The use of an oil-water emulsion is an effective technique for reducing the viscosity of heavy high-viscosity oil when pumping it through a pipeline. However, this viscosity reducing method has serious technical difficulties. The main difficulty of pumping heavy high-viscosity oil using this technique is choosing a surfactant for specific oil, capable of maintaining the emulsion stability throughout the entire pipeline, and ensuring the possibility of low-cost extraction of oil and the surfactant from the emulsion at the end pipeline point. If the surfactant or its concentration is chosen improperly, the oil-in-water emulsion may transform into a water-in-oil one, which extremely negatively effects on oil transportation through the pipeline. The use of this technique in the practice of foreign companies is
limited. The use of the emulsification method will be justified only after the preliminary technical and economic calculations and rationale of its use.

The coaxial flow creating technique is an effective way to improve the performance of the main pipelines. However, it still has not received wide commercial application since it is difficult to achieve the stability of the annular flow regime, at which the required transportation efficiency is reached. This technique is under active development.

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