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RHEOLOGY OF A HEAVY CRUDE OIL

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Received: 01.03.2023
Accepted: 26.07.2023

The growing demand for oil is encouraging the development of heavy oil and bitumen, the world's huge energy reserves. However, their high viscosity is a big problem in their use, because they cannot be transported without a proper method. A number of methods have been developed to transport heavy oil, including diluents, heated pipelines, emulsions, and crude oil upgrades.

It is known that the common characteristics of heavy oil are high viscosity, high specific gravity, high molecular content and low hydrogen-to-carbon ratio, high carbon residues, and high content of asphaltenes, heavy metals, sulfur, and nitrogen. Heavy oils are a strategic source of hydrocarbons because their reserves are on the same scale as those of conventional oils. The production of these raw materials remains low, especially due to their very high viscosities.

Heavy oil rheology problems caused by the hydrodynamic interaction of heavy particles in oil (asphaltenes, paraffin, resins, and solid phase particles) were considered in the research work. Transporting heavy crude oil requires the viscosity to be low enough so that pipeline size and pumping requirements are economically optimal. There are several methods to achieve these properties, some of which have been validated in the field and are currently in use, while others are under development.

In our current research work, we have analyzed some of these methods and given our recommendations for improving the rheology of heavy oils for the future.

Keywords: *rheology, heavy crude oil, oil emulsions, viscosity, oil-in-water emulsions, water-in-oil emulsions.*

DOI: https://doi.org/10.59849/2409-4838.2023.3.20

INTRODUCTION

There are more than 150 different types of crude oil in the world. Heavy crude oils are less expensive for a refinery to purchase but more expensive to refine since they have greater costs from higher energy inputs and additional processing to meet environmental requirements.

Refineries process crude oil into a wide variety of refined products. The refining process separates, breaks down, reformates, and recombines the molecules of crude oil into refined products [1].

Each type of crude oil yields different types of refined products. Light crude oil is primarily used to create fuels such as gasoline, diesel, and jet fuel. Heavy crude oil provides feedstock for petrochemicals, other fuels, and road surfaces. Heavy oil can also be converted into transportation fuel.

Crude oil plays a very important role in countries that are in dire need of fuel, be it for industrial consumption, electricity, or transportation mobilization. Economic development and spectacular population growth in recent decades have led to increased demand for fossil fuels, which has resulted in the gradual depletion of conventional oil reserves, including light and medium crude oil reserves, which have become scarce and insufficient to meet ever-increasing oil reserves. Unconventional oil resources, including heavy oil, extra-heavy oil, shale, oil sands, tar sands, and bitumen, are alternative resources to fossil fuels [2]. However, unlike conventional oil, which is characterized by low production costs, unconventional oil cannot be recovered and then transported in its natural state by conventional production and transportation methods, generally requiring additional requirements to ensure its flow at acceptable flow rates. In the future, heavy and extra-heavy oils are expected to be an excellent alternative to conventional oil, but the complexity of their composition makes their flow extremely difficult under natural conditions without the problem of flow assurance.

Crude oil with API specific gravity below 20^0 is called heavy oil, and those below 10^0 are called extra heavy oil. Heavy oil cannot flow due to its high viscosity. Some researchers have explained the possible reason for the high viscosity of heavy oil. According to them, oil has evolved from natural source materials and has become heavier as a result of the elimination of lighter fractions through natural processes. A high proportion of asphaltene molecules that replace hetero-atoms in the carbon network, such as nitrogen, sulfur, and oxygen, also plays an important role in oil hardening. Therefore, heavy oil, regardless of its source, always contains heavy fractions of asphaltenes, heavy metals, sulfur, and nitrogen. Large asphaltene molecules determine the increase or decrease in density and viscosity of the oil. Removal or reduction of asphaltene dramatically affects the rheological properties of a particular oil [3].

Heavy oil/bitumen is characterized in terms of SARA fractions and divided into four different pseudo-components such as saturates, aromatics, resins and asphaltenes. A four-parameter equation of state developed by Adachi et al is used to calculate the values of solubility parameters, molar volume, and density of each SARA fraction [4-8].

Asphaltenes are defined as the heaviest compounds in crude oil that are completely soluble in aromatic solvents such as toluene and precipitate when paraffinic solvents such as n-alkanes are added.

Asphaltenes constitute the most refractory, polar, and heaviest component in crude oil [9]. Because of these distinctive characteristics, asphaltene is considered a prime factor that causes difficulties in many petroleum operations such as production, transportation, refining, even wax crystallization, crude oil emulsification, and de-emulsification. Any thermodynamic changes in pressure, temperature, or oil composition can cause asphaltene deposits, which result in many problems in transmission, production, and processing facilities in the oil industry.

The problems caused by the presence of asphaltene do not depend only on the amount of asphaltene in the oil. What is important is the stability of those asphaltenes, and stability depends on how well the rest of the oil is a solvent for the asphaltenes [10].

Many experimental methods are available to detect asphaltene precipitation, such as gravimetric, acoustic resonance IFT measurement, dynamic method, high-pressure microscopy, and infrared spectroscopy. In addition to experimental measurements, a large number of thermodynamic models have been used to model asphaltene precipitation and predict its onset point, including the solid model, micellization model, colloid model, solubility model, and equation of state models [11-13]. The solid model is the simplest model for predicting asphaltene precipitation, which treats asphaltenes as a single solid component and evaluates the behavior of other phases with an equation of state. However, the problem with this model is that it requires a lot of empirical parameters and experimental data. The colloidal model presented by Leontaritis [14] uses VLE calculation and EOS to estimate fluid composition. In this model, asphaltenes are treated with solid colloidal particles surrounded by large resin molecules and suspended in crude oil. On the other hand, in the dissolution model, asphaltenes are dissolved in the solvent liquid state and form a uniform solution [15]. Among the many thermodynamic approaches used to predict asphaltene precipitation, regular solution theory along with the equation of state models are the most common methods [16, 17].

METHODS FOR RECOVERING HEAVY CRUDE OILS

Oil is kept in the reservoir mainly due to capillary, gravity and viscous forces. It was determined in the research that the interaction between these forces during oil flow in a porous medium can be measured by capillary number and mobility ratio [18]. Capillary number (Ca) is defined as follows:

$$Ca = \frac{\eta v}{\gamma} \quad (1)$$

Here, η - is the viscosity of the liquid, v - is the flow rate through the pores, and γ - is the interfacial tension between the liquids.

Fluid mobility in porous media is determined based on the Darcy equation.

$$u = \frac{k}{\mu}\frac{dP}{dx} \quad (2)$$

u - Darcy surface velocity of liquid, k - conductivity, μ - viscosity, P - pressure, x - length.

For 1 phase, k represents the absolute conductivity, and for multiphase flow, the effective conductivity. The mobility of the liquid phase is defined as follows:

$$\lambda = \frac{k}{\mu} \quad (3)$$

Then the mobility speed

$$M = \frac{\lambda_2}{\lambda_1} \quad (4)$$

M-is an important parameter in displacement processes, it expresses the dimensionless viscosity ratio given by parameters λ_1 and λ_2 [19].

Transportation of heavy crude oil and natural bitumen requires viscosity to be low enough for pipeline size and pumping requirements to be economically optimal.

There are several methods to achieve these properties, some of which have been validated in the field and are currently in use, while others are under development. These methods are:
Effect of heat
Effects of diluents
With O/W emulsions
Core annular flow
Partial field upgrading

RHEOLOGICAL BEHAVIOR OF HEAVY CRUDE OIL BY HEAT TREATMENT

The thermal impact is a widely used method to reduce the high viscosity of heavy crude oil and improve flow in pipelines. Pipeline heating (ie, raising the temperature) results in a rapid reduction in viscosity to reduce the oil's resistance to flow. Figure 1 shows the viscosity response in the heat treatment temperature range of 30–60° for heavy crude oil at different shear rates. The fan-shaped rheogram shows the effectiveness of the method in improving flow characteristics, since the viscosity between the flowing feedstock and the pipe wall, and therefore the shear stress, decreases by several orders of magnitude with increasing temperature. When the raw material is heated to a temperature above 40°C, the rheological properties remain practically unchanged at higher shear rates and the slopes of the plots begin to decrease, indicating good flow behavior. The unique behavior of crude oil can be explained by the high paraffin content and the average paraffin-to-resin ratio, which indicates the change in structural properties and destruction of the chemical structure of heavy components of crude oil [20].

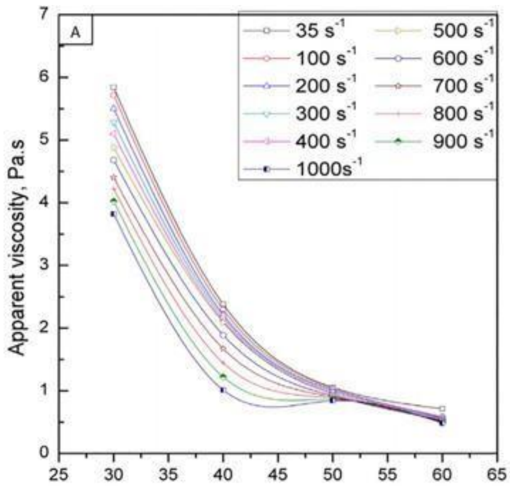

Fig. 1. Viscosity response of heavy oil in the heat treatment temperature range of 30–60° [21]

Figure 2 shows the effect of temperature on the typical flow behavior of heavy crude oil in terms of viscosity-shear rate. The figure clearly demonstrates the non-Newtonian shear thinning behavior in the range of shear rates where the apparent viscosity decreases significantly with temperature. This also shows that the differences in viscosity are greater at low shear rates than at high shear rates. This can be attributed to the strong effect of temperature on the viscosity and chemical structure of heavy crude oil components such as wax and asphaltene [12]. In addition, the viscosity of heavy crude oil is shear rate dependent, meaning that flow encounters less resistance at higher shear rates. As the shear rate increases, the chain-like molecule unwinds and reorients parallel to the driving force, reducing the viscosity of heavy crude oil. Therefore, the apparent viscosity depends on the shear rate at constant temperature and decreases with increasing temperature [23].

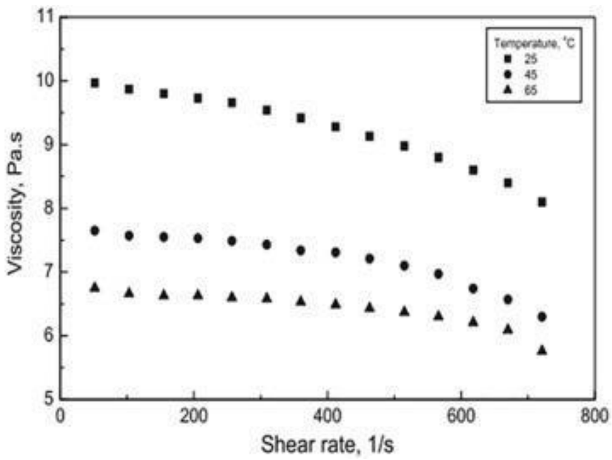

Fig. 2. Apparent viscosity as a function of shear rate of heavy crude oil at different temperatures [22]

In research studies [24-32], heating to raise the temperature of crude oil requires a considerable amount of energy and cost. Other problems include higher temperatures, greater internal corrosion due to the large number of heating stations required, and heat losses along the pipeline due to the low flow of heavy oil. However, in most cases, the pipeline is insulated to maintain high temperatures and reduce heat loss to the environment. In addition, sudden expansion and contraction along the pipeline can cause difficult problems. As a result, the cost of operating heating and pumping systems over long distances between the oil field and the final storage or processing plant is high [33]. This may not be a viable method for transporting crude oil through subsea pipelines. Finally, the cooling effect of the surrounding water, as well as the soil, reduces the efficiency of the method.

RHEOLOGICAL BEHAVIOR OF HEAVY CRUDE OIL IN WATER EMULSION

One of the effective ways to reduce the viscosity of heavy oil is the formation of oil-in-water emulsions with the help of surfactants.

Emulsions consist of a dispersion of an immiscible liquid (dispersed phase) in another liquid (continuous phase), usually with a drop size in the micrometer range. They generally fall into three categories (Figure 3): oil-in-water (O/W), water-in-oil (W/O), and complex or multiple emulsions. Many emulsions have continuous-phase droplets within dispersed phase droplets such as oil in water (W/O/W). In the emulsification method, droplets from the oil phase are dispersed into the water phase using suitable surfactants to form a stable oil-water emulsion. Thus, the formation of an emulsion significantly reduces the pour point as well as the viscosity of crude oil. Since water is a stable phase, the risks of wax deposits on the pipe surface, clogging of pipelines and corrosion are avoided. Optimizing the economics of the transportation process is always a priority for the oil industry. For maximum efficiency and economy, it is important to keep the oil content as high as possible while minimizing the viscosity of the crude oil. For efficient transportation of heavy crude oil, a stable oil-water emulsion must be prepared so that the water does not separate until it reaches the desired destination. Techniques used to create oil droplets to form emulsions include the use of devices such as dispersers, rotor-stator mixing, colloid mills, high-pressure homogenizers that apply high shear stresses, membrane emulsification, and ultrasonic waves.

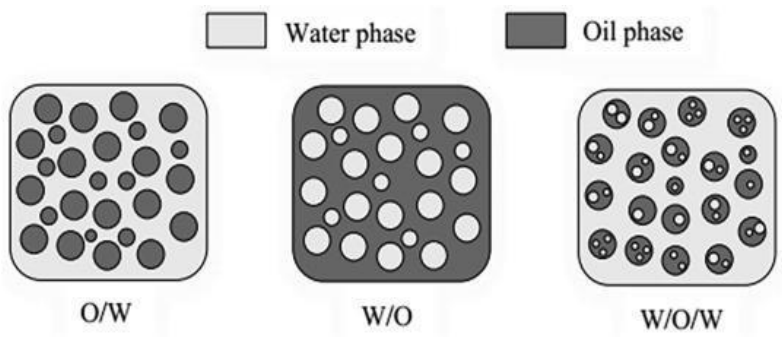

Fig. 3. Classification of oil emulsions [32]

CORE ANNULAR FLOW METHOD

The core annular mode flow is another method used to increase the transport of viscous crude oil. This method is based on the development of a core annular flow (CAF) to reduce pressure loss caused by friction in the pipeline. In this method, a less viscous fluid, such as water, is introduced into the flow to act as a lubricant that absorbs the shear stress that exists between the pipe walls and the fluid, thus reducing the resistance to flow and creating an overall pressure drop [33].

This method can be problematic because the crude oil tends to stick to the walls of the pipeline, thereby restricting and eventually clogging the flow system. Such problems are exacerbated where the flow has to be stopped for a period of time, allowing oil and water phases to stratify and increase oil adhesion. Restarting flow in such a stopped system may require a large pressure, possibly exceeding the pressure rating of some or all components of the flow system. In such a problem, it is also mandatory to flush the flow system to remove the adhering oil, which leads to additional costs and the failure of the flow system. A lot of work has been done in this direction to solve the problem.

PARTIAL UPGRADING METHOD

Another method of transporting heavy oil is to change it before it is transported. Partial upgrading is the process of changing the composition of crude oil by making it less viscous, without significantly changing its processing characteristics. Full upgrading completely changes the crude composition, turning it into a light synthetic crude oil that is more convenient to transport and more valuable [34].

The main advantage of this technique is that crude oil can be transported without any changes in the pipeline system.

Another advantage of this process is that it does not accumulate large volumes of coke by-product that must be stored or transported offsite. The produced coke is consumed by the process itself and converted into energy on the spot.

CONCLUSION

Despite the recent discoveries of huge oil fields consisting of conventional oils, heavy oil and bitumen still constitute a large part of the world's oil reserves. If the price of oil is favorable and suitable technology is available to produce and transport these oils, heavy oil reserves can be essential to meet the global energy demand for fuels and oil derivatives. The transportation strategy of these oils depends on the oil properties such as viscosity, API weight and asphaltene content and the potential to obtain high value products after the distillation process.

In this research work, several factors influencing the rheology of heavy oil raw materials were analyzed and various models were considered. At the same time, transportation of viscous oils, various methods of reducing their viscosity were considered. Many methods have been proposed to transport heavy oils; however, many of them fail in terms of commercial application either as a recovery method or as a pipeline flow improvement method.

An increase in temperature significantly reduces the viscosity of the raw material, which indicates a change in the rheological behavior. As the temperature increases, the viscosity of the heavy crude oil decreases, reducing the shear stress between the circulating crude oil and the pipe wall, thereby reducing the pressure drop and ultimately improving transportability. However, it has disadvantages such as high capital cost and fuel consumption, as well as difficulty in restarting after shutdown. In addition, special design, insulation, and welding technology degrees are required to manage the transportation of this type of pipeline.

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AĞIR XAM NEFTİN REOLOGİYASI

F.R. Şıxıyeva, V.İ. Kərimli, M.R. Manafov

Artan neft tələbatı dünyanın nəhəng enerji ehtiyatları olan ağır neft və bitumun inkişafını təşviq edir. Lakin onların yüksək özlülüyü onların istifadəsində böyük problemdir, çünki lazımi üsul olmadan nəql edilə bilməz. Ağır neftin daşınması üçün bir sıra üsullar işlənib hazırlanmışdır ki, bunlara duruldurucuların, qızdırılan boru kəmərlərinin, emulsiyaların və xam neftin təkmilləşdirilməsi daxildir.

Məlumdur ki, ağır neftin ümumi xarakterik xüsusiyyətləri yüksək özlülük, yüksək xüsusi çəkisi, yüksək molekulyar tərkibi və aşağı hidrogenin karbona nisbəti, yüksək karbon qalıqları və asfaltenlərin, ağır metalların, kükürdün və azotun yüksək tərkibidir. Ağır neftlər karbohidrogenlərin strateji mənbəyidir, çünki onların ehtiyatları adi neftlərin ehtiyatları ilə eyni miqyasdadır. Bu xammalların istehsalı, xüsusən onların çox yüksək özlülüklərinə görə aşağı olaraq qalır.

Tədqiqat işində neftin tərkibindəki ağır hissəciklərin (asfaltenlər, parafinlər, qatranlar və bərk faza hissəcikləri) hidrodinamik qarşılıqlı təsiri nəticəsində əmələ gələn ağır neft reologiyası problemlərinə baxılmışdır. Ağır xam neftin daşınması özlülüyün kifayət qədər aşağı olmasını tələb edir ki, boru kəmərinin ölçüsü və nasos tələbləri iqtisadi cəhətdən optimal olsun. Bu xüsusiyyətlərə nail olmaq üçün bir neçə üsul var ki, onlardan bəziləri sahədə təsdiqlənib və hazırda istifadə olunur, digərləri isə inkişaf mərhələsindədir.

Hazırki tədqiqat işimizdə biz bu üsullardan bəzilərinin analizini aparmış və gələcək perspektiv üçün ağır neftlərin reologiyasının yaxşılaşdırılmasına dair öz tövsiyələrimizi vermişik.

Açar sözlər: *reologiya, ağır xam neft, neft emulsiyaları, özlülük, suda neft emulsiyası, neftdə suda emulsiyası*

РЕОЛОГИЯ ТЯЖЕЛОЙ НЕФТИ

Ф.Р. Шихиева, В.И. Керимли, М.Р. Манафов

Растущий спрос на нефть стимулирует разработку тяжелой нефти и битума, огромных мировых запасов энергии. Однако их высокая вязкость является большой проблемой при их использовании, поскольку их нельзя транспортировать без надлежащего метода. Был разработан ряд методов транспортировки тяжелой нефти, включая разбавители, обогреваемые трубопроводы, эмульсии и обогащение сырой нефти.

Известно, что общими характеристиками тяжелой нефти являются высокая вязкость, высокий удельный вес, высокое молекулярное содержание и низкое отношение водорода к углероду, высокое содержание углеродистых остатков и высокое содержание асфальтенов, тяжелых металлов, серы и азота. Тяжелые нефти являются стратегическим источником углеводородов, поскольку их запасы не уступают запасам обычных нефтей. Производство этого сырья остается низким, особенно из-за его очень высокой вязкости.

В работе рассмотрены проблемы реологии тяжелой нефти, обусловленные гидродинамическим взаимодействием тяжелых частиц в нефти (асфальтены, парафины, смолы, частицы твердой фазы). Транспортировка тяжелой сырой нефти требует, чтобы вязкость была достаточно низкой, чтобы размер трубопровода и требования к перекачиванию были оптимальными с экономической точки зрения. Существует несколько методов достижения этих свойств, некоторые из которых были проверены в полевых условиях и используются в настоящее время, а другие находятся в стадии разработки.

В нашей текущей исследовательской работе мы проанализировали некоторые из этих методов и дали свои рекомендации по улучшению реологии тяжелых нефтей на будущее.

Ключевые слова*: реология, тяжелая нефть, нефтяные эмульсии, вязкость, эмульсии масло-в-воде, эмульсии вода-в-масле*