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A Review of Improving the Heavy Crude Oil Transportation Process Using Additives

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ABSTRACT

Transporting heavy crude oil from the wellhead to the oil refineries. It is essential because worldwide oil production is on the rise. These oils are characterized by high viscosity and low API gravity. Due to these specifications, the flow of oil through pipelines is complex, and to facilitate its transportation, it must be treated. In this paper, the additives that reduce the viscosity and density of crude oil and reduce the asphalt materials in it, which, if their percentage increases, are deposited in the transport pipelines. Additives are not only to reduce the viscosity and density of heavy oils, but their use aims to reduce the content of asphalt and sulfur materials and as a result of all this friction and pressure losses between crude oil and pipes will be reduced during transportation, with a decrease in viscosity and density of crude oil will increase its movement, and with a reduction in sulfur content will reduce corrosion that causes severe damage to pipes. Solvents (such as naphtha, toluene, gasoline, and kerosene), surfactants (including petroleum sulfonates and polymeric surfactants), and nanoparticles (like Al_2O_3 and Fe2O3) are the key additives that enable this enhancement and optimization for the transportation of crude oil through pipelines. One of the essential additions that improves heavy crude oil is the addition of solvents with low viscosity and density. These solvents reduce the viscosity of heavy crude oil, decrease the proportion of metals such as nickel and vanadium, and lower the sulfur content in crude oil.

Introduction

The growth of the world's population, combined with the limited industrialization of developed countries and a significant increase in energy consumption, has led to a rise in global demand for crude oil. However, one of the significant challenges is the decline in light crude oil reserves, which would prompt major international companies to focus on exploiting heavy and extra-heavy oils to meet energy requirements due to limited extractable oil capacity. Heavy crude oil and bitumen are defined as crude oil with an API gravity of 22 or less (denser than water) [1]. Despite the importance of reserves for heavy crude oil, which is larger in size than light oil, one of the significant challenges is in its development, production, and refining, as these processes are complicated due to its chemical and physical properties. In particular, it has a high density and high viscosity. Hence, its attractiveness is low due to the high API and high hydrocarbon content. It usually contains HO and EHO with a high percentage of compounds

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and components that are Heavy, Such as resins and asphalt compounds, which reduce the attractiveness of the API and significantly increase the raw viscosity [2]. API gravity is a qualitative gravimetric property that defines the quality of crude oil in terms of its lightness or heaviness. According to the American Petroleum Institute (API), the relative density of all different petroleum liquids, whether crude oil or petroleum products, is expressed in degrees. The lower the API number, the heavier the crude oil or oil product, and the greater its specific gravity. The important and distinctive properties of heavy crude oil are that it has a high viscosity, a high specific gravity, a high molecular structure, a low hydrogen-to-carbon ratio, a high carbon residue, and a high content of asphalt, heavy metals, sulfur, and nitrogen [3]. For the optimization required to transport heavy crude oil to the surface, heating stations and pumping pipes employ conventional techniques, including emulsifying and diluting with less viscous solvents, as well as reducing friction [4, 5]. And with all this, all these techniques are considered remarkably expensive. Due to the high global demand for raw materials and the urgent need to transport them over long distances through large pipelines, the need for additional operations to transport crude oil has become crucial [6, 7]. Therefore, numerous papers have been presented that highlight the various techniques available to improve the movement of heavy crude oil, along with their advantages and limitations [8]. The search for new technologies to improve the process of heavy crude oil flow is of great importance, so nanomaterials appeared as a new and alternative technology to reduce the viscosity of heavy crude oil and improve its other specifications, because of the specifications and features of nanomaterials, nanoparticles, and flood parts, which made them very useful [9, 10]. The usual techniques for transporting heavy and very heavy oil are expensive and expensive in addition to being dangerous, so nanotechnology has emerged as a complementary technology that can strongly compete technically and economically because it shows high and distinctive potential, which leads to improving the movement of oil due to the reduction of viscosity, which occurs through the interaction of fine particles with the asphaltene in the crude [11]. When particles are reduced to the nanoscale, they are characterized by their high absorbency because the ratio of the mass of adsorbent to the volume of solution (A/V) is very high [12]. In addition, the nanoscale is not a problem in blocking the porous grooves of conventional crude oil deposits, because its surface is known to have a significant affinity with the asphaltene found in crude oils, which is much greater than the affinity of crude oil it is significantly larger than the convergence of asphaltene aggregates of crude oil, so it is expected that when this happens, the molecular weight of these aggregates will also decrease, so a significant decrease in viscosity is obtained [13]. Petroleum is the most important consumer material worldwide [14]. Because the oil product not only provides raw materials for the petrochemical industry and other products, but also serves as a fuel for energy, heating, and transportation, it is utilized in all industries [15]. Petroleum consists of many organic compounds, in particular hydrocarbons, trapped in special geological formations with a trace of water and minerals [16]. The composition of crude oil encompasses a diverse range of hydrocarbons with varying organic functions, sizes, and molecular weights [17]. This configuration varies depending on the age of the field, the depth, and the location of the tank [18]. The following is a brief description of the diverse chemical families identified in crude oil [19]. Kinds of paraffin are saturated hydrocarbons (ordinary and isoparaffin, respectively), and these compounds (paraffin) are considered to have branched chains or straight chains. These chains are connected by single covalent bonds between carbon atoms. Paraffinic oils are white oils. Naphthene is a cycloparaffin. They are molecules with a saturated ring structure, and the saturated ring contains 5, 6, or 7 carbon atoms. Most naphthenes have paraffinic side chains with more than one ring in the molecule. Mononaphthene, di-naphthene, and tri-naphthene. Also, the rings can be merged or unintegrated [20]. Compounds containing at least one benzene ring are aromatic hydrocarbons, such as monophenyl, diphenyl, and triphenyl. Crude oil fragrances typically contain paraffin side chains and may also include naphthalene rings [21]. The non-molten and molten rings in this group of hydrocarbon compounds are aromatic and naphthenic. Aromatic compounds increase significantly with the increase in the number of rings due to the large number of possible formations of naphthalic and aromatic rings and side chains [22]. All heterogeneous compounds are considered hydrocarbon compounds of the classes mentioned above, where one or more heterogeneous atoms (N, S, O, V, NI, FE) are part of the molecule. The presence and elasticity of these heterogeneous atoms contribute to the complexities of hydrocarbon structures. Heterogeneous compounds are typically part of the high-molecular-weight fractions of petroleum liquids [23]. Heavy oil and bitumen make up 70% of the world's oil reserves, as shown in Fig. 1.

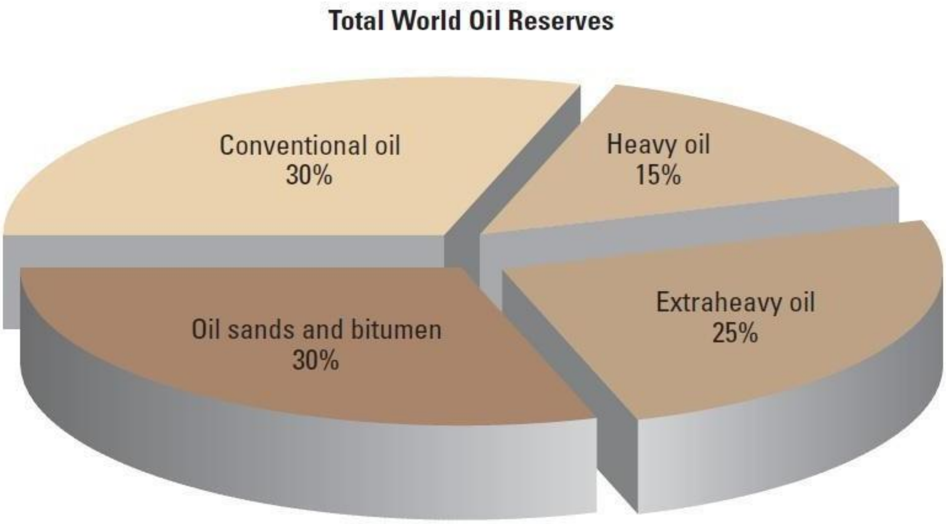

Fig. 1. Total distribution of oil reserves in the world by classification [24]

It is known that unconventional oil reserves have a very high resistance to flow and transfer, and their density is significantly higher than that of conventional oils (Fig. 2) [25].

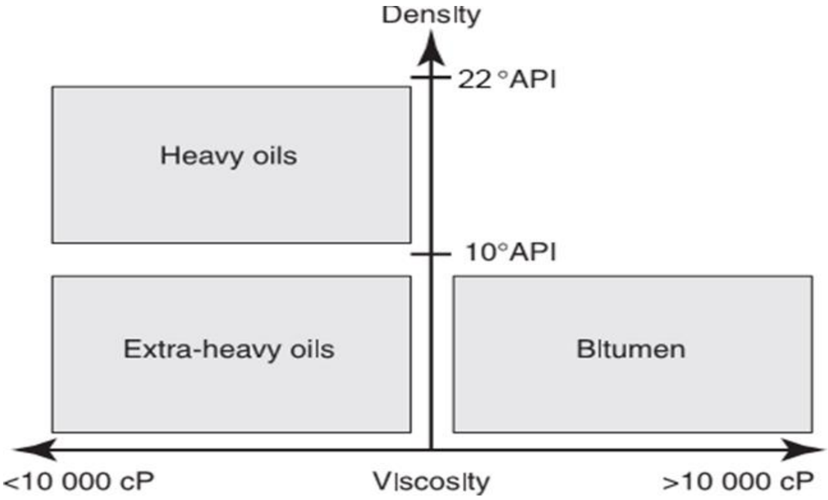

Fig. 2. Values for API of different oils [26]

Fig. 3 illustrates the very popular oil split. The knowledge of the type of oil and the determination of its physical properties is done through the most famous and prominent chemical sections in the liquid [27]. Generally, paraffin oils have lower boiling points, viscosities, and densities than naphthene oils. The most excellent boiling points, viscosities, and densities have been found in oils with a high content of heterogeneous and aromatic compounds. This classification clearly shows that conventional oils are the most common, comprising both naphthenic and paraffinic liquids, while heavy, very viscous, and bitumen oils contain a high percentage of hydrocarbons, polar, and aromatic heterogeneous compounds [28, 29].

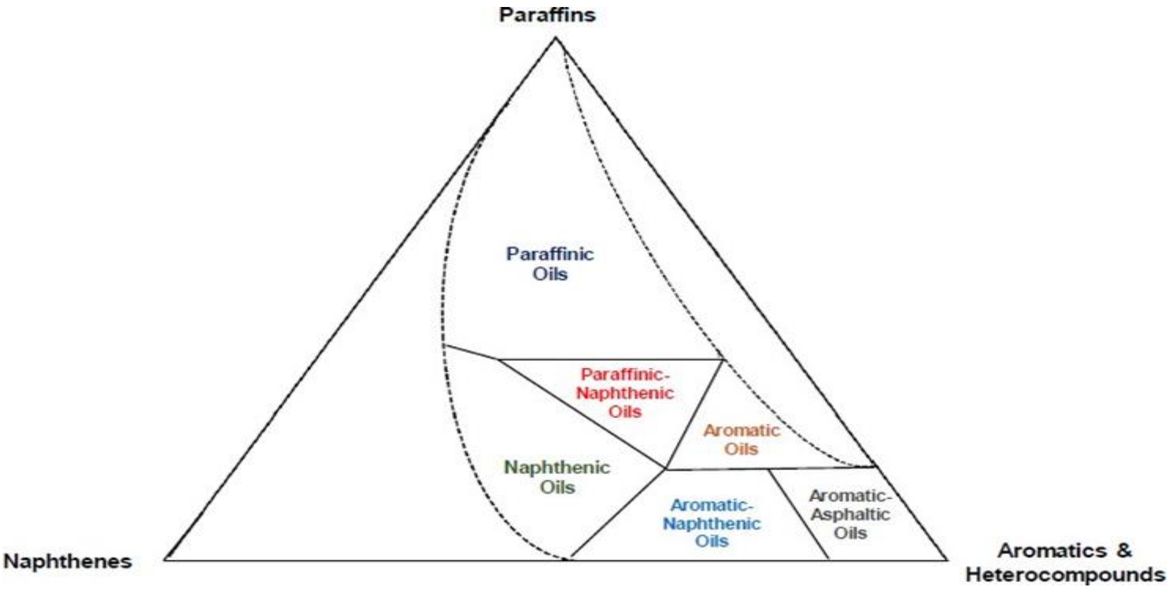

Fig. 3. The types of crude oil in different regions [30]

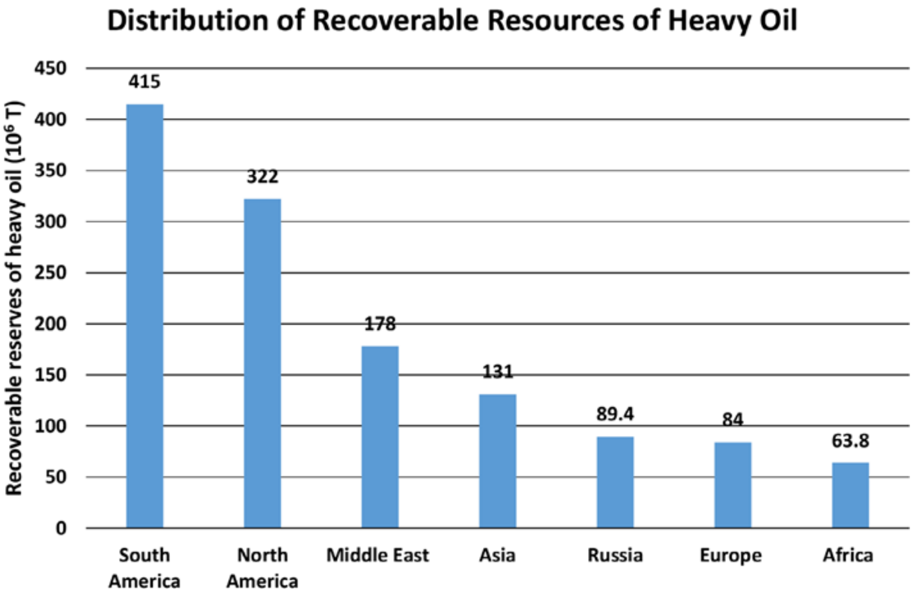

Fig. 4. Distribution of recoverable oil in different regions [31]

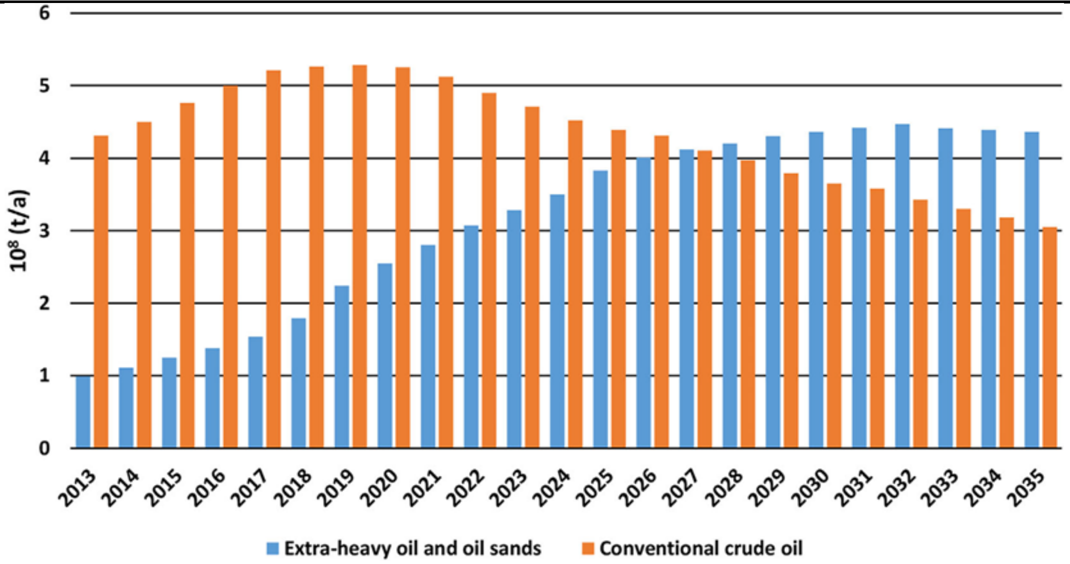

Fig. 5. Oil production forecasts over the next twenty years [32]

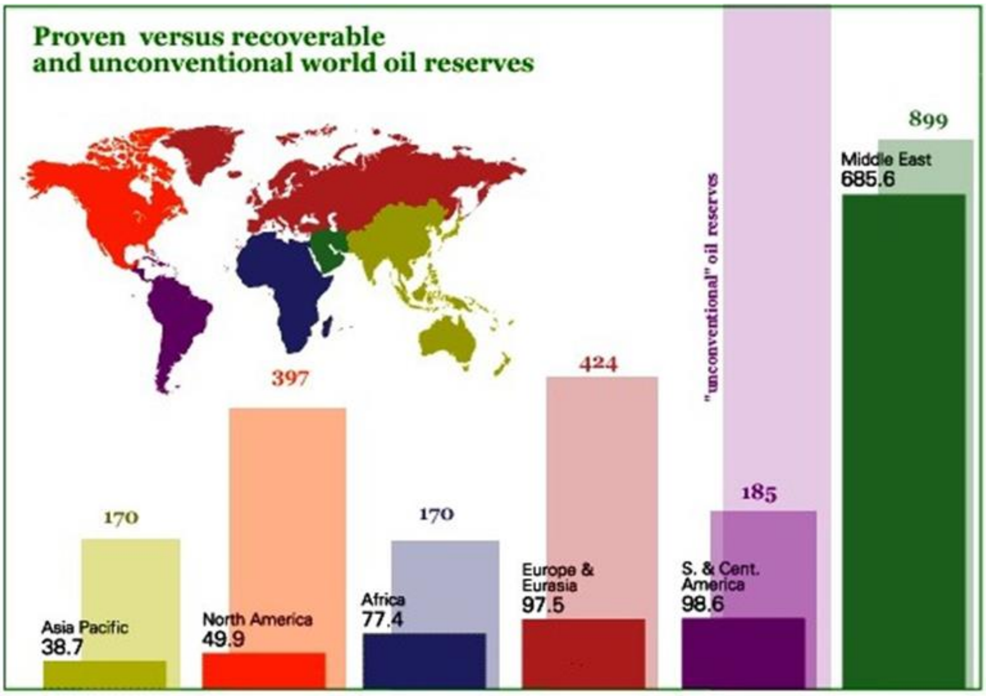

Fig. 6. Distribution of proven oil reserves that can be extracted in billions of barrels [33, 34]

Table 1. Geographical distribution of heavy oils and bitumen reserves [34]

Region	Heavy oil		Bitumen	
	Recovery Factor	**Reserve (BBO)**	**Recovery Factor**	**Reserve (BBO)**
North America	0.19	35.3	0.32	530.9
South America	0.13	265.7	0.09	0.1
Africa	0.18	7.2	0.10	43.0
Europe	0.15	4.9	0.14	0.2
Middle East	0.12	78.2	0.10	0.0
Asia	0.14	29.6	0.16	42.8
Russia	0.13	13.4	0.13	33.7
Total	**-**	**434,3**	**-**	**650,7**

Crude Oil Characterization

Characterization of crude oil in terms of composition is the first step to determining and measuring its chemical and physical properties, predicting and identifying its thermodynamic behavior, whether in oil reservoirs [35], oil wells, surface equipment, installations, or refineries for refining. For example, the nature and type of products obtained at refineries when refining operations depend to a considerable extent on the specifications and characteristics of crude oil entering the refinery for refining [34, 36]. According to his concept of continuity [37], the distribution of the properties of the components of crude oil is through a wide range of molecular weights, ranging from the lowest to the most significant components. As the boiling point and molecular weight increase, other properties, such as odors and heteroatom content, also increase, as shown in Fig. 4 [38].

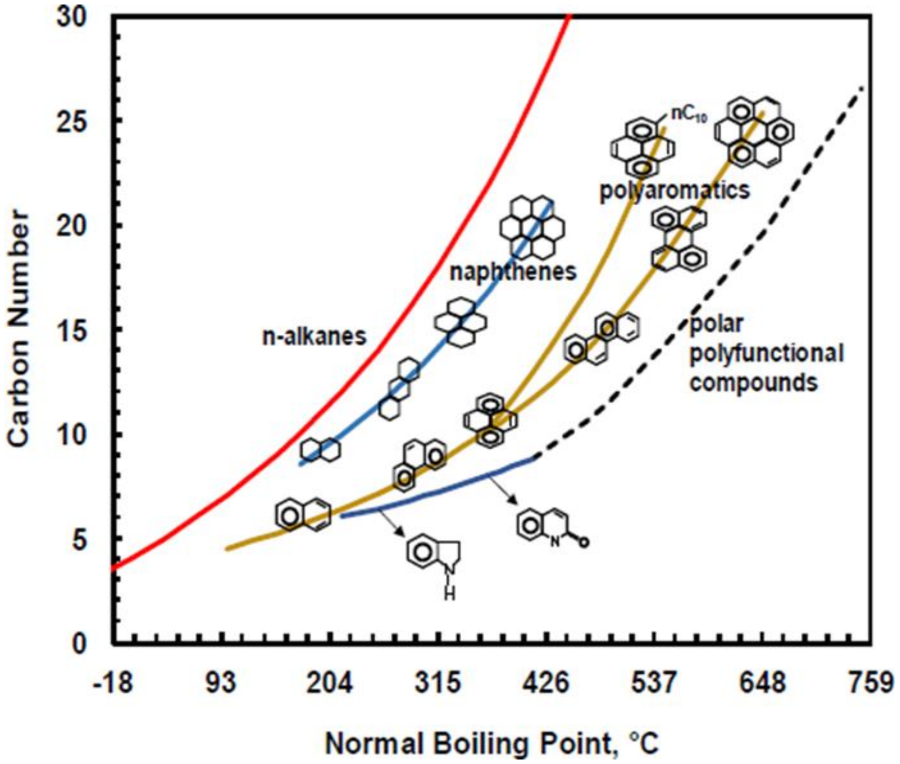

Fig. 7. The effect of boiling point on the various chemical components present in crude oil.[39]

Fig. 8 Shows that the properties of transporting oils, such as viscosity, also systematically vary with the boiling point. The viscosity and boiling point of light crude are almost very close to those of n-alkanes. However, the viscosity of medium and heavy oil pieces is trending and tends to have high viscosity. Deviation arises from an excess of naphthene and aromatics in oils. The exponential increase in the viscosity of the heaviest wounds is due to the presence of a large and different group of multinucleated aromatics and heterogeneous polar compounds [40].

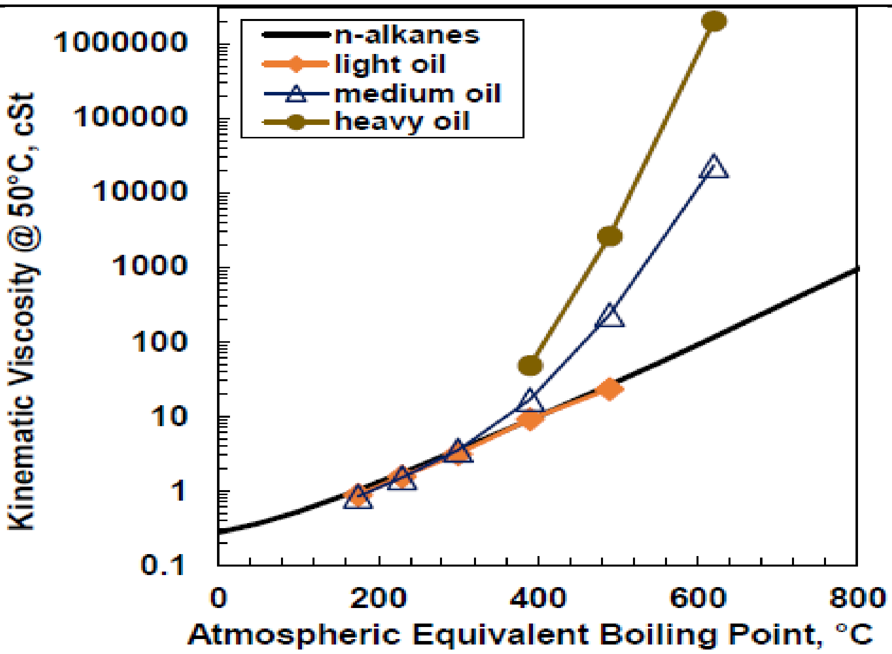

Fig. 8. Kinematic viscosity at 50°C in the atmosphere compared to boiling points of normal alkanes and distillate fractions of light, medium, and heavy crude oils [19, 41]

What we need to characterize this wide distribution of properties is a starting point test. Many types of crude oil analysis methods have been developed, each capable of providing valuable information about the nature of the crude oil. However, not all methods give the same information, so the choice of characterization depends on the nature of the information required to analyze the process in question. For example, distillation is the preferred method for characterizing crude oil in an oil refinery, as it provides comprehensive information about products such as cooking gas, gasoline, kerosene, lubricants, and basic stocks [42]. In contrast, a choice is made for soluble-based characterization to ensure flow, as the solubility data provide more information about the components that can be deposited under specific conditions. A variety of techniques for characterizing crude oil have been described in detail elsewhere [18, 42]. Often, the analysis of SARA (saturated, aromatics, resins, and asphaltic) is used to characterize heavy and heavy crude oil.

Density, API Gravity

API is an acronym for American Petroleum Institute, which uses the API to determine the specific gravity (SG) of crude oil. Specific gravity, density, and API gravity are the most important physical properties that are essential in the characterization of each oil part [43]. Each of these three characteristics mentioned above is measurable and closely related to the other. We do not necessarily need to calculate all these properties separately. Still, some of them can be calculated, while others are defined by the mathematical relationships that link these properties to each other. For instance, if the general gravity of crude oil or any oil product is calculated, the density and API attractiveness of this oil or product can be determined [44]. One of the characteristics of heavy crude oils is that they are more viscous, have a higher boiling point, and higher densities, which results in less attraction to API. Specific gravity is defined as the ratio of the density of crude oil to the density of water at 15.6 °C (60 °F). By calculating the API, crude oil can be classified, where the gravitational value of heavy oil is less than 10, and if it is between 10 and 22, the oil is heavy. The average is between 22 and 32, while light is when the value of gravity is greater than 32 and more than 40 [44]. The density and specific gravity were determined at 20 °C according to ASTM D 1217 [45].

Heavy crude oils are typically rich in aromatics and tend to contain more residual substances, including asphaltene, heterocyclic compounds, and sulfur, nitrogen, and oxygen-containing hydrocarbon isotopes [46].

Table 2. Crude oil classification by the National Petroleum Agency of Brazil [47]

Oil Class	°API
Light	°API ≥ 31
Medium	22 ≤ °API ≤ 31
Heavy	10 ≤ °API ≤ 22
Extra-heavy	°API ≤ 10

Crude Oil Viscosity

Viscosity can be defined as the measure of fluid flow resistance necessary for tank studies. The viscosity of oils is a crucial physical property that influences the flow of crude oil and impacts transportation through porous media and pipes [48]. Heavy oil viscosity is a decisive factor that significantly affects the production of crude oil, upstream operations, surface transportation, and refining of crude oil [49]. A better understanding of how high viscosity forms significantly aids in identifying more effective and reliable approaches and methods for the recovery of heavy oil, as well as reducing related capital and operating costs [50]. Forecasting the viscosity of crude oil is achieved through a variety of theoretical models and empirical comparisons [51]. However, due to its relatively complex composition, accurately designed models cannot be applied to the viscosity estimation of a sample of heavy crude oil. Heavy crude oil can exhibit significant variations in its physical and chemical properties from one reservoir to another [52, 53]. The measurement of the results of Mexican asphalt viscosity indicates a noticeable increase in viscosity with the addition of the asphalt material. When measuring the viscosity of the reconstituted oil at room temperature, its value was 367 times higher than that of the deasphalted crude oil (maltine) at a 20 percent volume. He also concluded that the significant increase in viscosity with asphalt content is most likely due to the accumulation of strong asphalt particles. Note that he had done another test [54] 5 wt., percent of asphalt on a model of Athabasca bitumen with 16 initial weight and then found that the viscosity of bitumen had increased from 300,000 to 1,000,000 MPa [55].

Effects of Various Solvents on the Viscosity of Heavy Oils

It is clearly demonstrated by the adjustment of the asphalt concentration in the malting [56], where a decisive density was observed, and the entanglement of colloidal particles was observed. It significantly increases the amount of structural change. It is more likely that viscosity will be reduced by reducing interference [57]. The interactions between the polar compounds, the solvent of the crude oil (primarily asphalt), and the fraction result in improved reactions. These interactions are between asphalt and asphalt. The parameter δt is considered a representation of molecular interactions, according to the theory of "Hildebrand and Scott" [58]. The solubility parameter is determined by:

$$бt = \sqrt{\frac{ELv}{VM}} \qquad (1)$$

where $E_{LV} = \frac{\Delta H - RT}{VM}$ is the cohesion energy (kW), VM (mol/L) represents the molar volume, and ΔH is the heat of evaporation. For the ability to differentiate and distinguish between polar reactions, dispersion forces, and hydrogen bonding, Van Hansen [59] divided this solubility factor into three parts: the polar part, the dispersion part, and the hydrogen bonding part, as well as the polar component, which is referred to as the cohesion force parameters.

$$\text{б}t = \text{б}d^2 + \text{б}p^2 + \text{б}H^2 \tag{2}$$

Pipeline Transport

Heavy oil would be transported through the pipeline network. In addition, the specifications and properties of HO have issues with flow control due to their very high viscosity, which is not present in lighter hydrocarbon streams [60]. It is known that conventional pipelines cannot transport heavy crude oil; instead, it must be transported through additional processing operations [49]. These additional treatments are used to reduce viscosity (dilution, upgrade, heating, emulsion, and oil in water). Or in reducing friction in the pipe's basic annular flow [61]. Since time immemorial, clouds have been identified as the primary cause of energy loss in conveyor channels, pipelines, and other similar systems. The contribution of this drag is mainly due to the viscosity of the flow as well as the friction against the walls of the transmission pipes [62]. These energy losses can be determined by the decrease in pressure, which inevitably leads to an increase in pumping energy consumption. The very high viscosity makes transportation extremely difficult and complex, so additional processing procedures must be implemented [49, 63].

Drag Reduction

The phenomenon of drag reduction aims to minimize the friction of the flowing fluid as much as possible. The airway in turbulent flow is reduced by using a small amount of added material [64]. This is beneficial because pumping power requirements can be reduced [65, 66]. In general, extensive research has been conducted to reduce turbulent drag in pipelines used for transporting crude oil, to achieve energy savings and improve flow [67, 68]. When reducing drag using surfactants discovered through his experimental work on pipe flow, using a dilute solution of cetyl trimethyl ammonium bromide (CTAB) at 508 ppm, it was observed that the drag reduction in the large-diameter pipe was greater than in the smaller diameter [69]. The smallest, at a finite value of the flow, the Reynolds number ends due to the deterioration that occurred as a result of oxidation after a period of several days [70]. In their investigation, Dioctates use aluminum in toluene as a drag reducer. They showed that the method of preparing a disoap solution has a severe effect on the flow behavior [71]. They found that a very high shear temporarily splits the structure of the solution. They noted that the losses due to friction would be lower as the concentration of aluminum dioctates increased [72]. He conducted his investigation using several non-ionic surfactants for linear primary alcohol in aqueous solution. The effects of surface actor structure, temperature, concentration, and mechanical degradation on drag reduction have been studied. The most effective surfactants were additives that reduced drag. All surfactants used are repairable, i.e., after mechanical decomposition, they can regain their ability to reduce drag when they reach an area with low shear forces [73]. The towing effects on drag reduction are similar to those observed in high-polymer solutions, where an increase in drag reduction percentage (Dr%) is achieved by reducing the pipe diameter [74]. Different types of cationic surfactants are used as cloud reduction agents, such as ammonium chloride trimethyl ethyl (CTAC), trimethyl ammonium lipolysalicylate (TTAS), aero ethyl triethylammonium salicylate (ETAS), and trimethyl ammonium chloride (STAC) [75]. The closed-loop flow and heat transfer device has been used to measure clouds and to reduce heat transfer in turbulent pipe flow [76]. They concluded that the variety of different types of surfactants used was effective. High in reducing both drag and heat transfer in turbulent pipe flow. It has been proven that surfactants simultaneously reduce the friction of pipe flow and the individual heat transfer coefficient from pure water. Additionally, surfactants have a critical temperature and a Reynolds number above which the heat transfer coefficient and friction of pipe flow return to those of water [77]. The percentage of cloud reduction increased by increasing the concentrations of surfactants from 50 to 500 ppm [78, 79]**.** The surfactant effect (Habon G 530 ppm aqueous solution) on the wall disturbance structure has been experimentally investigated [80]. To prove that the drag reduction in their work exceeds the predictions of the maximum drag reduction, Virk, using the surfactant Habon G [C16H33N (CH3) 2C2H4OH] +, consists of 53.5% active surfactant, 10.2% isopropanol, and 36.3% water [81]. The average speed of the flexible sublayer was the sharpest of Virk's proposed features of near-maximum drag reduction solutions. They concluded that surfactant solutions could reduce turbulent friction loss more effectively than the Virk maximum drag reduction approach, which suggested the use of polymers. It was also shown that the turbulence intensity of the surfactant system, which reduces drag, decreases by 25% to 35% compared to pure water [82]. When reviewing shear and drag reduction, the measurement of expansion rheometers in cationic aqueous surfactants was studied. Cryo-TEM has been used to show the image and size of the surfactant solvency [83]. Argued 16-50, with three similar concentrations, 2-, 3, or 4-chlorobenzoate at 12.5 molar has been used as a withdrawal reducer. Each isomer exhibited a range of different rheological and micelle structures [84]. The chlorine system has shown no low drag reduction, low outward existential viscosity, and only spherical microlar. The 3-chloro system has demonstrated an excellent drag reduction ability, achieving a maximum drag reduction of 50%. The 4-chloro system has demonstrated an excellent withdrawal reducer, achieving a maximum drag reduction of 70% [85]. High-definition elongated viscosity has been obtained, and a thread-like Meckler mesh has been obtained [86]. The effects of positive surfactant mixtures on reducing streamlined behavior and drag have been experimentally proven [87]. Cationic alkaline trimethylammonium (IV) surfactants have been blended with an alkyl chain length from C12 to C22 in varying molar ratios [88, 89]. A variety of surfactants, including three anionic surfactants and non-ionic surfactants, have been tested as drag attenuators in the flow of turbulent oil pipelines in Iraq, with diameters ranging from 0.5 to 3 inches [62, 90].The researcher was able to determine that the withdrawal rate decreases with a high concentration of the active substance on the surface (within certain limits) and the flow rate of the solution. and the diameter of the crude oil transport pipeline. The maximum extraction rate was achieved using SDBS, which was 56.5% at a concentration of 200 ppm. Experiments were conducted to verify and confirm that four different types of anionic surfactants (SDBS, SLS, SLES, SS), all of which reduce drag agents in refining products such as gas oil and kerosene, were tested at varying concentrations (50-300 ppm) [91]. Three closed flow loop systems (1.91, 2.54, and 5.08 cm) tube diameters were used in his experimental work. The researcher found that the process of reducing drag is increased by increasing the surfactant concentration and flow rate (Reynolds number), as well as by decreasing the diameter of the oil transport pipe. The maximum of 53% of the Dr was reached using 300 ppm of (SDBS), which is dissolved in gas oil flowing through a 1.91 cm defined tube. The maximum of 48% was reached using 300 ppm of SLES, which is dissolved in kerosene flowing through a 1.91 cm knowledge tube. It was observed that the four anionic surfactants used had no clear effect on the apparent physical properties of both gas oil and kerosene. The researcher concluded that the reduction of drag occurs when the surfactant molecules form a type of molecular lattice structure [92]. These structures extend when subjected to high shear, which increases their effective viscosity, suppresses smaller vortices, and reduces their ability to absorb energy from the average flow [93]. Drag reduction measurements in oil and gas alloy flow are presented in two stages in their study. Two types of oils with different viscosities were examined in horizontal tubes with an inner diameter of 10 cm to evaluate the effect of oil viscosity on total pressure loss and the effectiveness of drag reduction factors (DRAs) in reducing pressure drop in slug flow [94, 95]. The total pressure drop in 50 cp oil was more significant than in 2.5 cp oil, particularly when the gas flow rate increased. However, they noted that DRA was more effective in reducing the overall pressure drop in 2.5 cp oil plus; the higher oil velocity, and therefore the higher oil volume fraction, has increased the DRA effect of both liquids [96]. The effect of two surfactants (sodium dodecyl benzene sulfonate (SDBS) and sodium lauryl sulfate (SLS)) in crude oil was studied using a closed-loop system for three pipes of different diameters (0.75, 1, and 1.5 inches) of 2 meters each. Three different temperatures (30°C, 40°C, and 50°C) were used [62]. The concentrations of each surfactant used range from 50 to 300 ppm. The final results showed that the greatest reduction in clouds (% DR) was 23.67% (flow increase was 16%). This value is obtained when 200 ppm of SDBS is added at 30°C. The high viscosity of crude oil, as a dominant transport fluid property, poses significant challenges in the production and refining of crude oil in refineries, as well as during its transport through wells and pipelines [48, 49, 97]. Friction on the wall, viscous drag, and pressure drop in the pipeline are significantly greater for heavy crude oil compared to conventional light crude oil. The drag effect is caused by pressures on the wall due to fluid shear, resulting in low fluid pressure [7, 98, 99]. This makes it very difficult to pump oil over long distances [100, 101]. For this, drag reduction is a basic annular flow-based lubrication technique used to reduce pressure when transporting heavy crude oil through pipelines [7, 99, 102]. Commonly used friction reduction techniques include the enhanced pipeline transport of heavy crude oil through the use of additives that reduce drag and improve basic loop flow [103].

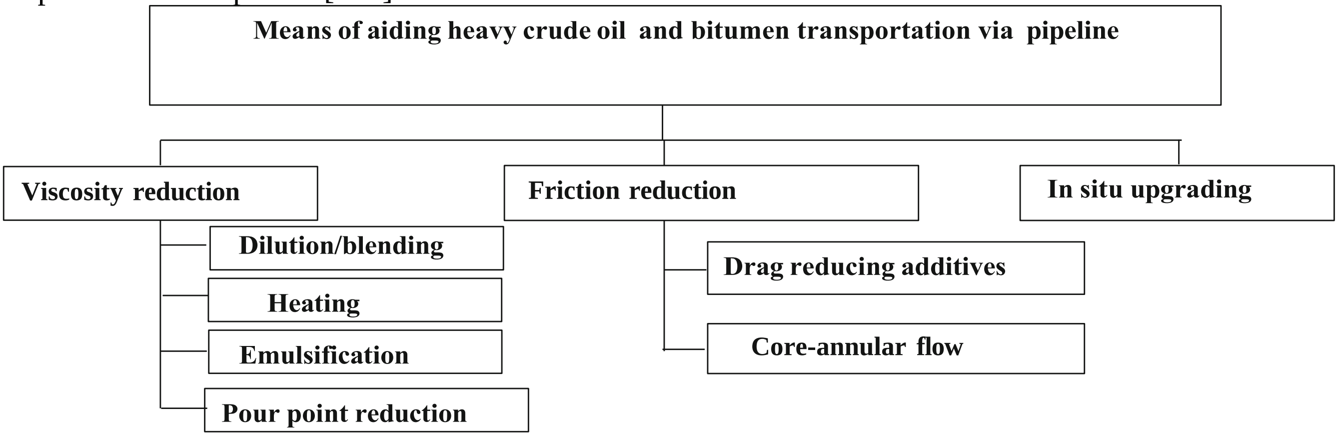

Fig. 9. Methods for improving the flow of heavy crude oil through pipelines [7, 103]

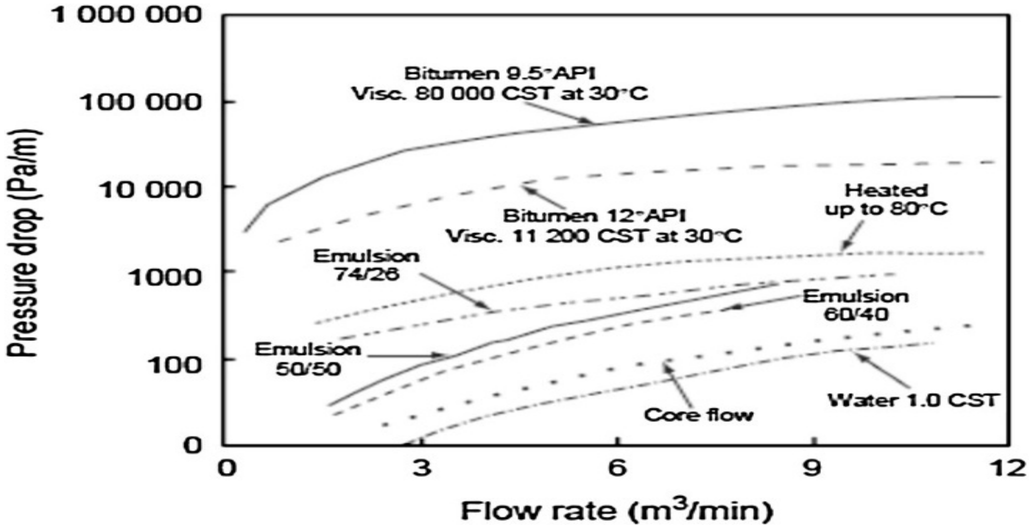

Fig. 10. (ΔP Vs Q) of various heavy crude oil transport mechanisms [104]

Viscosity Reduction

One way to reduce the viscosity value of heavy oils is by mixing with hydrocarbons that are less viscous and dense, such as condensate, naphtha, kerosene, or light oil. The process is called dilution [48]. To achieve acceptable and economical transportation limits, it is necessary to have up to 30% of the attenuators by volume, which requires a large-capacity oil transport pipeline [105]. A potential issue is the availability of diluents [62]. The dilution process may be a suitable solution for transporting heavy oil; however, it requires a significant investment to install an additional return pipeline [106]. That condensate was used until the end of the 1980s to transport the full production of Canadian crude oil [107]. According to forecasts and calculations made at the end of the 1980s and subsequently confirmed [108], it has been predicted that condensate production will be unable to meet market demands, as demand is directly linked to the development of heavy oil production [109]. It is essential to know that condensate is a poor solvent for asphaltene. One of the influential problems is the formation of asphaltene deposits that partially clog the lines [110]. Light oils were used in the range of 35° to 42 API to reduce the viscosity of heavy crude oil [48, 111]. All this leads to a significant increase in the volume of effluent, resulting in additional capacity for crude oil pipelines [112, 113]. As for condensate, the supply of light oils may fluctuate, and their use as a diluent may be limited, as this will reduce the amount of light oil available for the refinery's supply. Finally, due to their high saturated content, some light oils are weak asphaltene solvents and, like condensate, can catalyze asphaltene deposits [114, 115]. Examined alcohols, particularly pentanol, for reducing heavy oil viscosity at least twice as much as kerosene [116-118]. The hydrocarbons selected in the study are nonane and naphtha. It has been noted that for naphtha, the relative viscosity of diluted oil is greater than that of nonane due to its aromatic content, where naphtha is a suitable solvent for asphaltene [119]. On the contrary, nonane is known to be a bad solvent for asphaltene [120].

Dilution

It is known that the prices of heavy crude oil are low due to its high viscosity, which makes transportation and refining difficult and expensive, thereby complicating the processes of transportation, processing, and refining [121, 122]. Therefore, the dilution method is one of the first and most popular methods for reducing the viscosity of heavy oils [123, 124]. This method (mitigation method) encounters some problems, making it less attractive. Due to the significant need to extract crude oil from the ground, substantial expenses are required to access the oil reservoirs, including drilling and completion, surface treatment, transportation, and refining. It can’t benefit from heavy crude oil, unless it is refined and converted into valuable and precious light products [49]. However, the process of delivering it to refineries poses a significant challenge due to the high viscosity and density of heavy oil [117], which requires substantial energy and pumping, resulting in increased economic costs. Therefore, diluting heavy crude oil by adding a low-viscosity diluent is one of the solutions used [125]. This attenuator is usually a very light gas condenser (C5+ or "Pentane Plus") or any light, low-viscosity hydrocarbon [126, 127]. When using thinners to improve transport, two primary methods achieve this: the first involves reusing the diluent, and the second does not [128, 129]. In both cases, a larger diameter of the transmission pipeline is needed, as a large suspension will be imposed by the attenuator [130, 131].

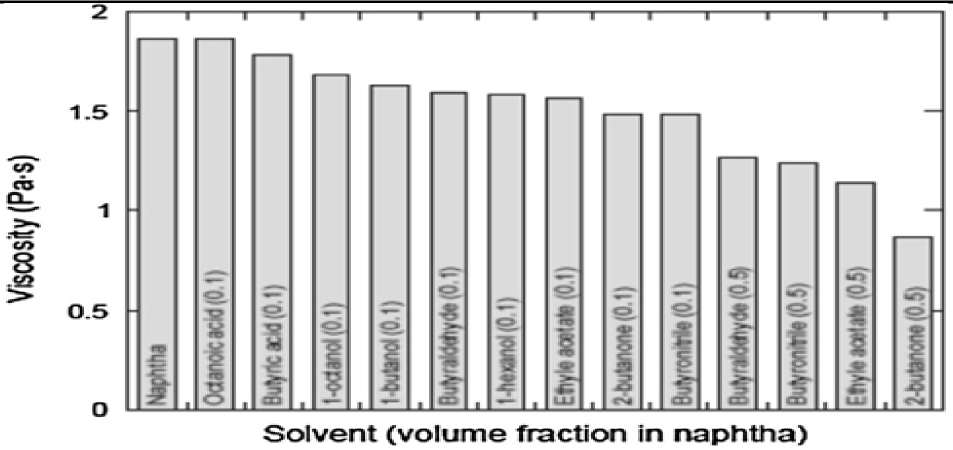

Fig. 11. The relationship between the effect of adding solvents to crude oil and viscosity values [132]

Summary of Previous Experiments

Table 3. Summary of previous studies on the effect of solvents on the flow of heavy crude oil

Authors	Additives	Additive concentration
Y. Wen; A. Kantzas (2006) [133]	Kerosene, toluene, naphtha, heptane, hexane, and pentane	All additives were added to the oils in several predefined mass fractions: 100% oil, 99%, 96%, 93%, 90%, 85%, 80%, 70%, 50%, 30%, and 0% (100% solvent)
Peng Luo et al. (2007) [134]	propane solubilities	7.0 – 14.0 wt%
Pradeep Ananth Govind et al. (2008) [135]	Solvent SAGD	1:10 and 1:15
Samane Moghadam et al. (2009) [136]	solvent vapour extraction (VAPEX)	16.9 wt.%
Guo Jixiang, et al. (2010) [137]	Propenoic acid, docosyl ester, maleic anhydride, and styrene,	3:2:2 The monomers are 2-propenoic acid, docosyl ester, maleic anhydride, and styrene, respectively
V. Pathak, et al. (2011) [138]	Butane and propene	1:12 -1:20
Mohammad Kariznovi, et al. (2012) [139]	Methane and Ethane	15.0 -17.0 wt%
Hamad Motahhari, et al. (2013) [140]	Solvent-Diluted	15 to30 wt%
Hussein Qasim Hussein, et al. (2014) [141]	polar solvents (toluene, methanol, mixed xylenes, and reformate)	12 wt.% and 0.5-1 wt.% solvent and dispersant concentration, respectively.
Akbar Mohammadi Doust et al. (2015) [142]	Solvent, and ultrasound waves	1:3 solvent from fuel oil
Faris, H.A., Sami, N.A., 2015 [143]	Toluene and naphtha	10 wt.% naphtha and toluene.
Amir Hossein Saeedi Dehaghani et al. (2016) [118]	Heptane, methanol, toluene, gas condensate, and naphtha	Add 4, 8, or 12 vol.% from solvent.
Fuxin Yang et al. (2017) [144]	Organic solvents	Add 1:3 solvent
Sherif Fakhe et al. (2018) [145]	Low molecular weight hydrocarbon	Added with 5, 10, and 20 wt% to the crude oil.
Jimoon Kang et al. (2018) [146]	Supercritical methanol	1:1 supercritical methanol
G I Volkova et al. (2019) [147]	Alkaline solution of isobutyl alcohol	1.75 wt% alkaline solution of isobutyl alcohol

Rana Abbas Azeez et al. (2020) [148]	Organic solvents	Heavy crude oil was diluted with toluene, dimethyl ketone, and their 50/50 mixture, at 0–15 wt%, and 298.15 K.
Manigandan Sekar et al (2020) [149]	Naphtha and kerosene with silica nanoparticles	5-15 wt.% solvent and 500, 1000, 2000, and 10000 ppm silica nanoparticles
Firas K. Al-Zuhairi et al. (2020) [150]	Different organic solvents	5, 10, and 20 wt.% of n-heptane, toluene, and a mixture of varying ratios of toluene/n-heptane)
Ali Nasir Khalaf et al. (2021) [151]	Naphtha and kerosene	Additives are mixed with heavy crude oil at different concentrations, ranging from 3-12 wt.%
Soleimani, Ali et al. (2021) [152]	Kerosene	5-30% v/v at 25 °C
Noor I. Jalal et al. (2022) [114]	Acetone	20 wt. % of aceton
Eman M. Saasaa et al (2022) [153]	Naphtha & toluene, naphtha & xylene, naphtha & kerosene	4, 8, and 12 wt%, and temperatures 15, 25, 35, and 45 °C
Sandeep Badoga, et al. (2023) [154]	toluene, dichloromethane, ethyl acetate, and n-pentane	21.8- 54.3 wt.%
Adan Y. Le´ on et al. (2024) [155]	Naphtha	3–9 wt.% naphtha
Jafar Qajar et al. (2024) [156]	Toluene and n-heptane	Add 1:5, 1:7, 1:10 solvent to crude oil
Ming Zhang et al. (2025) [157]	In-situ solvent generation for SAGD	Solvent yields varied from 3.29 to 35.04 wt.%

Emulsions

Emulsions occur naturally in oil production and pipeline lining, primarily in water-in-oil (W/O) emulsions, which are more complex than oil-in-water emulsions (O/W) (Fig. 12) [158]. All these emulsions mentioned are harmful to oil production because the μ of oil rises, leading to increased corrosion problems. Additionally, it is difficult to break them in desalination and drying units before refining. Nevertheless, emulsions can be used as a method of transporting heavy or hefty crude oil, and the dispersion of (O/W) or in “brine” may be a substitute method for transporting highly viscous crude through pipelines to reduce viscosity [159].

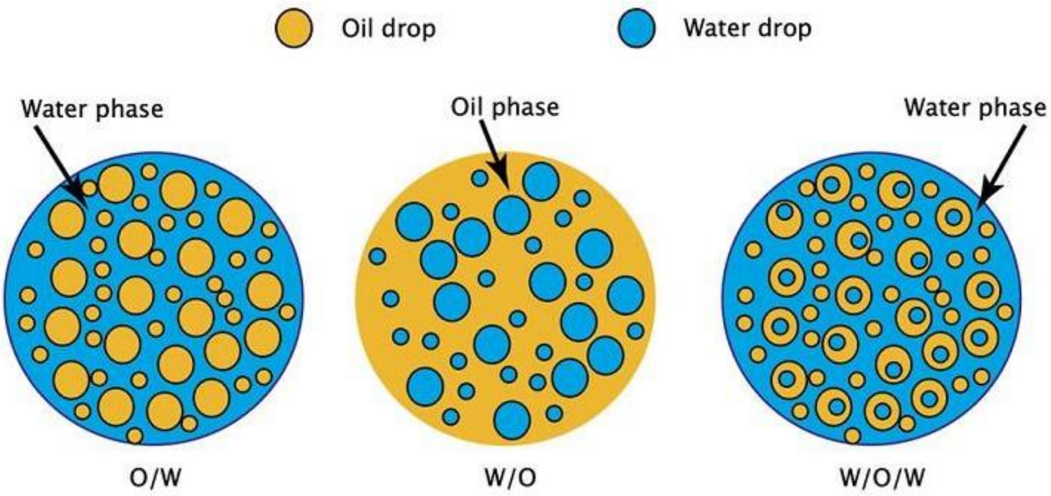

Fig. 12. Various emulsions used in the transport of heavy crude oil [160]

O/W dispersion emulsion is a mixture of two miscible fluids where the crude oil phase is dispersed in the continuous phase of water, as in Fig. 11 [161]. This method may be more suitable for use than the mitigation method in some locations, as hydrocarbon or lighter crude diluents may not be available on-site. In contrast, freshwater, seawater, or even formation water may be readily available to disperse crude oil. O/W Emulsions are often produced intentionally to reduce the viscosity of high-viscosity crude oils so that they can be easily transported through pipelines [162]. The O/W emulsion reduces the viscosity of heavy crude oils and bitumen and may be a successful alternative to the use of attenuators or heat to reduce viscosity in pipelines [163].

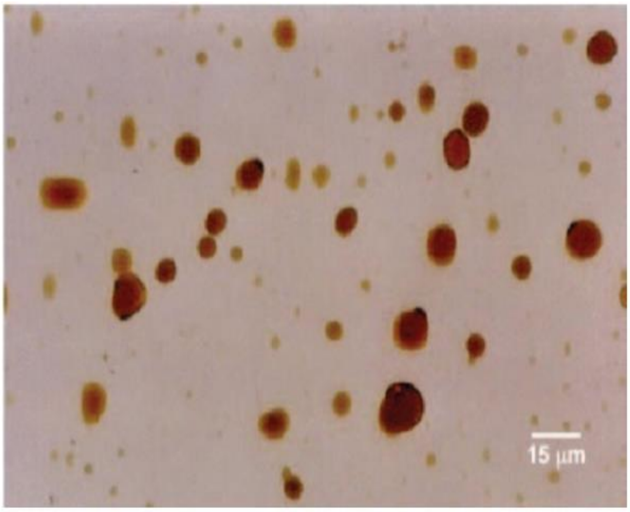

Fig. 13. (O/W) Photomicrograph [164]

O/W emulsions can be formed by adding specific concentrations of surfactants, and it is considered an effective and beneficial method for reducing the viscosity of heavy crude oil [165]. In the emulsification process, the heavy crude oil is transferred into the aqueous phase as fine oil droplets [161]. To ensure the stability of the emulsion during transport in the pipeline, it is necessary to add surfactants to reduce the interfacial tension between the oil and the aqueous phase. At other times, additional substances are added as stabilizers to prevent phase separation. In general, non-ionic surfactants are a helpful option because they are not affected by water salinity and are relatively cheap [166, 167].

Main Annular Flow

In the transmission system, the pumping pressure necessary for the current generated by lubrication can be equivalent to the pressure of the liquid alone, provided by a liquid layer covering the base of the oil, which acts as a lubricant [168, 169]. The primary issue with specific transport designs is that crude oil continues to adhere to the pipe wall, thereby blocking the flow mechanism [63]. During the shutdown process, which stratifies the oil and water phases, requiring a significant restart, the pressures may exacerbate this type of difficulty. There are other methods available to facilitate the transportation of heavy oils, such as oxidation and reduced travel [123, 170].

Friction Reduction

Blending with hydrocarbons is considered less viscous than condensate, kerosene, naphtha, or light crude, and this process is known as dilution [171]. To establish acceptable limits for the transportation of crude oil, it is necessary to have a fraction of up to 30% of attenuators by volume, which requires a large capacity in the transport pipelines [172]. New problems may arise regarding the availability of boosters (Crandall et al, 1984) [53]. Mitigation can be a suitable solution for transporting heavy crude oil, but it requires significant investment to install an additional return pipeline [49]. Several studies have shown that condensate was used until the end of the 1980s to transport almost the entire production of Canadian crude oil [173]. The condensate is a type of oil considered very light, obtained through the production of natural gas by separating the lighter phase. Condensates are, unfortunately, poor solvents for asphalt; this is because asphalt deposits may form that partially obstruct the pipelines [174, 175]. Additionally, condensate is a poor solvent for asphalt. Asphaltene deposits may form, partially blocking the lines [176]. Light oils are used in the 35 to 42 ° API range to reduce oil viscosity, although up to twice the volume of light oil compared to condensate may be required to achieve the same viscosity reduction [48]. This leads to a significant rise in the volume of effluent, causing additional capacity for transport pipelines [177]. As for condensate, light oil supplies may fluctuate, and the use of attenuators may be limited, resulting in a reduced amount of light oil available for refinery use. Finally, due to their high saturated content, some light oils are weak solvents for asphaltene and, like condensate, can catalyze asphaltene deposits [113]. Research and laboratory experiments have demonstrated that methyl tertiary butyl ether (MTBE) and triethyl methyl ether (TAME) can serve as alternative diluents for heavy oils [178]. An exponential relationship has been found between the resulting viscosity of the mixture and the volumetric fraction of the dilution, making dilution a highly effective and efficient method [118]. Alcohols, especially ethanol, have been studied to reduce the viscosity of heavy crude oil by at least twice the amount of kerosene [179]. Simple organic solvents (heptane, toluene,...) are used, which are not descriptive of heavy and complex crude oil (from 0 to 20% by weight) [116]. These results contribute to the understanding of the characteristics and specifications of the flow of heavy crude oil, aiming to enhance its transportation [117]. Many low-viscosity hydrocarbons have been used as diluents for heavy oils, in particular naphtha and kerosene. For tests containing attenuators, four attenuation rates (5, 10, 15, and 20% weight) and five temperatures (3, 20, 40, 60, and 80 °C) were tested for each attenuator [180]. Other hydrocarbons, such as nonane and naphtha, have also been used. For naphtha, the relative viscosity of diluted oil is greater than that of nonane [181]. Due to its aromatic content, naphtha is a good solvent for asphalting. On the contrary, nonane is known to be a bad solvent for asphalt [182]. The pressure drop encountered when transporting heavy oils through transmission pipelines is more severe when the oil is transported over long distances. So, reducing the withdrawal by including a chemical addition becomes a suitable option. Heavy crude oil is transported through pipelines, and the flow system is often turbulent. Additionally, high friction loss due to high viscosity results in waste and a significant loss of energy used for transporting heavy crude oil [183]. High drag in turbulent flow occurs due to radial transmission of flow momentum by fluid vortices [185, 186]. The reduction of polymer clouds was discovered a few decades ago by Toms (1948), who observed a decrease in the withdrawal value by 30-40% when the polymer [187, 188] (methyl methacrylate) was added to the disturbed chlorobenzene flowing through the transport pipeline [189, 190]. In this regard, additives contribute and help reduce friction near the walls of transport pipelines and inside the turbulent liquid core of the moving fluid. Technology has evolved over the years. Even the classification of drag reduction additives into three categories: polymers, fibers, and surfactants [191-193]. Hence, drag decrease is an oiling procedure that relies on the main annular flow to decrease the pressure in transporting heavy crude oil through transport pipelines [194]. Widespread and well-known friction reduction technologies aim to augment the transport of dense oil through complete pipelines by means of additives that reduce intake and basic annular flow [195]. Equally, techniques decrease flow drag by altering the speed range, for example, by inhibiting turbulent oscillation in the wall area near the transmission pipeline. In contrast, the flow in the heavy crude oil pipeline is laminar or slightly turbulent, with minimal flow resistance due to the significant viscosity effect on flow drag [196, 197].

Pour Point Reduction

The collection and precipitation of large Valentine particles in petroleum contribute significantly to its density and great speed, making heavy crude oil extremely difficult to flow in transport pipelines [198]. Then, destroying or preventing this result via the use of pouring point inhibitors will help to enhance the properties and specifications of heavy oil flow [199]. Oil casting is the lowest degree at which it stops flowing due to the loss of flow properties [200]. For example, it is challenging to transport heavy crude oil and wax through pipelines in cold climates. Due to the low temperature, the growth of crystals prevents oil molecules from flowing. Crystallization depends on the environment, the arrangement of the oil, temperature, and pressure during the transport of heavy oils [201]. It is known that there are several ways to reduce wax and valeting deposition, and the use of polymer inhibitors is an essential and effective alternative [202, 203]. Adding together copolymers, for instance, “polyacrylates, polymethacrylate, co-ethylene acetate, methacrylate, etc”, all prevent sedimentation and transport stability. It has been found from viscosity measurements that at the temperature at which wax crystals begin to form, the copolymer has shown a significant and very influential effect in reducing viscosity [204, 205].

Additives to Improve Heavy Oil Transportation

There are several methods used to improve the process of transporting heavy oil through pipelines, and one of the essential methods used in this is enhancing the properties of crude oil by adding different chemicals [206]:

Nanoparticles

It is scientifically and practically known that a nanoparticle is "a microscopic particle whose size is measured in nanometers, usually limited to so-called nano-sized particles (NSPs; < 100 nanometers in aerodynamic diameter), and their other name: nanoparticles [207, 208]. Nanotechnology has been developed in recent years to include applications in the oil industry to inhibit composition damage [209]. Upgrading heavy oil and ultra-heavy oil, improving oil recovery processes (IOR) [210], improving oil recovery (EOR), because particle sizes, between 1 and 100 nm, the large surface area available, the large dispersion and the adjustable chemical and physical qualities and properties [211], the nanoparticles are predisposed and able to absorb asphaltene and inhibit their self-bonding selectively. In a previous research and study [212]. The research group focused on the use of silica, alumina, and magnetite nanoparticles to prevent asphaltene accumulation under varying temperatures and solvent ratios with varying asphaltene concentration [213]. Hence, the characterization of nanoparticles is of great importance in understanding the role of particles in reducing the viscosity of heavy crude oil and heavy oil [214]. The size of the nanoparticles is a key parameter that must be considered when evaluating these materials for in situ applications [215]. It is essential to verify that the materials used for injection into reservoirs comply with size constraints, thereby preventing nanoparticles from causing additional damage to the reservoir through pore or throat blockage or bridging [216]. According to the principles of the arc from the third to the seventh, the particle size of the bridge/blockage may be shared as follows: i) particles larger than 1/3 of the pore size are prone to generating pore blocking, b) particles in the range 1/7 - 1/3 of the pore size will generate a bridge in the throat of the pores that will generate a blockage of the pores and c) particles whose sizes are less than 1/7 of the pore size can pass through the pores of the throat. Most nanotechnology publications in the oil and gas industry are reports of laboratory experiments [217]. Therefore, there is a need for additional field trials to advance nanotechnology in the oil industry further. While nanoparticles are not inexpensive, their cost would be appropriate if the lowest possible concentrations of nanoparticles were used at an optimal performance level

[218]. More studies are needed to improve nanotechnology research in the near future. To obtain less expensive, more efficient, and environmentally friendly oil extraction methods, most NPs used are considered environmentally friendly, compared to chemicals, which are usually costly, with potential damage in their preparation and use [219]: for example, silicon dioxide is the most critical component of silicon nanoparticles; in short, NP are effective and environmentally friendly. Large-scale nanoparticles, such as TiO2, SiO2, and Al2O3, with diameters ranging from 1 to 100 nm, are smaller than pores, and in other sizes [220]. It is possible to easily flow through porous media until they become trapped, without reducing extreme permeability as a result of the small size of the particles; the ratio between surface area and size is considered very high. A large area increases the atomic percentage on the surface of the pulp, and the nuclear ratio of the core on the nanoparticles is significantly high [221]. Fig. 12 shows the definition of the expanded layer with low particle size. Due to the special and exceptional properties of nanoparticles, such as their large surface area and catalytic properties that depend on size and shape, nanoparticles can also be used as adsorbents and/or catalysts to enhance the dissolution of the reservoir [222]. Multiple nanoparticles have been incorporated onto the substrate for the first time by adsorption and eventual catalytic pyrolysis of asphaltene [223]. The kinetics and thermodynamics of asphalt absorption of nanoparticles α-Al_2O_3 have been confirmed and investigated through his previous study [224]. The author explained that adsorption was achieved quickly, within less than two hours, when adsorption scales were reached. This was the result of the non-porous nature of the material that dominates the external adsorption. Several studies have been conducted on the absorption of n-C7 asphalt extracted from Colombian crude oil in recent years [225] using NiO nanoparticles supported by silica and alumina nanoparticles. The adsorption and equilibrium periods were very short. The authors have found that nanoparticles exhibit high adsorption efficiency [226]. Due to the small size of the nanoparticles and their large surface area per unit size, which endows them with unique properties, they are more responsive to other molecules, posing significant challenges to chemical processes [227].

It is the clogging of pores and the injection of trapped chemicals into porous media, which leads to a decrease in the permeability of the composition and increased injection costs [228, 229].

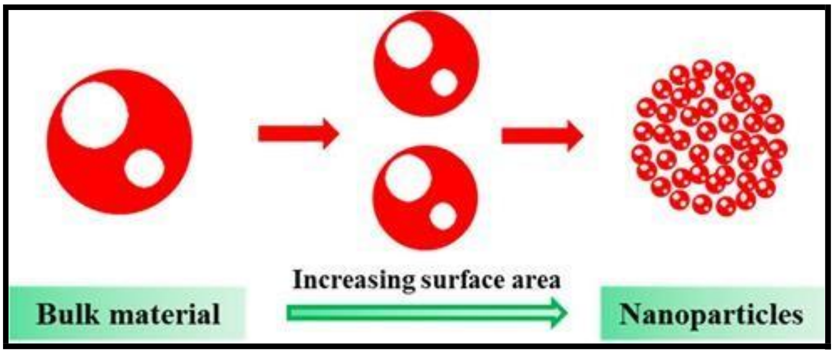

Fig. 14. The diagram of the high surface-to-size ratio of nanoparticles (NPs) [230]

The common name for silicon dioxide is silica, and by its nature, it is in the form of quartz and sand. Silica nanoparticles contain silicon and oxygen, a chemical compound with a SiO_2 composition [231, 232]. Laboratory studies have been conducted on oil recovery from light and moderate oil reserves to determine and examine the effectiveness of modified silica Nano plastics [233]. The calculation of the optimal concentration of nanofluid for the injection stage has been done for all studies with interfacial stress measurements [234]. They note that Nano silica reduces interfacial stress, allowing for separation to be achieved [235].

Summary of previous experiments

Table 4. Summary of previous experiments on the streamlined behavior of heavy crude oil by adding nanoparticles

Authors	Additives	Additive concentrations
Maher Al-Jabari, et al. (2007) [236]	Fe_3O_4	10 g/L
Stanislav R. Stoyanov, et al. (2008) [237]	Zeolite nanoparticle	500-1500 ppm
Binshan Ju a, et al. (2009) [238]	SiO_2	0.1 wt.%
Xiangling Kong; Michael M. Ohadi (2010) [239]	Micro and nano Technologies	Recent developments in the oil and gas industry are briefly reviewed, accompanied by two case study examples.
Nashaat N. Nassar et al. (2011) [240]	Fe_2O_3, Co_3O_4, and NiO	100, 500, and 1000-10000 ppm
Belal J, et al. (2012) [241]	NiO nanoparticles	2.8 g asphaltene/g nanoparticles
Negahdar Hosseinpour, et al. (2013) [242]	Fe_2O_3, and ZrO_2	2.75 and 12.34 mg of KOH/g
Kewen Li, et al. (2014) [243]	Carbon nano-catalysts	0.1 w% of nanoparticle
Rohallah Hashemi, et al. (2014) [244]	Nanoparticle technology	0.1 – 0.4 w% nanoparticle
Abdullah Al-arshed, et al (2014) [244]	Nanoparticle technology for heavy oil in-situ upgrading	0.03−0.4 wt. %
Mohsen Rahimi Rad, et al. (2014) [245]	Multi-wall carbon nanotube (MWCNT) supported Co–Mo	Co/Mo with a 1/3 weight ratio
Osamah A. Alomai et al. (2015) [246]	Nanoparticles: silicon oxide, aluminum oxide, nickel oxide, and titanium oxide	Oil phase: paraffin oil, n-octane, or toluene Oil fraction: 50 %(v/v) C(NP): 0.5 wt.%
Esteban A. Taborda et al. (2016) [9]	Nanoparticles/nanofluids on the rheology of heavy crude oil	1000- up to 10,000 ppm of nanoparticles in the mixture
Ashley R. Brown et al. (2016) [247]	Biogenic nanoscale magnetite (BnM; Fe_3O_4).	0.1-0.5 w% of nanoparticles
Esteban A. Taborda et al. (2017) [13]	SiO_2, Fe_3O_4, and Al_2O_3	0.1- 0.4 w% of nanoparticles
Luqing Qi et al. (2018) [248]	DMAEMA PNPs exceed that of DMAEMA homopolymer additives	Oil phase: Canadian heavy oil Oil fraction: 50 % (v/v) C (NP): 0.1 wt.%
Jaber Taheri-Shaki et al. (2018) [249]	Nanomaterials of Fe, titanium oxide (TO), and super activated carbon (CA)	4 wt.% of each nanoparticle in each step.
Dong Lin et al. (2018) [250]	Synthesize recyclable magnetic $Fe_3O_4/HZSM\text{-}_5$ catalyst	Viscosity reduced by 85.0 %
Luisana Cardona et al. (2018) [251]	NiO and PdO functionalized SiO_2 nanoparticulate	0.1 wt% % of NiO and PdO nanocrystals, respectively, to improve the catalytic activity of the nanoparticles
Sanaz Tajik et al. (2019) [252]	Silica-graphene nanohybrid supported molybdenum disulfide (MoS_2)	0.1-0.5 wt.%
Rincy Anto, et al. (2020) [253]	Silica and alumina nanoparticles	500-2000 ppm
Luisana Cardona et al. (2021) [254]	The nanofluids $AlNi_1$, and $AlNi_1Pd_1$	$AlNi_1$ nanofluid: 500 mg/L alumina doped with 1.0 wt% Ni $AlNi_1Pd_1$ nanofluid: 500 mg/L alumina doped with 1.0 wt% Ni and 1.0 wt% Pd

Zihan Gu et al. (2022) [255]	SiO_2 nanoparticle foam system	0.2-0.5 wt.% nanoparticles in solution
Alcides Simão et al. (2022) [256]	MgO, $CaCO_3$, Fe_2O_3, NiO, ZrO_2 and WO_3	500, 1000, 1500, and 2000-10000 ppm
Eynas Muhamad Majeed et al. (2023) [257]	Nanoparticles (silica and gamma-alumina)	500, 1000, 1500, and 10000 ppm
Jingnan Zhang et al. (2023) [258]	Manganese chloride ($MnCl_2$) solution, sodium dodecyl benzene sulfonate (SDBS) solution, and silica (SiO_2) nanofluids	0.5 wt.% nanoparticles
Vladimir E. Katnov, et al. (2023) [259]	Na nanoparticles	2 wt.%
Abdullah Al-Marshed et al. (2024) [260]	Nanoparticulate iron oxide	0.03−0.4 wt. %
Mohammed T. Naser et al. (2024) [261]	Modified silica and magnesium oxide nanoparticles	3 wt% of surface-modified silicon dioxide (SiO2) and magnesium oxide (MgO)
Saeed Zeinali Heris et al. (2024) [262]	Carbon nanotubes (MWCNTs) and sodium dodecyl sulphate (SDS)	1:1 ratio of MWCNTs to SDS
Azin Khajeh Kulaki et al. (2024) [263]	Nano γ-Al_2O_3/SiO_2 modified	0.1 wt.% of γ-Al_2O_3 and SiO_2 NPs
Abbas Khaksar Manshad et al. (2024) [264]	SiO_2/bentonite nanocomposites (NCs)	4000 and 2000 ppm of SiO2
Rubén H. Castro et al. (2024) [265]	SiO_2, Al_2O_3, and TiO_2	100-10000 ppm of nanoparticles
Salem J. Alhamd et al. (2025) [266]	Nano silica and nano molybdenum disulfide	0.3 wt.% of silica nanoparticles
Deja Hebert et al. (2025) [267]	NiO_2, and Fe_2O_3	0.1-0.5 wt% of nanoparticles

Surfactant

Antara first coined the term surfactant in 1950 [268]. These organic compounds consist of at least two parts, the first of which is the soluble part in a given solvent, and the second is the insoluble leophyll part. This dual property of surfactants makes them amphibious in nature. If the solvent is water, the terms commonly used are hydrophilic and hydrophobic [269]. Mostly and lustrously, the hydrophobic chain is branched or linear with 8-18 carbon atoms in length, and the polar head group may be ionic or non-ionic depending on the charge of the molecule in the solution. The hydrophobic group extends outside the bulk aqueous phase, while the water-soluble head group is found in the aqueous phase [270]. When the surfactant molecule moves to the surface, it disrupts the structure of the water molecules, causing them to lose hydrogen bonds with other water molecules. The result is: a decrease in surface tension. Surfactants typically reduce the surface tension of water from 72 to 35 dyne/cm, contributing to the formation of an emulsion that facilitates easier diffusion between different liquids [271]. When the surfactant is present at low concentration, it is absorbed on the interfaces. Another essential property of surfactants is that, in solution, they tend to form aggregates of a monomer called micelles, and this assembly process is called micellization [272]. The concentration at which the micelle composition first appears is known as a critical micelle concentration (CMC). At a very low concentration of surfactant, micelle formation occurs, which reduces the free energy of the system [273]. Mecellates are also used to enhance the solubility of substances that are often poorly soluble or insoluble in a dispersed medium, a process known as solubility [274]. It is the spontaneous dissolution of an insoluble substance in an imultaneous soluble solution by means of a surfactant [275]. The minimum temperature at which the formation of micelles from the surfactant occurs is called the Kraft Point or Kraft Temperature [276]. When the temperature is lower than these, CMC formation does not occur. Therefore, it is the transition point of the phase, and above it, the solubility of the actor at the surface rises at a very high speed due to the occurrence of the discharge process [277]. Kraft point is obtained as a result of attenuating the forces of attraction between the hydrocarbon chains through the micelle [278]. When the surface reactor solution is heated with an oxyethylene group, it becomes turbid within a specific temperature range, resulting in the formation of a cloudy solution [279]. This temperature is referred to as the cloud point. It depends on the length of the polyoxymethylene chain of the surfactant. In the case of increased surface actor concentration, other groups are also formed, called liquid crystals, which are inherently heterogeneous [280]. Numerous studies, articles, and research papers have been written and published on surfactants, their properties, and applications. Some studies have also addressed their classification and applications in various fields simultaneously [281]. Several studies have provided a systematic classification, detailed critical structural features, and multiple applications of surfactants. This type of review article may be helpful for researchers involved in the field of surfactants and their application [282].

Classification of Surfactants

The primary surfactants are classified based on the charge of the polar head group [283]. If this charge is negative, the surfactant is referred to as anionic. If this charge is positive, the surfactant is referred to as a cation. If the surfactant has a head with two oppositely charged groups, it is referred to as zwitterionic. Depending on this charge, surfactants are classified as anionic, cationic, nonionic, and zwitterionic [237].

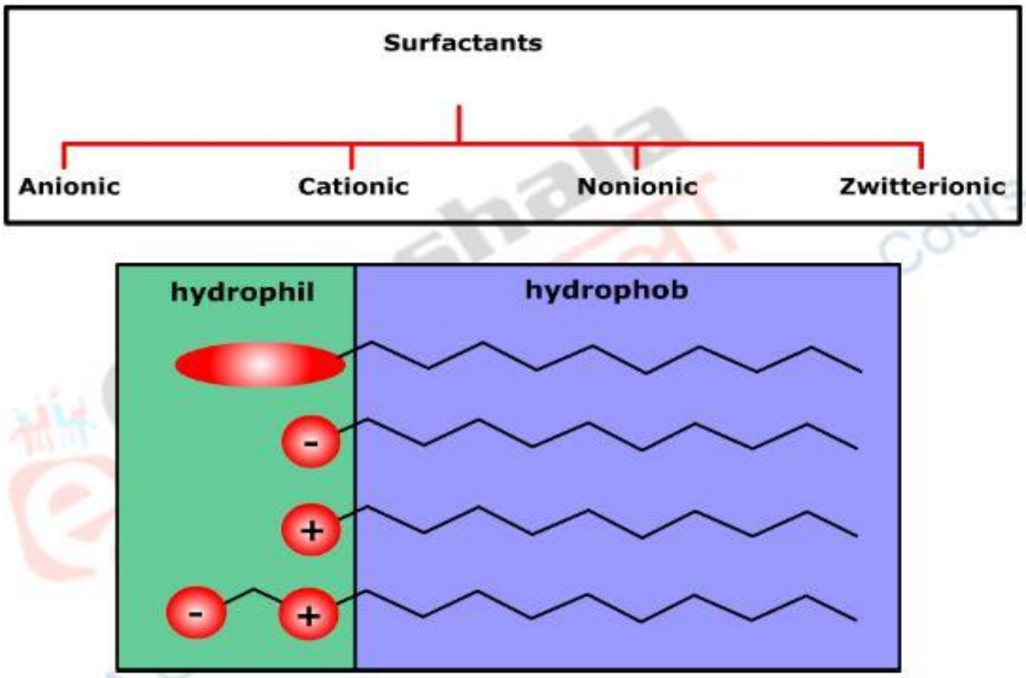

Fig. 15. The division of surfactants according to the charges on them [284]

Anionic Surfactants

Anionic surfactants consist of anionic functional groups on top of them, such as phosphates, sulfates, carboxylates, and sulfonates [285]. Anionic surfactants are used in a larger volume than the rest of the classes of surfactants, as they are used in most detergent formulations, where alkyl and alkyl aryl chains obtain the best resistance to localization in the C12-C18 range [286].

Soap, as it is known, is the single most significant type of anionic surfactant, which is obtained through the process of saponification of natural oils and fats. Soap is a generic term that refers to the mineral salt of an alkaline carboxylic acid, originating from animal fats or vegetable oils. Soap bars are usually based on fatty acid mixtures produced from coconut, lard, and palm oil. For the past fifty years, soap has been replaced by better, more efficient materials such as alkyl sulfate, alkylbenzene sulfate, and alkyl sulfate [287]. Anionic surfactants are highly sensitive to water hardness. The most commonly used anions are potassium, sodium, ammonium, and calcium, as well as many alkyl proton amines. Sodium and potassium give solubility in water, while calcium and magnesium provide solubility in oil. On the other hand, amine/alkanolamine salts give oil- and water-soluble products [288].

Cationic Surfactants

In this species, the hydrophilic part is positively charged. This group does not contain any washing activity effects, but it is fixed on surfaces, where it produces other vital effects, namely softening, antistatic, antibacterial, soil repellency, or corrosion inhibition [289]. The ideal and diverse applications of this type include their use as softeners (such as fabric softeners) and anti-static agents. The anti-cationic surfactant ion is generally methyl sulfate or a halide. Primary, secondary, and tertiary amines depend on pH: primary and secondary amines are positively charged with pH < 10 [290].

Nonionic Surfactants

This type of surfactant is a non-ionized surfactant. This type of material is suitable for cleaning purposes and is insensitive to water hardness. This type has wide applications in cleaning detergents and includes groups such as polyglycosides, alcohols, fatty alcohols, ethoxylates, etc. Long-chain alcohols exhibit some surfactant properties [291]. Notable among the most prominent are stearyl alcohols and fatty alcohols, cetosteryl alcohol (mainly consisting of cetyl alcohol and stearyl), cetyl alcohol, and oleyl alcohol [292].

Zwitterionic Surfactants

The zwitterionic surfactant consists of two groups with opposite charges. Zwitterions are usually known as "amphoteric", but these terms are not the same. An oscillating surfactant is a surfactant that converts into a net cation via a zwitterion to a pure anion as the pH changes from low to high. The acid is not charged, and the primary site is not continuously and permanently charged, i.e, the compound is only zwitterionic on a pH limit range [272]. It is noted that at the isoelectric point, the chemical-physical behavior is usually similar to that of non-ionic surfactants [293]. There is a gradual shift above and below the electric isotope point toward the cation and anion character, respectively. Zwitterion is a group with excellent properties that do not affect the skin [294]. So, to prevent any irritation to the eyes and skin, they are suitable for use in shampoos and various personal care products (cosmetology). Zwitterionic (amphoteric) surfactants are composed of an anion and a cation center bonded to the same molecule. The cationic fraction depends on primary, secondary, tertiary, and quaternary ammonium cations [295]. Sulfate is the internal sulfonic acid salt of a strong inorganic acid and is often referred to as such, such as sulfobutane [296]. It is similar to betaine, which is considered to be an internal carboxylic acid salt for weak organic acids [297]. Both molecules are zwitterionic at pH 7, where the nitrogen in the hydrophobic tail is quadruple-cationic [298]. The polar head sets an anion and adds to the hydrophilic properties of the molecule. Quaternary nitrogen is usually considered positive; these molecules, at any pH, do not get an anionic nature and are not really oscillating, although they are commonly referred to as some common types of zwitterionic surfactants that are N-alkyl derivatives of simple amino acids, such as glycine (NH_2CH_2COOH), betaine ((CH_3) $(2NCH_2COOH)$), and aminopropionic acid ($NH_2CH_2CH_2COOH$). Petinis, for example, cocamidopropyl betaine [285].

Drag Reduction by Using Surfactants

(White, A., 1967). This study demonstrated through experimental work on the flow of conveyor pipes using a dilute solution of cetyl trimentol ammonium bromide (CTAB) with 508 ppm, the study showed that the drag reduction in conveyor pipes with a large diameter was greater than the smaller diameter and ended at a low value of the Reynolds number flow due to the deterioration that occurred due to oxidation after a period of several days.

(Hershey et al., 1971) [5] In their study and research, they used aluminum dioctate in toluene as a drag reducer. They found that the method of preparing a disoap solution significantly affects the flow behavior. It appeared to them that a very high shear temporarily splits the structure of the solution. They found that friction losses would be lower the higher the concentration of aluminum dioctates. Some studies conducted using a combination of non-ionic surfactants have shown that linear primary alcohols in aqueous solution exhibit drag reduction. The effects of surfactant structure, concentration, temperature, and mechanical degradation on drag reduction have been investigated. Almost all surfactants were effective as additives that reduced drag. It has been confirmed that all the surfactants used are repairable; that is, after being mechanically decomposed, they can regain their ability to reduce drag when they reach an area with low shear forces. The towing effects on reducing drag are similar to those observed in high polymer solutions (increase in Dr% by reducing pipe diameter) [299, 300]. They have used different types of cationic surfactants, drag-reducing agents, such as ammonium chloride trimethyl ethyl (CTAC), trimethyl ammonium salicylate grease (TTAS), triethyl triethylammonium salicylate (ETAS), and trimethyl ammonium chloride (STAC) [301]. A closed-loop flow and heat transfer device was used to measure drag and reduce heat transfer in turbulent pipe flow. They discovered that the different types of surfactants used were highly effective in reducing both heat transfer and drag in turbulent transport pipes [302]. They have demonstrated that surfactants simultaneously reduce the friction of pipe flow and the single heat transfer coefficient of pure water [303]. Additionally, surfactants exhibit a critical temperature and a Reynolds number above which the heat transfer coefficient and friction of pipe flow revert to those of water. The percentage of cloud reduction increased with higher concentrations of surfactants (50 to 500 ppm) [304]. Several studies and research have examined shear reduction, pulling, and radial measurement by dilation in aqueous surfactant solutions [305]. Cryo-TEM (cryo-transmission electron microscopy) technology was used to visualize the size and image of surfactant solvents. Argued 16-50 was used in three close concentrations, 2-, 3-, or 4-chlorobenzoate at 12.5 mmol as a withdrawal reducer [306]. Each isomer exhibited distinct rheological and micelle structures. The chlorine system did not show any decrease in clouds, low elongation viscosity, and spherical peeling only. The 3-chloro system has demonstrated a significant ability to reduce drag by up to 50% of the maximum drag reduction, % Dr. The 4-chloro system showed an excellent withdrawal reducer with a maximum of %Dr up to 70%. We have reached a combined high viscosity reduction, interconnected like a Meckler grid [307]. The effects of positive surfactant mixtures on reducing streamlined behavior and cloud formation have been experimentally verified and confirmed [308]. Positive alkyl trimethylammonium (IV) surfactants were experimentally mixed with an alkyl chain length from C12 to C22 in different molar ratios. It was then demonstrated that by adding 10% moles of C12, the effective drag reduction temperature range expands to 40-120 °C, compared to 80-130 °C with surfactant C22 [309]. As a result, mixing cationic surfactants with different alkyl chain lengths is an efficient and convenient way to adjust the drag reduction temperature range [310]. Experimental results in micrographs showed that the micellar network corresponded to the filaments of surfactant solutions in the cloud reduction temperature range. At the same time, vesicles were the dominant microstructures at non-cloud-reducing temperatures, which supports the widely held hypothesis that filament-like micelles are necessary to reduce surfactants [311]. Three anionic surfactants, as well as non-ionic surfactants, have been studied as drag attenuators in the flow of turbulent Iraqi crude oil through transport pipelines, with specific diameters of 0.5, 1, and 3 inches [312]. The researchers concluded that the percentage of drag reduction (%DR) increases with the high concentration of the surfactant (within certain limits), the flow rate of the solution, and the diameter of the transport pipe [313]. Maximum withdrawal reduction of 56.5% obtained at 200 ppm SDBS concentration. Finally, the mechanism of reducing clouds was demonstrated and clarified through the interaction of surfactant micelles with heavy crude oil, allowing the suppression and prevention of turbulence [314]. Four types of anionic surfactants (sodium dodecyl benzene sulfonate (SDBS), sodium lauryl sulfate (SLS), sodium laureth sulfate (SLES), and sodium stearate (SS) have also been experimentally compared as withdrawal reducing agents with refining products such as gas oil and kerosene, at different concentrations (50-300 ppm) [315]. Three closed flow loop systems, with conveyor pipe diameters of 1.91 cm, 2.54 cm, and 5.08 cm, were used in their experimental research. The researcher found that drag reduction increases with higher flow rates (increased Reynolds number) and surfactant concentrations, thereby reducing the pipe diameter [316]. The maximum of 53% of Dr was reached using 300 ppm of surfactant SDBS dissolved in gas oil flowing through the specified 1.91 cm transfer pipe. The maximum of 48% was reached using 300 ppm of SLES dissolved in kerosene flowing through a 1.91 cm cognitive pipe [317]. Drag reduction measurements in the flow of oil and gas alloys have been introduced in two stages. Two types of heavy oils with significantly varying viscosities were examined in horizontal conveyor pipes with an inner diameter of 10 cm to evaluate the effect of oil viscosity on total pressure loss and the effectiveness of drag reduction agents (DRAs) in reducing pressure drop in slug flow [318]. The drop in total pressure in 50cp oil has always been more significant than in 2.5cp oil, especially when the gas flow rate increases [319]. However, they found that DRA was more effective in reducing the overall pressure drop in 2.5 cp oil. Moreover, this increased the speed of the liquid, increasing the effectiveness of both oils' DRA [320]. Some researchers have studied the efficacy and effect of two surfactants (sodium dodecyl benzene sulfonate (SDBS) and sodium lauryl sulfate (SLS)) in heavy crude oil using a closed-loop system for three pipes of different diameters (0.75, 1 and 1.5 inches) and a length of 2 meters each, using three different temperatures :(30°, 40° and 50°C) [321]. The concentrations of each surfactant used range from 50 to 300 ppm. It was discovered that the final values of the results showed the largest decrease in clouds (% DR) to be 23.67% (corresponding to a 16% increase in flow rate). This value was achieved by adding 200 ppm of SDBS at 30 °C [322].

Summary of Previous Experiments

Table 5. Summary of previous experiments on the streamlined behavior of heavy crude oil by adding surfactant

Authors	Additives	Additive concentrations
Yousef Al-Roomi et al. (2004) [323]	Commercial non-ionic surfactant, and Triton X-100	A 1000 ppm aqueous solution of surfactants
T. Babadagli1 (2005) [324]	Surfactant solution	0.1, 0.2, 0.3, 0.4, and 0.5 w%
J.R. HOU et al.(2006) [325]	NaOH	0-1.2 wt% NaOH concentration
G. A. R. Rassoul and Ati A. A. Hadi (2007) [326]	Anionic surfactant (ISOBS)	50, 100, 150, 200, and 250 ppm

Dennis Denney (2008) [327]	Alkali/surfactant (A/S)	0.05-0.1 w%
J. Bryan and A. Kantzas (2009) [328]	Alkali-Surfactant	50, 100, 150, 200, 300, and 500 ppm
V.S. Millioli1 et al. (2009) [329]	Rhamnolipid biosurfactant	1, and 15 mg
Jinxun Wang; Mingzhe Dong (2010) [330]	Alkaline/surfactant	0.05-0.1 w%
Amedea Perfumo et al. (2010) [331]	Biosurfactants	1-10 g/l surfactant to oil
P. Srivastava; L. Castro (2011) [332]	Thin film spreading agents (TFSA)	250 ppm of TFSA
George J. Hirasaki et al. (2011) [333]	Alkaline/surfactant	0.1 and 0.3 w%
S. Trabelsi et al.(2012) [334]	Sodium dodecyl benzene sulfonate (SDBS)	200 ppm from surfactant
Haihua Pei et al. (2012) [335]	Alkaline/surfactant	0.1, 0.2, 0.3-1 w%
Lifeng Chen et al. (2013) [336]	Alkaline/surfactant	Alkyl poly-glucoside (0.05%)
Mehdi Mohammad Salehi et al. (2013) [337]	Surfactant alternating gas (SAG)	0.1 – 1.2 w% from SAG
Kumar et al. (2014) [338]	Mineral oil, SDS, CTAB, and Brij S-20	50-80% mineral oil and 0.1%wt/v of each surfactant
Kwan Min Ko et al. (2014) [339]	Dodecyl alkyl sulfate	0.01 – 0.5 w%
Tarun Kumar Naiya et al. (2015) [340]	Naturally extracted surfactant	500-2000 ppm
Banerjee et al. (2015) [341]	Sapindus mukorossi (soapnut), water, and ethanol	8% w/w of each additive
Zhihua Wang et al. (2015) [342]	Enzymatic syntheses	surfactant additive at a concentration of 100 mg/L
Banerjee et al. (2016) [343]	Sapindus mukorossi (soapnut)	1%, 2%, 3%, 4%, and 5% w/w
Kumar et al. (2016) [344]	Brij 30, mineral oil, and 3-pentanol	5% w/w, and 10% w/w of each additive
Kumar et al. (2017) [345]	Sapindus mukorossi (soapnut), and Brij-30	1000, 1500, and 2000 ppm of each surfactant
Kumar et al. (2017) [346]	Madhuca longifolia (Mahua)	500-2000 ppm of surfactant concentration
Gudala et al. (2017) [347]	Mahua surfactant and dispersed water	0-1000 ppm Mahua surfactant for viscosity measurements, 0-2000 ppm Mahua surfactant, and 0-15% dispersed water for drag reduction measures
Gudala et al. (2018) [348]	Potato starch and dispersed water	5-15 v/v% of dispersed water, and 0-2000 ppm of potato starch concentrations
Xuefan Gu et al. (2018) [349]	Cetyl trimethyl ammonium chloride (CTAC), cetyl trimethyl ammonium bromide (CTAB), and octadecyl trimethylammonium chloride (OTAC)	CTAB, CTAC, and OTAC at 0.01-1.0 wt% to the crude oil samples
Hamad Al-Adwani and Adam Al-Mulla (2019) [350]	Various polyacrylamide (PAM)	70 ppm of PSSS.
Al-Dawery and Shereiqi (2019) [351]	Palm fiber, walnut shell, roasted date kernel, and date kernel	10, 20, and 100 ppm of each bio-material, with particle sizes of 75-150 mm

Negi et al. (2020) [8]	Chitosan-based cationic surfactant (CBCS)	200, 400, and 600 ppm
Jing Gao et al. (2021) [352]	Ex-situ surfactant/solvent	Brij-58/1, 2-dimethylbenzene mixture
Deneb Zamora García Rojas et al. (2021) [353]	Non-ionic surfactants	water-heavy crude oil emulsions (W/O) at a ratio of 30/70 (w/w %)
Hao Ma et al. (2022) [354]	Surfactant-polymer composite system	0.03 moles of APG, 60 ml of Tetrahydrofuran, and 0.05 moles of Hydrogen hydroxide
Yilu Zhao et al. (2022) [355]	Surfactant-biopolymer combined system	0.1 wt% anionic surfactant (fatty alcohol poly-oxyethylene ether sulfate, SC), and 0.05 wt% biopolymer (xanthan gum, XG)
Mayda Maldonado et al. (2023) [356]	Surfactant and water at different temperatures	1.2–2 wt% %.
Yanping Wang et al. (2023) [357]	Synthesized gemini surfactants CEA	Oil/water ratio of 7:3
Ehsan Hajibolouri et al. (2024) [358]	Sodium dodecyl sulfate (SDS), Boronic Ester Anionic Non-Ionic (SYW), SYW Complex with Oleic Acid, and Ethanol-Amine (SYG)	Combined Annealing Simulation (CSA) values AARE, R, MAE, MSE, and RMSE 8.982, 0.996, 0.004, 0.0002, and 0.0132, respectively.
Wanfen Pu et al. (2024) [359]	Surfactants—sodium dodecyl sulfate (SDS), sodium oleate (SO), and APG0810	0.3% SO with 0.5% n-pentanol
Temurali Kholmurodov et al. (2024) [360]	Nonionic surfactants and catalysts	Aluminum oxide and sodium hydroxide solution, processed for 4 hours with temperature changes
Xianwu Zhang et al. (2025) [361]	Cationic polymeric surfactant	0.001 wt% Q-g-PN concentration via the proposed temperature-regulated

Comparison Table of Heavy Crude Oil Transportation Improvement Technologies

Through this comprehensive study, we can summarize the fundamental differences between surfactants, nanoparticles, and solvents in the transportation process of heavy crude oil.

Table 6. Comparison table of heavy crude oil transportation improvement technologies

No.	Evaluation Criterion	Surfactants	Solvents	Nanoparticles
1	Mechanism of action	Reduces viscosity by forming a stable emulsion	Direct dilution by blending (dilution method) or by separation of asphalt components (extraction method)	It breaks up asphaltins and adsorbs them because it has a very high surface area.
2	Its efficiency in reducing viscosity	Good to very good (depending on the type of surfactant)	Very good and fast	Very good, and according to the types used
3	Its thermal stability	Very good to excellent (depending on the type of surfactant)	Medium to weak	Excellent operating at various temperatures and at high pressures
4	Impact on the environment	Low and may increase depending on the type of surfactant	Low to medium	Low

5	Cost	Medium	Sometimes it is low, and sometimes it is high, depending on the type of solvent.	Higher than the previous ones
6	Ease of application in the field	Easy and based on the mixing concentration control	very easy	More complicated, because it needs a special technique
7	The extent of its interaction with asphaltins	Effective in breaking up asphaltins	Efficient, especially aromatic solvents	Very effective through adsorption and fragmentation at the nanoscale
8	Reuse	Mostly can't	Possible	Possible through the process of separation and activation
9	Safety (health hazards)	Moderate	Highly flammable solvents	Low to moderate
10	The extent of its impact on transportation	Improves flow and reduces pressure difference	Improves flow and reduces pressure difference	Improves flow and reduces pressure difference excellently if applied correctly.

Result and Conclusion

For the optimal utilization of heavy oil and bitumen, it is essential to advance technology that facilitates their transportation through pipelines. This review paper presents additives used to enhance the transportation of heavy crude oil and bitumen through pipelines. Each of the three methods used to decrease viscosity and facilitate the transportation of a heavy crude oil pipeline was presented. The technologies used take into account oil characteristics, regional logistics between the wellhead and the refining location, operational issues, transportation distance, cost, environmental concerns, and legislation. However, the current strategy in the oil industry is to integrate on-site modernization into enhanced oil recovery methods, due to the cost, the energy efficiency they provide, and their environmental benefits. By examining previous studies that employed various techniques to enhance the transport of heavy crude oil in pipes, it was found that the most effective optimization method involves using a mixture of solvents with the addition of nanoparticles. The addition of nanostructured silica particles to a solvent, such as naphtha or kerosene, can reduce the viscosity of heavy crude oil by 80% to 90%. Furthermore, adding surfactants to the mixture of solvents and nanoparticles significantly reduces the viscosity of the oil. In addition to the above, studies have also shown that the percentage of surfactant added must be in an appropriate amount; otherwise, high percentages of added surfactant lead to the opposite result, as the viscosity of crude oil increases. Therefore, it is necessary to select an appropriate percentage of the added surfactant to achieve the objectives of the addition. The same applies to adding nanomaterials. Adding high and inappropriate percentages of nanoparticles can lead to the agglomeration and aggregation of the particles. Thus, they will lose their properties, which are essential for adsorbing metals and impurities in crude oil. Through the nanoparticles' adsorption of minerals and contaminants in the crude oil, the process of upgrading the crude oil occurs. However, if the added percentages increase, agglomeration of the nanomaterials will occur, and they will lose their ability to improve the properties of the heavy crude oil. Instead, their agglomeration, aggregation, and deposition increase the percentage of impurities in the crude oil, and thus, the pulling force increases, which in turn increases the viscosity percentage. For all of this, we cannot determine a single ratio applicable to all types of nanoparticles or surfactants; therefore, it cannot be said that this ratio is suitable for all types. Instead, the proper ratio to be added is determined through experiments and practical studies, as research papers have shown. Regarding the solvents used, studies have also demonstrated that the volumetric percentages added vary depending on the type of solvent and its physical properties. Therefore, it is not possible to determine a single volumetric ratio; thus, it is said that the optimal ratio to use for all types of solvents is not applicable. Instead, each solvent must be studied separately. For some solvents, the optimal volumetric ratios to be added to crude oil are: 1:15, and for others: 1:10, Some of them: 1:8, some of them: 1:5, some of them: 1:4, some of them: 1:3, some of them: 1:2, and some of them: 1:1. With the caveat that the optimal ratio is not the best in improvement, but rather it is the ratio that achieves improvement at the lowest cost. Otherwise, adding high percentages of solvent leads to a significant improvement and upgrade; however, this upgrade comes at a high cost. Therefore, engineers and scholars in the oil industry are seeking to achieve the necessary adjustments at the lowest possible price.

Nomenclature

Symbol	**Definition**
DRA	Drag reduction agents
EOR	Enhanced oil recovery
IOR	improve oil recovery
MEK	Methyl ethyl ketone
HO	Heavy oil
EHO	Extra heavy oil
SARA	Saturates, Aromatics, Resins, and Asphaltenes
ELV	Cohesion Energy
V_M	Molar Volume
NPs	Nanoparticles
DME	Dimethyl Ether
T	Temperature
Δ	Hansen Parameter
µ	Kinematic Viscosity
Δp	Polar Component
Δd	Dispersion Component
Δh	Hydrogen Component
VR	Viscosity Reduction

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