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An Overview on the Recent Techniques for Improving the Flowability of Crude Oil in Pipelines

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Abstract. Crude oil is considered as a major source of energy all over the world. Midstream refers to the various methods of transportation. Important issues that oil transportation methods face are spills and inadvertent emissions. Therefore, most of the technology developments in transportation methods are aimed at reducing emissions, increasing efficiency, or preventing spills and leaks. Piping systems are the safest and most efficient and cost-effective way for crude oil transportation. The process suffers from serious problems such as: asphaltene and paraffin structures interactions, pipes pressure drop, and high pumping energy consumption. One of the economical important challenges in oil pipeline transportation is to keep the flowability and reduce the pressure drop along the pipe. The current review highlights the recent and most development techniques which have been used to enhance the fluidity of crude oil in pipelines.

1. Introduction

The economic development and the dramatic population growth recorded in recent decades, cause a rising demand for fossil fuels, that result in a gradual decline in the conventional oil reserves, including both light and medium crude oil reserves, which have become scarce and insufficient to meet the continuous increase in energy demand. Unconventional oil reserves, including heavy oil, extra heavy oil, oil sand, tar sands, oil shale and bitumen reserves represent an alternative resource for fossil fuels. However, in contrast with conventional oil, unconventional oil cannot be recovered and subsequently transported in their natural state by the typical production and transportation methods, it generally requires an additional effort to guarantee its flowability in an acceptable flow rate. Therefore, the development of new technologies becomes crucial for the economical production of unconventional oils. Heavy oils are expected to become a great alternative to conventional oil in the future.

2. Fossil Fuel

Fossil fuels are hydrocarbons created from dead animals and plants decomposition, that were sunk to the bottom of the ocean, covered by deposits of sedimentary rock, subjected to intense heat and pressure over millions of years, and then transformed into oil and gas. Hydrocarbons migrate through permeable sedimentary source rock toward the earth surface, trapped beneath impermeable sedimentary cap rock, and then formed oil and gas reservoirs. The origin of oil is shown in (Figure 1). A reservoir is a porous sedimentary rock that has tiny spaces which can hold large quantities of water, gas, and oil. Three different types of fossil fuels were formed, coal, gas, and oil, that depend on the organic material combination, burial depth and time length, and pressure and temperature conditions. About 82% of global energy is supplied by this type of fuel, also it considered as non-



renewable energy source, as it has taken millions of years to form [2, 3].

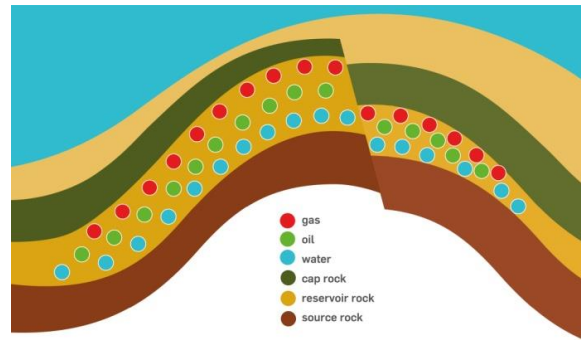


Figure 1. Origin of oil [1].

3. Crude Oil

Crude oil is extracted from a reservoir by drilling a well, then pumping the oil up the well. As soon as the oil is recovered, it is transported to a refinery where it undergoes a complex refining process that produces different petroleum products. Crude oil can be classified into different categories.

Light and heavy crude oil deals with oil density.

Sweet and sour crude oil deals with the sulfur content, sour crude oil has sulfur greater than 0.5%.

Conventional and unconventional crude oil deals with different extraction methods, conventional crude oil is extracted by traditional extraction methods and requires minimal processing techniques after being produced, while for unconventional crude oil, it is extracted by advanced extraction methods and requires additional processing techniques after being produced in order to be transported and refined, since unconventional oil cannot be recovered and transported in its natural state [2-3].

3.1 Heavy Oil

Heavy oil is one form of unconventional oil, that is characterized by high viscosity, high density, high specific gravity, low H/C ratio, as well as high contents of asphaltenes, resins, sulfur, and heavy metals. API (American Petroleum Institute) is a measure of oil lightness and heaviness as:

$$API = \frac{141.5}{SG} - 131.5$$

Where specific gravity is the ratio of oil density to density of water at standard conditions [2-3]. The classification of crude oil with respect to viscosity and API is shown in Figure 2.

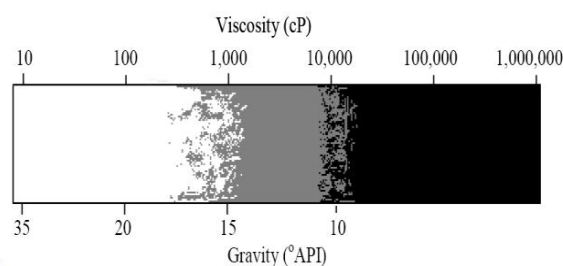


Figure 2: Classifications of crude oil [4].

4. Oil Transport through Pipelines

Midstream refers to the various transportation methods used to move oil from one location to another, that includes tank trucks, rail cars, tanker ships, and pipelines. Crude oil is extracted in remote sites away from where it is stored, processed, or consumed. Therefore, transportation networks have been built to transport crude oil from extraction site to storage facilities or refineries where it is stored or processed, and to transport refined products from refineries to distribution facilities where it is consumed. In the near future, it is expected that these four transportation methods will continue to be used, unless a new transportation method is found. Therefore, most of the technology developments in transportation methods are aimed at increasing efficiency, reducing emissions, or preventing spills and leaks [5-8]. Transportation methods comparison is summarized in Table 1.

4.1 Pipelines

About 70% of all petroleum products are transported by pipelines. Pipelines have several competitive advantages over other forms of oil transportation. They are considered as an expensive technique that has high capital and maintenance costs, and takes a significant time to set up. Moreover, pipelines require a series of pumping stations, usually referred to as booster pumps, situated at various intervals along each route, thus further adding to transportation costs. However, they transport more crude oil and refined products at less cost and require less human capital capacity. Pipelines are eco-friendly and considered as the most cost efficient and the most energy efficient form of oil transportation, that uses less fuel and has less rates of carbon footprint. They perform the best related to spill risks, human fatalities, environmental impacts, and property destruction. Spill risks are rare in relation to the massive volume of oil being transported. Spill risks caused by pipelines are 4.5 times less compared to rails [5-8]. Kirkuk - Ceyhan pipeline of 970 km used to deliver crude oil to Botas terminal in Ceyhan, Turkey, is shown in Figure 3.

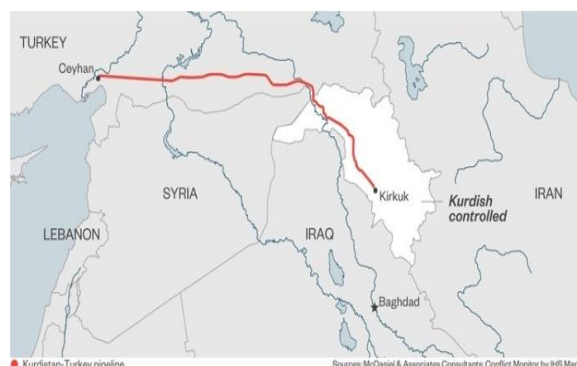


Figure 3: Kirkuk - Ceyhan pipeline [9].

5. Flow Improving Techniques

There are several techniques used to enhance the crude oil transportation via pipelines, the most popular and common techniques are: dilution, heating, core annular flow, drag reduction additives, and electric or magnetic field. The following paragraphs review briefly the flow improving techniques.

5.1 Dilution

Dilution is generally the oldest and most popular techniques to reduce the high viscosity of heavy oil since the 1930s. The basis of this technique is that the addition of less viscous oil to high viscous crude oil decreases the viscosity of the later to an acceptable level for pumping, since the mixture of two oils with different flow properties results in a mixed oil with a flow property between those of the initial oils. Dilution is an effective technique to improve the crude oil flow properties, and to

facilitate certain operations such as dehydration and desalting. Dilution requires two pipelines, one for the oil and the other for the diluent. A ratio of 20% to 30% of solvent is sufficient to enhance the crude oil transportation via pipelines. According to [10], dilution requires large amount of diluent to reduce the heavy oil viscosity to an acceptable limit for transportation, that might reach 30%, that causes an increase in the transportation volume, which requires large pipeline capacity. Therefore, it requires substantial investments in pipelines, that results in a cost increase. As explained by [11], dilution causes asphaltenes precipitation, that results in an instability during transportation and storage, which leads to a subsequent pipeline blockage, and therefore requires compatibility testing between the oils. Moreover, the oil mixture has a lower selling price than the diluent, due to the lower quality of the heavy oil. Based on the ideas of [12], dilution requires predetermine the mixing ratio and reliable measurement of mixture viscosity and compatibility, since simple mixing rules do not directly apply, and any change in oil composition may affect the required mixing ratio.

5.1.1 Light crude oil as diluent

On the other hand [13] suggested a recycling of diluents for re-use, due to the increasing scarcity of light oil and the declining reserves of conventional light crude oil. However, it requires installing a diluent recovery unit, that separates the diluents and subsequently returns it to the oil production site, which requires substantial investments to operate an additional pipeline system, and therefore results in a cost increase. Dilution with light oil is less efficient than with condensate in the dilution of heavy oil. According to [14], dilution with light oil has much better results than with alcohol. In an experiment with heavy oil, a dilution with 10% of light oil that has a viscosity of 300 cP, causes a decrease in heavy oil viscosity from 10000 cP to 1200 cP. In an experiment with heavy oil, a dilution with 20% of light oil that has a viscosity of 300 cP, causes a decrease in heavy oil viscosity from 10000 cP to 350 cP. As explained by [15], dilution with light oils is an expensive technique that has low efficiency in the dilution of heavy oil, causes asphaltenes precipitation and requires further heating. In an experiment with heavy oil, a dilution with 30% of light oil, and an increase in the applied temperature from 20 °C to 30 °C, causes a decrease in heavy oil viscosity from 15000 cP to 1000 cP. In an experiment with heavy oil, a dilution with 30% of light oil, and an increase in the applied temperature from 20 °C to 50 °C, causes a decrease in heavy oil viscosity from 15000 cP to 300 cP.

5.1.2 Alcohol as diluent

Based on the ideas of [14], dilution with light oil has much better results than with alcohol. In an experiment with heavy oil, a dilution with 10% of alcohol, causes a decrease in heavy oil viscosity from 10000 cP to 2000 cP. In an experiment with heavy oil, a dilution with 20% of alcohol, causes a decrease in heavy oil viscosity from 10000 cP to 940 cP. According to [16], dilution with alcohol is doubly effective than with kerosene in the dilution of heavy oil.

5.1.3 Naphtha as diluent

As explained by [16], naphtha is a liquid hydrocarbons mixture separated from the crude oil, that has low density, low viscosity, and high API gravity. Dilution with naphtha is an alternative to condensate, that has good compatibility with asphaltenes and high efficiency in heavy oil dilution. A mixture of naphtha and organic solvent causes a decrease in the amount of diluent required to reduce the heavy oil viscosity to an acceptable limit for transportation. Based on the ideas of [17], in an experiment with crude oil, a dilution with naphtha, causes a decrease in crude oil viscosity from 250 cP to 40 cP.

5.1.4 Condensate as diluent

According to [18], condensate is a liquid hydrocarbons mixture separated from natural gas, that has low density, low viscosity, and high API gravity. Dilution with condensate causes asphaltenes precipitation. Condensate availability depends on natural gas. Therefore it is insufficient to meet the

increasing heavy oil production needs. As explained by [17], in an experiment with crude oil, a dilution with condensate causes a decrease in crude oil viscosity from 250 cP to 50 cP.

5.1.5 Kerosene as diluent

Based on the ideas of [13], dilution with kerosene is an expensive technique, that requires large amount of diluent to reduce the heavy oil viscosity to an acceptable limit for transportation, ranges from 0% to 20% for heavy oil, and from 25% to 50% for bitumen.

5.2 Heating

Heating is generally the most commonly used technique to reduce the high viscosity of heavy oil carried via pipelines. The basis of this technique is that viscosity decreases with increasing temperature, making it less difficult to pump oil. Heating is an attractive technique to facilitate crude oil flow properties mobility in the pipeline, and to decrease the resistance to flow. According to [19], preheating the heavy oil then subsequent heating the pipeline is required to reduce heavy oil viscosity and to improve heavy oil flow ability. However, the increase in temperature affects the heavy oil macromolecular structures, keeping monomer units scattered, that results in an instable flow. Moreover, heating losses occur along the pipeline to the surroundings during crude oil transportation. Therefore heating requires number of heating stations, that causes an increase in implementation costs. Crude oils with viscosity less than 500 cP can be economically pumped. As explained by [13], pipeline insulation is required to reduce heat losses and to maintain the high temperature at which the oil is extracted at the wellhead. For short distances, pipelines are insulated and crude oils are moved as quickly as possible to minimize temperature losses. However, for longer lengths of pipelines, insulation becomes ineffective. Moreover, temperature variation causes pipeline expansion. Sudden expansion and contraction causes challenging problems. Therefore, for above ground pipelines, expansion loops are used to absorb the expansion, while for buried pipelines, thicker steel is required. Based on the ideas of [10], reheating the heavy oil at pumping stations through direct fired heaters is required to minimize temperature losses and to compensate gradual cooling in the pipeline. A direct-fired heater is generally used to raise the temperature of the oil. Heaters can be natural gas or fuel oil fired. Plugging generally occurs when the pipelines are cooled down to ambient temperature. Therefore displacement oil must be used during start-up and shutdown operations to secure future start-up without difficulty. According to [14], electrically heated subsea pipeline is a difficult technique because of the cooling effect exerted by the seawater, the complexity of the pipeline design, the difficulty of installing, maintaining, and power supplying submerged subsea pumping and heating stations. As explained by [20], in an experiment with medium crude oil that has a density of 0.929 g mL^{-1} , an increase in the applied temperature from 10°C to 30°C , causes a decrease in viscosity from 700 cP to 300 cP. Based on the ideas of [11], heated pipeline is an expensive technique that has high capital and operational costs and involves technical considerations regarding pipeline expansion, pipeline internal corrosion, heat loss estimations, number of pumping and heating stations, and the fact that it is necessary to heat the whole pipeline length. On the other hand [21] suggested an electrically heated subsea pipeline of a concentric pipe-in-pipe configuration for offshore pipeline transportation of heavy oil at cold temperature of subsea environment, where the electrical current flows along an inner electrically insulated pipe, which is surrounded concentrically by an outer pipe.

5.3 Core Annular Flow

Core annular flow is a water-oil two-phase flow technique. The basis of this technique is to surround the crude oil and to lubricate the pipeline wall with water, which acts as a lubricant that absorbs the shear stress existing between the oil and the pipeline wall, since the less viscous phase migrates to the high shear region near the pipeline wall. In this regard, the water flows as the annulus while the crude oil flows as the core. A ratio of 10% to 30% of water is sufficient to enhance the crude oil transportation via pipelines. According to [22], oil tends to adhere to the pipeline walls. The gradual adherence of oil leads to a subsequent pipeline blockage, that can be aggravated during a shutdown

operation, where stratification of the oil and water occurs. However, increasing the pressure restores the system. As explained by [11], large density difference between the fluids causes a buoyancy force, that pushes the oil core up to the pipeline wall, which leads to an instable core annular flow. The stable and instable core annular flow is shown in Figure 4.

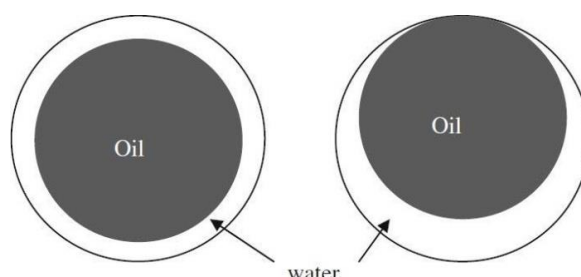


Figure 4: Stable and instable core annular flow [19].

Moreover, velocity difference between the fluids creates waves at the oil-water interface, that result in a wavy core annular flow. However, increasing the velocity enhances the core stability. Based on the ideas of [23], core annular flow causes a pressure drop reduction by 90%, compared to that without water lubrication. According to [24], perfect core annular flow is very rare and may only exist for fluids of possibly similar densities. There have been only two industrial core annular flow examples since 1970, and it seems that no project concerning this method is planned today.

5.4 Drag Reduction Additives

Drag force is defined as the force that must be overcome to drive the fluid through the pipeline during transportation. The basis of this technique is that the drag reduction additive molecules can be stretched out to long chains due to their elastic properties, and form films or layers inside crude oil matrix, that act as shock absorbers, that have the ability to damp and suppress smaller eddies, which are responsible for the drag in turbulent flow, and cause a drag reduction or a decrease in pipeline turbulence, and therefore an increase in flow rate. Drag reduction additives can be classified into three main categories: surfactants, fibers, and polymers. Surfactants reduce friction near the pipeline walls, while fibers and polymers suppress the growth of turbulent eddies within the turbulent fluid core. It was first discovered in 1948. As explained by [25], drag reduction is difficult with heavy oils, due to their high viscosity. The increase in viscosity causes an increase in frictional loss, that results in an inefficient flow and wasted energy, which requires an additional dilution or heating technique. Moreover, the transportation over long distances causes an increase in pressure drop, that requires an application of more pressure to maintain a constant flow rate. However, specifications of pipeline design may limit the amount of pressure required, and therefore causes a decrease in investment costs. Based on the ideas of [26], high molecular weight polymers are by far the most efficient drag reducers, that cause a drag reduction with heavy oils by 28% to 36%, compared to commercial drag reduction additives, that cause no drag reduction with heavy oils. According to [27], a mixture of polymer and surfactant causes more efficient drag reduction than that of additives alone. When the shear stress increases and reaches a critical shear stress value, the drag reduction caused by the surfactant solution alone disappears, while that of polymer remains. As explained by [28], polymers should have high molecular weight, shear degradation resistance, quick solubility in the fluid, and stability against heat and chemical agent. Current generation of drag reduction additives have ultra-high molecular weight polymers, that have long chain of hydrocarbons, which act as an intermediate layer between the fluid and the inner wall of the pipe to reduce energy loss caused by turbulence. However, commercial drag reduction polymers do not perform well with heavy oils having low API gravities and high asphaltene content. Based on the ideas of [29], surfactants cause less drag reduction than polymers. However, after the critical shear stress is decreased to a certain level, surfactants have the ability to recover its microstructures and re-assume its own drag reduction. According to [30], a dosage of 10 ppm of

polyisobutylene was required to keep a constant pressure drop. However, determining the dosage required to maintain constant pressure drop is challenging. Moreover, smaller diameter and rougher surface pipes cause an increase in Reynolds number, that cause an increase in drag reduction. As explained by [31], drag reduction additives of polymeric suspensions have a difficulty when dissolved in heavy oils, and a tendency to separate when stored, and degrade when passed through a pump or severe constrictions, that limit their use and reduce its effectiveness dramatically.

5.5 Electric and Magnetic Field

This electrical field technique does not change the crude oil temperature, it temporary aggregates paraffin and asphaltene suspended particles inside the crude oil into short chains along the field direction. The particle aggregation changes the crude oil rheological property and leads to viscosity reduction. The mechanism of electrical field technique is shown by Figure 5.

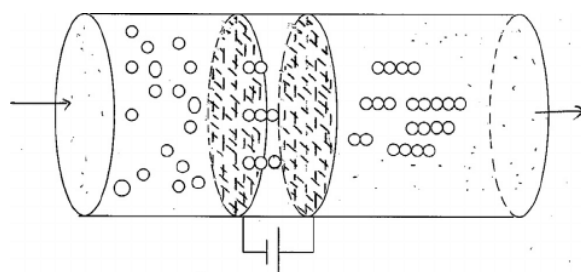


Figure 5: Mechanism of electrical field technique [36].

However, this viscosity reduction is temporary and not permanent, it lasts for hours. Therefore, reapplication of the electric field along the way is needed. It is well-known that there is always some water content inside asphalt-base crude oil, and accidental discharge sparks or dielectric breakdown may occur. However, it does not cause any fire due to the lack of oxygen, since the electrodes are fully immersed inside the crude oil. For the magnetic field technique, it is considered safer than the electric field technique because it does not have that accidental discharge spark issue. Based on the ideas of [32], bunker diesel is the cheapest and heaviest fuel that has high amounts of sulfur and serious pollutants issue, that is obtained after gasoline and diesel distilled away from crude oil. Bunker diesel is any type of fuel oil used aboard ships, that cannot be used on cars and trucks, because it needs to be heated in order to make it flow. In an experiment with bunker diesel fuel, an application of 1.5 kV mm^{-1} of electric field for 18.8 s, causes a decrease in viscosity by 50%, that results in an increase in flow rate by 30%. According to [33], biodiesel is an alternative diesel engines fuel that is produced by a reaction of a vegetable oil or animal fat with an alcohol which is not derived from petroleum, has higher viscosity and less rates of carbon footprint compared to petroleum products. In an experiment with biodiesel, an application of 1.667 kV mm^{-1} of electric field for 10.86 s, causes a decrease in viscosity from 3.65 cP to 2.91 cP, by 25.5%, that results in an increase in flow rate from 1.4 mg s^{-1} to 1.77 mg s^{-1} , by 20%, which leads to a decrease in droplets size by 41%, and therefore causes an increase in engine combustion by 20%. As explained by [34], in the experiment with asphaltene base crude oil, an application of 1.612 kV mm^{-1} of electric field at 23°C , causes a decrease in viscosity from 715.8 cP to 383.4 cP, an application of 1.704 kV mm^{-1} of electric field at 16°C , causes a decrease in viscosity from 1821.2 cP to 1022.0 cP, an application of 1.704 kV mm^{-1} of electric field at 12°C , causes a decrease in viscosity from 2750.5 cP to 1559.2 cP, and an application of 1.612 kV mm^{-1} of electric field at 6°C , causes a decrease in viscosity from 6003.7 cP to 3594.0 cP. On the other hand [35] used different values of applied voltage, electrodes distance, treatment time, and nanosilica concentration, that ranges between 140-220 V, 2010 cm, 0-60 s, and 0-700 mg L^{-1} respectively. In the experiment with 31.2 °API crude oil, an application of 188 V of voltage for 32 s, at 10°C , with a distance of 6.11 cm between the electrodes, causes a decrease in viscosity without nanosilica addition from 32.5 cSt to 20.479 cSt, by 37%, that results in an increase in flow

rate by 45.6%, and causes a decrease in viscosity with 100 mg L⁻¹ of nanosilica addition from 32.5 cSt to 12.8 cSt, by 60.6%, that results in an increase in flow rate by 77.8%. The electrical capacitor design is shown in Figure 6.

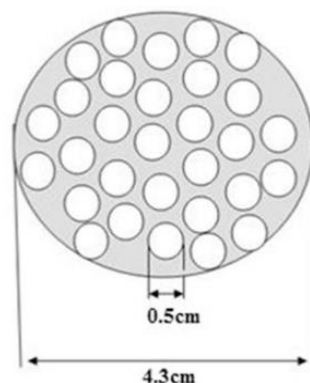


Figure 6: Electrical capacitor designed by [35].

Based on the ideas of [36], in the experiment with 34 °API crude oil, an application of 1.6 kV mm⁻¹ of electric field at 1.5 °C, causes a decrease in viscosity from 105.4 cP to 53.9 cP, by 48.9%, that results in an increase in flow rate from 4.95 mg s⁻¹ to 10.1 mg s⁻¹, by 104%, an application of 1.6 kV mm⁻¹ of electric field at -1.4 °C, causes a decrease in viscosity from 149.9 cP to 56.7 cP, by 62.2%, that results in an increase in flow rate from 3.633 mg s⁻¹ to 9.71 mg s⁻¹, by 167%, and an application of 1.6 kV mm⁻¹ of electric field at -3.1 °C, causes a decrease in viscosity measured by a capillary tube viscometer from 261.3 cP to 46.7 cP, by 82.1%, that results in an increase in flow rate from 2.08 mg s⁻¹ to 11.66 mg s⁻¹, by 460.6%, and causes a decrease in viscosity measured by a Brookfield rotational viscometer from 261.3 cP to 121.1 cP, by 53.7%, that increased to 151.2 cP, by 42.1% after 12 h, that further increased to 172.4 cP, by 34% after 24 h. According to [37], sulfur particles have high dielectric constant. Ultra low sulfur diesel viscosity reduction is much less than that of high sulfur diesel, therefore it needs much stronger electric field. In the experiment with high-sulfur diesel, an application of 1 kV mm⁻¹ of electric field for 2 s, causes a decrease in viscosity from 4.6 cP to 4.18 cP, by 10%. However, its viscosity takes more than 60 min to return to its original value. In the experiment with ultra-low-sulfur diesel, an application of 2 kV mm⁻¹ of electric field for 5 s, causes a decrease in viscosity by 23%, that results in an increase in flow rate by 30%, which leads to a decrease in droplet size by 41%. However, its viscosity reduction does not last long, its viscosity takes about 4 min to return to its original value. As explained by [38], a decrease in the fuel viscosity, causes a decrease in the fuel droplets size, that results in an increase in the fuel droplets surface area, which leads to a decrease in the incomplete combustion and carbon emissions, and therefore causes a cleaner and more efficient combustion. Diesel fuel viscosity is much higher than that of gasoline, therefore diesel fuel has much bigger droplets size. However, its viscosity takes quite a while to return to its original value. In an experiment with diesel fuel, an application of 1 kV mm⁻¹ of electric field for 2 s, causes a decrease in viscosity from 4.6 cP to 4.18 cP, by 9%, that results in an increase in the droplets number from 5.3% to 15.3%. In the experiment with gasoline, an application of 1.2 kV mm⁻¹ of electric field, causes an increase in the droplets number from 17.6% to 20.7%, by 18%.

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References

- [1] <https://krisenergy.com/company/about-oil-and-gas/origin.html>
- [2] Hyne N J 2012 *Nontechnical Guide to Petroleum Geology, Exploration, Drilling, and Production* (Tulsa, Okla: PennWell Books) ed. 3
- [3] Ala M 2017 *An Introduction to Petroleum Geoscience*. London: World Scientific Publishing.
- [4] Aske N, Kallevik H, Johnsen E E and Sjoblom J 2002 *Energy & Fuels* **16** 1287
- [5] Rodrigue J-P, Comtois C, and Slack B 2017 *The Geography of Transport Systems* (New York: Routledge) ed. 4
- [6] Hénaut I, Forestiere A, Heraud J P and Argillier J F 2007 *US Patent Application* 20070295642
- [7] Argillier J F, Henaut I and Gateau P 2006 *US Patent Application* 20060118467
- [8] Van den Bosch P J W M and Schrijvers F A M 2006 *US Patent Application* 20060144754
- [9] <http://www.digirev.us/kirkuk-map.html>
- [10] Martínez-Palou R, Mosqueira M L, Zapata-Rendón B, Mar-Juárez E, Bernal-Huicochea C, Clavel-López J C and Aburto J 2011 *Journal of Petroleum Science & Engineering* **75** 274
- [11] Sanière A, Henaut I and Argillier J F 2004 *Oil & Gas Science & Technology* **59** 455
- [12] Zaman M, Bjorndalen N and Islam M R 2004 *Petroleum Science & Technology* **22** 1119
- [13] Santos R G, Loh W, Bannwart A C and Trevisan O V 2014 *Brazilian Journal of Chemical Engineering* **31** 571
- [14] Hasan S W, Ghannam M T and Esmail N 2010 *Fuel* **89** 1095
- [15] Yaghi B M and Al-Bemani A 2002 *Energy Sources* **24** 93
- [16] Gateau P, Henaut I, Barre L and Argillier J F 2004 *Oil & Gas Science & Technology* **59** 503
- [17] Myers R D, MacLeod J B, Ghosh M and Chakrabarty T 2000 *US Patent Application* 6096192
- [18] Shigemoto N, Al-Maamari R S, Jibril B Y and Hirayama A 2006 *Energy & Fuels* **20** 2504
- [19] Hart A 2014 *Journal of Petroleum Exploration & Production Technology* **4** 327
- [20] Ghannam M T and Esmail N 2006 *Petroleum Science & Technology* **24** 985
- [21] Langner C G and Bass R M 2001 *US Patent Application* 6264401
- [22] Wylde J J, Leinweber D, Low D, Botthof G, Oliveira A P, Royle C and Kayser C 2012 Heavy Oil Transportation: Advances in Water Continuous Emulsion Methods. In: Proceedings of the world heavy oil congress, Aberdeen.
- [23] Bensakhria A, Peysson Y and Antonini G 2004 *Oil & Gas Science & Technology* **59** 523
- [24] Bannwart A C 2001 *Journal of Petroleum Science & Engineering* **32** 127
- [25] Johnston R, Lauzon P and Pierce J 2008 *Hydrocarbon Engineering* **13** 89
- [26] Milligan S N, Johnston R L, Burden T L, Dreher W R, Smith K W and Harris W F 2008 *US Patent Application* 20080149530
- [27] Matras Z, Malcher T and Gzyl-Malcher B 2008 *Thin Solid Films* **516** 8848
- [28] Peysson Y, Bensakhria A, Antonini G and Argillier J F 2007 *SPE Production & Operations* **22** 135
- [29] Zhou T, Leong K C and Yeo K H 2006 *International Journal of Heat & Mass Transfer* **49** 1462
- [30] Mowla D and Naderi A 2006 *Chemical Engineering Science* **61** 1549
- [31] Harris W F, Smith K W, Milligan S N, Johnston R L and Anderson V 2006 *US Patent Application* 20060148928
- [32] Du E, Xu X, Huang K, Tang H and Tao R 2018 *International Journal of Modern Physics B* **32**
- [33] Du E, Cai L, Huang K, Tang H, Xu X and Tao R 2018 *Fuel* **211** 194
- [34] Du E, Zhao Q, Xiao Y, Cai L and Tao R 2018 *Fuel* **220** 358
- [35] Ibrahim R I, Oudah M K and Hassan A F 2017 *Journal of Petroleum Science & Engineering* **156** 356
- [36] Tao R and Tang H 2014 *Fuel* **118** 69
- [37] Du E, Tang H, Huang K and Tao R 2011 *Journal of Intelligent Material Systems & Structures* **22** 1713
- [38] Tao R, Huang K, Tang H and Bell D 2008 *Energy & Fuels* **22**, 3785