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A review of technologies for transporting heavy crude oil and bitumen via pipelines

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Abstract Heavy crude oil and bitumen resources are more than double the conventional light oil reserves worldwide. Heavy crude oil and bitumen production is on average twice as capital and energy intensive as the production of conventional oil. This is because of their extremely low mobility due to high viscosity at reservoir conditions alongside the presence of undesirable components such as asphaltenes, heavy metals and sulphur making it more challenging to produce, transport as well as refine. It is well know that pipelines are the most convenient means of transporting crude oil from the producing field to the refinery. However, moving heavy crude oil and bitumen is extremely challenging because of their inability to flow freely. As such, without prior reduction in the heavy crude oil and bitumen viscosity, transportation via pipeline is difficult. This is because of the huge energy (i.e. high pumping power) required to overcome the high-pressure drop in the pipeline due to their high viscosity at reservoir conditions. To reduce this high-pressure drop and cost of transportation, several technologies have been proposed to improve the flow properties of the heavy crude oil and bitumen through pipelines. In this study, different technologies are reviewed and the advantages and disadvantages of each technology are highlighted with the view that the review will provide direction for improvement and development of novel technologies for bitumen and heavy oil transportation via pipelines.

Keywords Heavy oil · Bitumen · Transportation

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Introduction

The US Department of Energy, the International Energy Agency (IEA) and World Energy Council have projected that energy demand would increase year in year out as the world population is ever-growing. The world demand for crude oil has increased from 60 million barrels per day to 84 million barrels per day, in the past 20 years (Hasan et al. 2010). With this mindset, it therefore necessary to exploit other hydrocarbon sources as well as alternative energy resources to meet the ever-growing energy needs globally. In the past, heavy crude oil and bitumen production was considered to be uneconomic, because of the intensive cost of recovery, transportation, refining and low market value. Additionally, the decline of conventional middle and light crude oil as well as the ever-growing world energy demand drives the exploitation of this hydrocarbon resource. In Canada, about 700,000 barrels per day of synthetic crude oil is obtained from heavy crude oil and bitumen/tar sands and transported via pipelines to refineries in Canada and the USA (Hsu and Robinson 2006).

It is hard to recover and process heavy crude oil and bitumen, owing to their high viscosity (i.e. resistance to flow) at reservoir conditions (making their mobility extremely low) and high carbon-to-hydrogen atomic ratios. Hitherto, with the rising price of crude oil, declining reserves of medium and light crude oil and the abundance of unconventional crude oil (i.e. heavy oil and bitumen/tar sands), their exploitation is therefore favoured. However, heavy crude oil and bitumen exploitation is faced with technical challenges at all stages from recovery/production from the reservoir to transportation and refining. Transporting heavy crude oil and bitumen via pipeline is usually challenging due to their high density and viscosity (>1,000 cP) and very low mobility at reservoir temperature. Asphaltene deposition, heavy metals, sulphur and brine or salt content make it difficult to be transported and refined using conventional refinery methods without firstly upgrading them to meet conventional light crude oil properties (Zhang et al. 2010; Hart 2012). Also, the presence of brine or salt in the heavy crude stimulates corrosion problems in the pipeline (Martinez-Palou et al. 2011). In some cases, the formation of emulsion such as the oil–water mixture produced from the reservoir poses transportation difficulty.

Though the issue of the environment remains a concern, petroleum is still the dominant source of energy worldwide for our transportation fuels. The global demand for energy to meet our daily industrial and transportation needs is ever growing at an average annual growth rate of 1.6 % (OECD/IEA 2005). The estimated heavy crude oil reserve globally by the IEA is about 6 trillion barrels (OECD/IEA 2005). Despite this global magnitude of heavy crude oil and tar sand reserves, their production is still low (Saniere et al. 2004; Hart et al. 2013). However, it has attracted a growing interest presently by the petroleum industry. This current trend in heavy crude oil and bitumen exploitation is because of the decline of conventional middle and light crude oil reserves and the limited supply and rising price of crude oil. Consequently, Canada and Venezuela are the major countries presently exploiting heavy crude oil reserves. Pipelines are used to transport about 95 % of the heavy crude oil produced in Canada and Venezuela, respectively. This is because pipelines are the least expensive, environmentally convenient and the most effective means to transport crude oil from the field to the refinery.

The fundamental recovery technique like the primary recovery method, which depends on the natural energy within the reservoir to push the crude oil through the production well, is inadequate for heavy crude oil and bitumen recovery. This is because of their extremely high viscosity (i.e. resistance to flow). Therefore, enhanced oil recovery (EOR) techniques aim at producing the remaining oil left after primary and secondary recovery methods by introducing heat energy or injecting a fluid (Greaves et al. 2000; Hart 2012). The EOR methods are broadly classified into thermal, solvent displacement (i.e. light hydrocarbons, flue gas, carbon dioxide, nitrogen, etc.), chemical (i.e. surfactant flooding, alkaline flooding, polymer flooding, micellar flooding, alkaline–surfactant–polymer flooding, etc.) and microbial methods. Nonetheless, the most widely used EOR technologies are the thermal techniques. This is because they reduce the viscosity of heavy crude oil and bitumen by several orders of magnitude rapidly, in contrast to non-thermal methods in which the mode of viscosity reduction is quite slow as they depend on diffusion and dispersion to spread the fluids. Therefore, the commonly used thermal EOR methods by the petroleum industry are steam flooding, cyclic steam stimulation (CSS), steam-assisted gravity drainage (SAGD), in situ combustion (ISC), toe-to-heel air injection (THAI), etc. The objective of the techniques is to increase oil mobility of the heavy crude oil and bitumen by reducing their viscosity to improve recovery or production as well as transportation via pipelines. Subsequently, this drive of the petroleum industry to exploit heavy crude oil and bitumen resources has led to the development of several transportation techniques.

This increased heavy crude oil and bitumen production requires an adequate means of transporting them for storage or to the refinery. In view of this, pipelines remain the most convenient means for continuous and economic transportation of crude oils and its products. However, heavy crude oil and bitumen contain a high proportion of high molecular weight hydrocarbons such as saturates, resins, aromatics and asphaltenes. The asphaltenes portion of the heavy oils is known to be insoluble in straight-chain hydrocarbons such as pentane and heptanes. Therefore, problems due to asphaltenes instability such as precipitation due to depressurisation below asphaltene precipitation onset pressure may occur when transporting heavy crude oil (Eskin et al. 2011). Subsequently, a high-pressure drop along the pipeline is experienced due to high viscosity of the heavy oil making it cost and energy intensive (i.e. higher pump powder) to transport via pipeline. Additionally, clogging of the pipe walls due to asphaltenes deposition, which decreases the accessible cross-sectional area for oil flow that causes reduction in flow rate and rise in pressure drop and multiphase flow, may occur (Martinez-Palou et al. 2011; Eskin et al. 2011).

Improved heavy crude and bitumen transportation using pipelines can be achieved through preheating of the heavy crude alongside heating of the pipeline, blending or dilution with light hydrocarbon fluids as well as heavy oil-in-water emulsification, partial upgrading and core-annular flow (Al-Roomi et al. 2004; Saniere et al. 2004). Each of these techniques is aimed at reducing viscosity as well as the energy required for pumping, to enhance flowability of the oil via pipelines. The objective of this review is to assess the various technologies available for transporting heavy crude oil and bitumen and explore their individual advantages as well as disadvantages, with the aim that the findings would help direct further experiments and research towards providing a practical solution to improve the transportation of heavy oils economically.

Transportation technologies for heavy crude oil and bitumen

To transport heavy oils economically, the pressure drop in the pipeline must be lowered to minimise the pump power required to push the oil over a long distance. However,

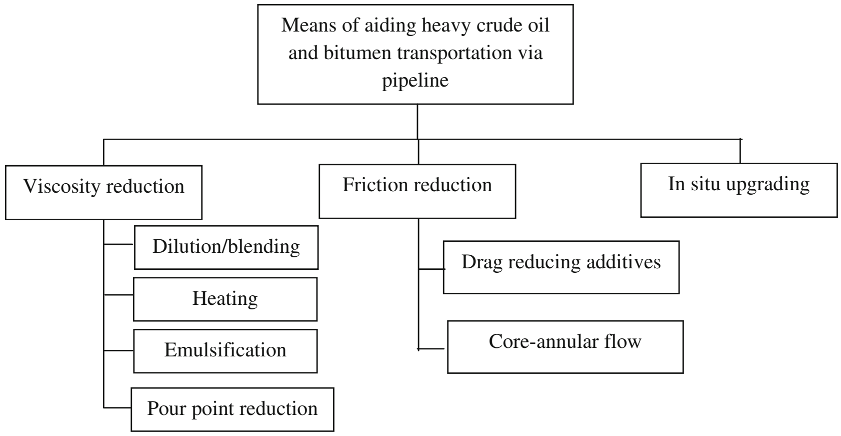

Fig. 1 Diagrammatic display of methods of improving heavy crude oil and bitumen flow via pipelines

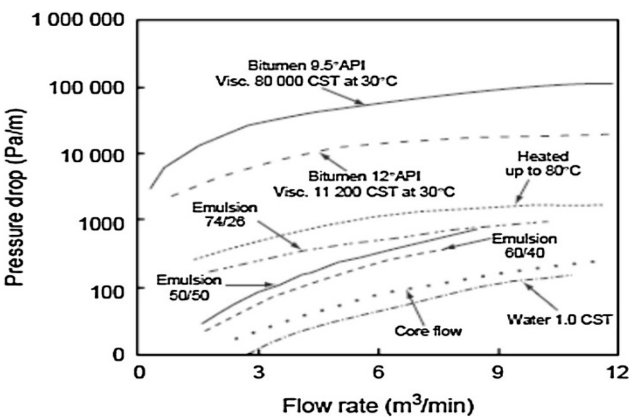

Fig. 2 Pressure drop against flow rate for the different heavy crude transport mechanisms Guevara et al. (1998)

because of their high viscosity at reservoir conditions compared to conventional light crude oils, conventional pipelining is not adequate for transporting heavy crude oil and bitumen to refineries without reducing their viscosity (Ahmed et al. 1999). The methods used for transporting heavy oil and bitumen through pipelines are generally grouped into three as shown in Fig. 1: (a) viscosity reduction [e.g. preheating of the heavy crude oil and bitumen and subsequent heating of the pipeline, blending and dilution with light hydrocarbons or solvent, emulsification through the formation of an oil-in-water emulsion and lowering the oil's pour point by using pour point depressant (PPD)]; (b) drag/friction reduction (e.g. pipeline lubrication through the use of core-annular flow, drag-reducing additive); and (c) in situ partial upgrading of the heavy crude to produce a syncrude with improved viscosity, American Petroleum Institute (API) gravity, and minimised asphaltenes, sulphur and heavy metal content. In Fig. 2, the pressure drop versus the flow rate for the several methods of transporting heavy crude oil and bitumen is presented.

Dilution

High viscosity at reservoir conditions is a major setback to heavy crude oil and bitumen recovery and transportation via pipelines. Thus, blending or dilution of heavy crude oil and bitumen to reduce viscosity is one of the several means to improve transportation via pipelines that is a most commonly used technique in the petroleum industry since the 1930s. The blending fluid or diluents is always less viscous than the heavy crude and bitumen. Generally, it well know that the lower the viscosity of the diluents, the lower is the viscosity of the blended mixture of heavy crude and bitumen (Gateau et al. 2004). The widely used diluents include condensate from natural gas production, naphtha, kerosene, lighter crude oils, etc. However, the use of organic solvents such as alcohol, methyl *tert*-butyl ether, *tert*-amyl methyl ether has been investigated (Anhorn and Badakhshan 1994). The use of these solvents is prompted based on their use in improving the octane number of gasoline. Subsequently, a mixture of hydrocarbons and organic solvents with polar group in their molecular structure has shown some effectiveness in viscosity reduction of heavy crude oil at constant dilution rate (Gateau et al. 2004). The use of diluents allows the transportation of large quantity or volume of heavy crude oil and bitumen.

Furthermore, the viscosity of the blended mixture is determined by the dilution rate as well as the viscosities and densities of the heavy crude oil and bitumen and the used diluents. The resulting blend of heavy crude oil and diluents has lower viscosity and therefore it is easier to pump at reduced cost. The dilution of heavy crude oil and bitumen to enhance transportation by pipelines requires two pipelines, one for the oil and another for the diluents. The use of diluents to enhance the transportability of heavy crude oil and bitumen in pipelines would be cost-effective, if the diluents are relatively cheap and readily available.

The amount of diluents required for heavy crude oil, i.e. the ratio of diluents in the blended mixture, ranges from 0 to 20 %, while for bitumen it is in the range of 25–50 %.

Light natural gas condensate (pentane plus or C_5+) is a low-density and less viscous mixture of hydrocarbon liquids, which is a by-product of natural gas processing. This condensate recovered from natural gas has been used to dilute heavy crude oil and bitumen in Canadian and Venezuelan oil fields in order to enhance their transport using pipeline. Though the viscosity of heavy crude oil and bitumen is reduced significantly on blending with the condensate, asphaltenes precipitation, segregation and aggregation cause instability during transportation and storage (Shigemoto et al. 2006). This is because asphaltenes present in the heavy crude oil are insoluble in alkanes such as *n*-pentane and heptanes, as the condensates are known to be paraffin-rich light oil. Additionally, asphaltenes have the tendency to interact and aggregate. The viscosity of the oil–condensate blended mixture depends on the properties of the heavy crude oil or bitumen, condensate, the dilution rate, heavy oil–condensate ratio and also the operating temperature. The limitations to the use of condensates includes: its availability depends on natural gas demand (Guevara et al. 1998); due to the growing production of heavy crude oil and bitumen, the production of condensate is not sufficient to sustain the demand for thinner; most of its components are not good solvents for asphaltenes and precipitation may arise; instability during storage.

Nevertheless, the use of light crude oil has also been considered, but it is less efficient in lowering the viscosity of heavy crude oil or bitumen in contrast to the condensate (Urquhart 1986). Consequently, light oil compatibility as well as availability in the face of declining reserves of conventional light crude oil has limited its use as diluents for heavy crude oil. In addition, light hydrocarbon such as kerosene has been found to be effective in enhancing heavy crude oil and bitumen transport via pipelines. Lederer (1933) developed a modified correlation similar to the classic Arrhenius expression for estimating the resulting viscosity of the blended mixture of heavy crude oil and diluents. The resulting mixture viscosity is as follows:

$$\log\mu = \left(\frac{\alpha V_o}{\alpha V_o + V_d}\right)\log\mu_o + \left(1 - \frac{\alpha V_o}{\alpha V_o + V_d}\right) log\mu_d \quad (1)$$

where V_o and V_d, are the volume fraction of the heavy crude oil and diluents, μ_o *and* μ_d are the viscosity of the heavy crude oil or bitumen and the diluents, respectively, and α is an empirical constant ranging from 0 to 1.

Thus, Shu (1984) proposed an empirical formula for determining the constant α for the blend or mixture of heavy crude oil or bitumen diluted with light hydrocarbon diluents. The relation depends on the viscosity ratio of oil to diluents (i.e. light hydrocarbons) and their densities, respectively.

$$\alpha = \frac{17.04(\rho_o - \rho_d)^{0.5237}\rho_o^{3.2745}\rho_d^{1.6316}}{\ln\left(\frac{\mu_o}{\mu_d}\right)} \quad (2)$$

Consequently, the mostly used light hydrocarbons for dilution of heavy crude oil and bitumen are expensive and are not readily available in large quantities. Therefore, recycling of diluents for re-use is essential. However, separating the diluents from the oil requires the installation of additional pipelines which subsequently add to the operating cost. In addition, to conveniently transport heavy crude oil and bitumen via pipeline, the diluted or blended oil viscosity must be less than for the classical maximum pipeline, that is, <200 mPa s (Kessick 1982). However, to achieve this pipeline viscosity specification requires the use of large volume of diluents, knowing that heavy crude oil and bitumen can have a viscosity of more than 10^5 mPa s.

Another common diluent used is naphtha, a petroleum fraction. Naphtha has high API gravity and shows good compatibility with asphaltenes. Gateau et al. (2004) proposed that a blend of naphtha and organic solvent would reduce the amount of diluents needed to lower the viscosity of heavy oil-to-pipeline transportation specifications. It was found that the relative viscosity of the blend of heavy oil diluted with mixtures of naphtha and organic solvent is reduced, as shown in Fig. 3. This is attributed to the increasing polarity or hydrogen bonding of the solvents and the ability of the polar solvent to act on the asphaltenes components of the heavy crude oil (Gateau et al. 2004). In that case, a higher polarity solvent causes a larger reduction in viscosity of the diluted heavy crude oil, thereby enhancing dilution efficiency. However, the viscosity of the solvent must approximate that of the hydrocarbon as well as the boiling point for easy recycling.

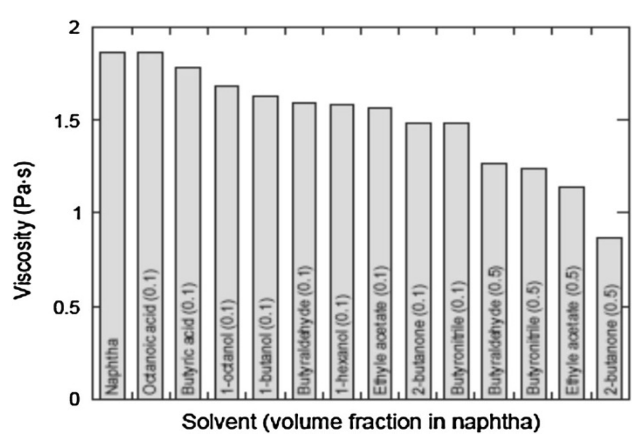

Fig. 3 The effect of organic solvent absolute viscosity of diluted heavy oil

Heating

Another method commonly used method to reduce the high viscosity of heavy crude oil and bitumen and improve the flowability is the effect of temperature. Heating (i.e. increasing temperature) the pipeline causes a rapid reduction in viscosity to lower the resistance of the oil to flow. The response of viscosity to changes in temperature for some heavy oil and bitumen is illustrated in Fig. 4. Therefore, heating is an alternative means of enhancing the flow properties of heavy crude oil and bitumen. This is because the viscosity of the heavy oils and bitumen is reduced by several orders of magnitude with increasing temperature. This involves preheating the heavy crude oil followed by subsequent heating of the pipeline to improve its flow.

However, heating to increase the temperature of the fluid involves a considerable amount of energy and cost as well. Other issues include greater internal corrosion problems, due to the increase in temperature. However, heating the pipeline may possibly induce changes in the rheological properties of the crude oil which may result in instability in flow. Many number of heating stations are required adding to the cost, in addition to heat losses occurring along the pipeline as a result of the low flow of the oil. However, most of the times the pipeline is insulated to maintain an elevated temperature and reduce the heat losses to the surroundings. Additionally, sudden expansion and contraction long the pipeline may induce challenging problems. Consequently, the cost of operating the heating as well as the pumping systems over a long distance from the oil field to the final storage or refinery is on the high side (Chang et al. 1999). The method might not be viable for transporting crude oil when it comes to subsea pipelines. Finally, the cooling effect of the surrounding water as well as the earth lowers the efficiency of the technique.

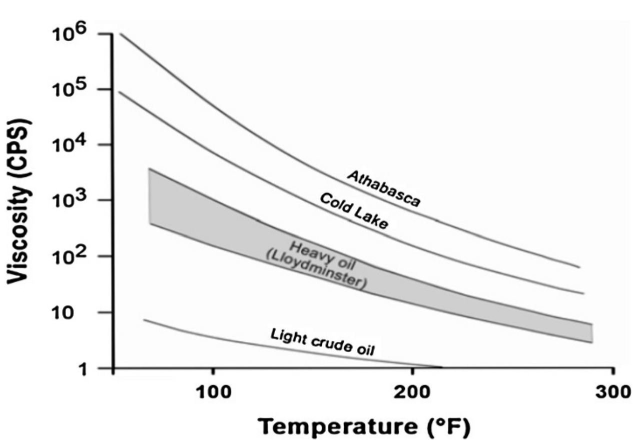

Fig. 4 Response of viscosity to increase in temperature (Raicar and Procter 1984)

Emulsification of the heavy crude in water

The emulsion of crude oil and water exists in the hydrocarbon reservoir, well bore, during drilling as well as transportation. This technology is one of the newest means of transporting heavy crude oil via pipeline in oil-in-water (O/W), water-in-oil (W/O) emulsion or in a double emulsion like oil-in-water-in-oil (O/W/O) and water-in-oil-in-water (W/O/W), with the drop sizes in micron range. The formation of oil-in-water emulsion has been an alternative technique of enhancing heavy crude oil flowability through pipelines. In this technology, the heavy crude oil is emulsified in water and stabilised with the aid of surfactants. The oil become dispersed in water in the form of droplets with the aid of surfactants and a stable oil-in-water emulsion with reduced viscosity is produced (Saniere et al. 2004; Al-Roomi et al. 2004). The methods used to generate the oil droplets to create the emulsions includes use of devices such as dispersing machines, mixing with rotor–stator, colloid mills, high-pressure homogenisers applying high shearing stresses, emulsification by membrane and ultrasonic waves (Hasan et al. 2010; Ashrafizadeh and Kamran 2010; Lin and Chen 2006). The different possible emulsions are illustration in Fig. 5.

The surfactant monolayer sits at the oil–water interface (see Fig. 6), to prevent drop growth and phase separation into single oil and water phases in the cause of transportation. The monolayer at the interface of the oil-in-water emulsion, the polar region (i.e. hydrophilic head) of the surfactant is in contact with the water and non-polar tail (i.e. hydrophobic region) in contact with the oil, as shown in Fig. 5. It is the properties of this adsorbed layer of surfactants that stabilise the oil–water surface and control the behaviour of the emulsion (Langevin et al. 2004).

Nevertheless, heavy crude oil is a complex mixture of hundreds of thousands of compounds. The asphaltenes act as natural emulsifiers. Other active surface components of crude oil include naphthenic acids, resins, porphyrins, etc. (Langevin et al. 2004). The presence of these component increases the complexity of crude oil emulsion, as the molecules can interact and reorganise at the oil–water interface. In that case, to transport heavy crude using emulsion technology involves three stages such as producing the O/W emulsion, transporting the formed emulsion and separating the oil phase from the water phase. However, recovering the crude oil entails breaking the oil-in-water emulsion. To achieve the separation stage the following techniques have been developed which include thermal demulsification, electro-demulsification, chemical demulsification, freeze–thaw method, pH modification, addition of solvent and demulsification by membranes (Ashrafizadeh and Kamran 2010; Yan and Masliyah 1998). The use of surfactants and water to create a stable oil-in-

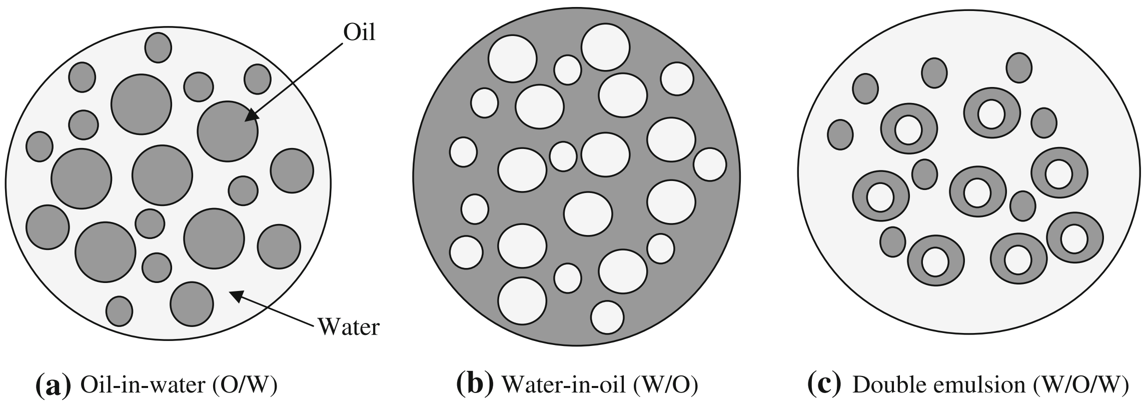

Fig. 5 The several emulsions that are used to transport heavy crude oil

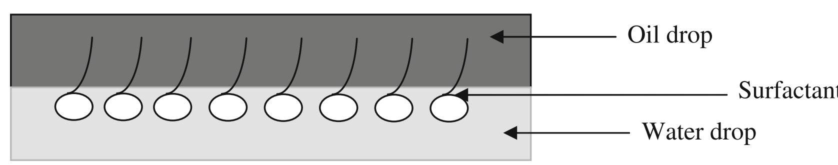

Fig. 6 Surfactant-stabilised emulsion

water emulsion with heavy crude oil to improve its transportability by pipeline has been a topic of several investigations with a series of patents. The potential of this technology to enhance pipeline transportation of heavy crude oil has been demonstrated in Indonesia in 1963, as well as in a 13-mile distance using 8 in. diameter pipeline in California (Ahmed et al. 1999).

In addition, the rheology of the formed emulsions is an important criterion for enhanced pipeline transportation. The rheology of the emulsion depends mainly on the volume of the dispersed oil and drop size distribution (Khan 1996). The drop size distribution depends on surfactant type, energy of mixing and pressure. The surfactants commonly used are non-ionic such as Triton X-114 based on their ability to withstand the salinity of the produced water, they are also cheap, their emulsion is easy to separate, and they do not form undesirable organic residues that affect the oil properties (Sun and Shook 1996). However, heavy crude oil emulsion exhibits either Newtonian behaviour at high shear rate or a shear thinning rheological behaviour at low shear rate (McKibben et al. 2000; Al-Roomi et al. 2004). The flow properties of the produced emulsion depend on the properties of the polar hydrophilic head and the non-polar hydrophobic tail of the used surfactants.

The principal challenges associated with the technology of transporting heavy crude oil are cost and selection of the surfactant, the ability of the surfactant to maintain the stability of the emulsion during pipeline transportation, the ease of separating the surfactant from the crude oil at the final destination since the density of heavy oil is close to that of water, the properties of the emulsion such as rheological characteristics and stability that depend on many parameters such as drop size distribution, temperature, salinity and the pH of the water, the components of the heavy crude oil, mixing energy and oil/water volume ratio (Hasan et al. 2010). Additionally, the presence of natural hydrophilic particles such as clay and silica in the crude oil may cause instability in the emulsion (Langevin et al. 2004). The different mechanisms by which destabilisation may arise in oil-in-water emulsion includes: Ostwald ripening, sedimentation or creaming due to density difference and coalescence of the drops. But the essence of the surfactant is to stabilise the emulsion against shear and decrease the interfacial tensions. At times, the oil-in-water emulsion system may contain solids and gas, which increases the complexity of the process. Generally, the smaller the drop size, that is, 10 μm or less, the better is the stability of the emulsion (Langevin et al. 2004). In general, the behaviour of heavy crude oil-in-water emulsion is complex due to the interaction of several components within the system and many other factors mentioned above. This method of transporting heavy crude oil has been used in the ORIMULSION® process developed by PDVSA (Petroleos de Venezeula) in the 1980s (Martinez-Palou et al. 2011). However, details of the process can be found in Salager et al. (2001) and Langevin et al. (2004).

Pour point reduction

Heavy crude oils have been described as a colloidal suspension consisting of solute asphaltenes and a liquid phase maltenes, that is, saturates, aromatics and resins (Saniere et al. 2004). The precipitation and aggregation of the asphaltenes macromolecules in the oil contribute greatly to its high viscosity and density, resulting in its high resistance to flow in pipelines. Therefore, suppressing this effect through the use of pour point depressants will help improve the oil flow properties. The pour of the oil is the lowest temperature at which it ceases to flow and loses its flow properties. For instance, it is extremely difficult to transport via pipeline waxy crude oil in cold weather. This is because decreasing temperature causes crystal growth which prevents the molecules of the oil from flowing. The crystallisation depends on climate, oil composition, temperature and pressure during transportation. There are several methods to minimise the cause of wax and asphaltenes deposition, and the use of polymeric inhibitor is considered an attractive alternative. The addition of copolymers such as polyacrylates, polymethacrylate, poly (ethylene-co-vinyl acetate), methacrylate, etc. inhibits the deposition phenomenon and stabilises transportation (Machado et al. 2001; Soldi et al. 2007). Machado et al. (2001) found from the viscosity measurements that only below the temperature at which wax crystals starts forming did the copolymer exhibit a strong influence in the reduction of viscosity.

The complex nature of heavy crude oil creates many challenges during its transportation through long distance, especially when using pipelines. To overcome such problem of wax crystal formation as an interlocking network of fine sheets that block pipelines, pour point depressants (PPD), which contains oil-soluble long-chain alkyl group and a polar moiety in the molecular structure, is used. The long-chain alkyl group is inserted into the wax crystal and the polar moiety exists on the wax surface and reduces wax crystal size (Deshmukh and Bharambe 2008). The PPD in most cases possesses highly polar functional groups.

Friction reduction

As the dominant transport fluid property, high crude oil viscosity poses great challenges to oil production, refining and transportation through wells and pipeline. The viscous drag, wall friction and pressure drop in the pipeline are much higher in heavy oil compared to conventional light oils. The drag is the result of stresses at the wall due to fluid shearing causing a drop in fluid pressure (Martinez-Palou et al. 2011). This makes it challenging to pump the oil through a long distance. Therefore, drag reduction is a lubrication technique based on core-annular flow to reduce pressure in the transport of heavy oil via pipelines. The commonly used techniques to lower the friction to enhance pipeline transportation of heavy crude oil include drag-reducing additives and core-annular flow. Both technologies reduce flow drag by varying the velocity field such as dampening the turbulent fluctuation in the near wall region of the pipeline, while the flow in the heavy oil pipeline is laminar or slightly turbulent with minimum flow resistance based on viscosity influence on flow drag (Chen et al. 2009). However, most studies on flow drag reduction pay attention mainly to reducing the viscosity by physical or chemical methods, but according to Newton's viscosity law flow drag depends upon fluid viscosity and velocity profile.

Drag-reducing additives

The pressure drop encountered in heavy crude oil transportation via pipelines is more acute when it is to be transported over a long distances; therefore drag reduction by incorporating an additive becomes an option. The transportation of crude oil via pipelines is mostly in the turbulent flow regime. Additionally, high frictional loss as a result of high viscosity causes much of the energy applied to transport the crude oil to be wasted. High drag in turbulent flow is caused by radial transport of flow momentum by fluid eddies. Polymer drag reduction was discovered decades ago by Toms (1948), who observed about 30-40 % drag reduction upon the addition of polymer (methyl methacrylate) to turbulent monochlorobenzene flowing via pipeline. In this respect, drag-reducing additives help to reduce friction near the pipeline walls and within the turbulent fluid core of moving fluid. Therefore, for energy conservation and high efficiency of bitumen and heavy crude oil transfer, drag reduction is vital.

Over the years, technology has developed. Drag-reducing additives are classified into three categories: polymers, fibers and surfactants. The key role of these additives is to suppress the growth of turbulent eddies through the absorption of the energy released by the breakdown of the lamellar layer (Martinez-Palou et al. 2011). Furthermore, drag additive helps reduce friction near the pipeline walls and within the turbulent fluid core during transportation, which results in high flow rate at a constant pumping pressure. However, details of the different categories of drag-reducing additives can be found in a review by Martinez-Palou et al. 2011. Consequently, solubility of the drag-reducing additives in the heavy crude oil is a key requirement. In addition, there should be degradation resistance and stability against heat and chemical agent.

The common difficulties encountered in the use of drag-reducing additives includes the tendency of the additive to separate when stored, difficulty in dissolving the additives in the heavy crude oil and the problem of shear degradation when dissolved in heavy crude oil. In addition, determining the dosage required to maintain constant pressure drop is challenging.

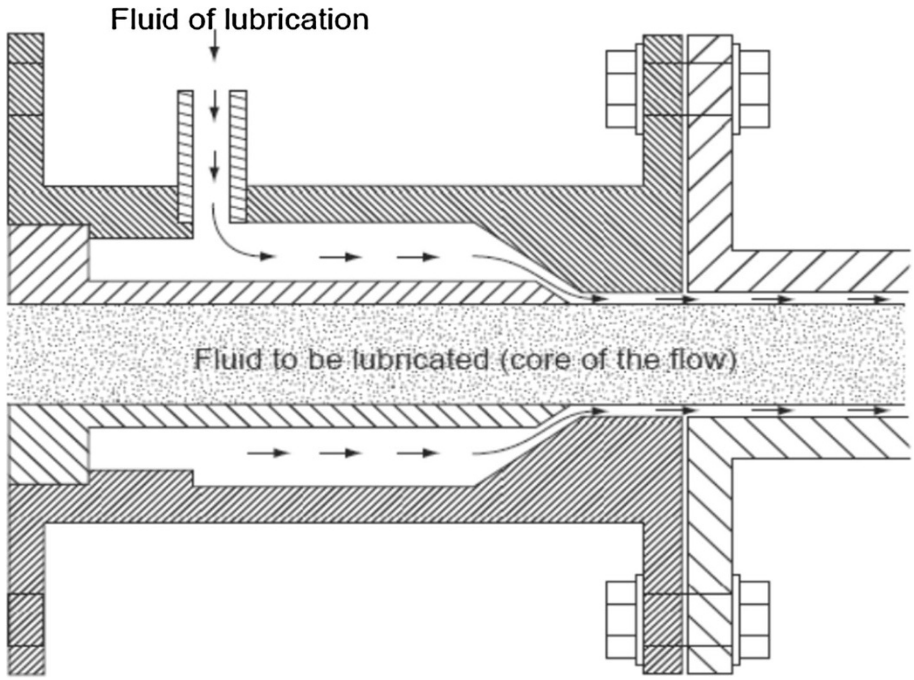

Fig. 7 Illustration of the core-annular flow injector configuration (Bensakhria et al. 2004)

Core-annular flow

The high viscosity of bitumen and heavy oil causes large pressure drop during transport through pipelines, which makes it impossible to simply pump the crude oil in a single-phase flow. Another method of reducing pressure drop in pipelines caused by friction in order to transport bitumen and heavy crude oil is developing core-annular flow. The main idea of this technique is to surround the core of the heavy crude oil as it flows through the pipeline with a film layer of water or solvent near the pipe wall, which acts as a lubricant, maintaining the pump pressure similar to that needed to pump the water or solvent. In this regard, the water or solvent flow as the annulus while the heavy crude oil is the core in the flow via pipeline, as illustrated in Fig. 7. The required water or solvent is in the range of 10–30 % (Saniere et al. 2004; Wylde et al. 2012). This implies that the pressure drop along the pipeline depends weakly on the viscosity of the heavy oil, but very closely to that of water. Furthermore, Bensakhria et al. (2004) found that with the heavy oil as the centre of the pipe and water flowing near the pipe wall surface, the pressure drop reduction was over 90 % compared with that without water lubrication. This technique was first reported by Isaacs and Speeds (1904) for the possibility of pipelining viscous fluids through the lubrication of pipe walls with water.

Additionally, core-annular flow is one of the flow regimes observed in two-phase flow via pipelines. In this flow regime, the solvent is at the pipe wall surface and lubricates the heavy oil at the core. In view of this, the heavy oil core is approximately in a plug flow. However, during the water and oil two-phase flow in the pipeline, several flow regimes are possible depending on the properties of the oil such as density, surface tension, shear rate of the flow and fluid injection flow rate.

Nevertheless, the technique is capable of reducing the pressure drop close to that of transporting water. However, some of the limitations include achieving perfect core-annular flow appears to be very rare and may only exist for density-matched fluid (Bensakhria et al. 2004). Bai et al. (1992) found that waves are created at the water and oil interface leading to wavy core-annular flow. Furthermore, when the density difference between the oil and water is large, a buoyancy force will produce a radial movement of the oil core. This effect, therefore, will push the core to the upper wall of the pipeline, as illustrated in Fig. 8.

Additionally, the stability of the flow system is still under investigation (Bai et al. 1992; Joseph et al. 1999). The flow velocity and capillary instability arising from surface tension break the core. But, increasing the velocity enhances the core stability.

If the core-annular flow is assumed to be perfect and well centred, then the pressure drop can be calculated from the following equation:

$$\frac{\Delta P}{L} = \frac{Q}{\frac{\pi}{8}\left[\frac{R^4}{\mu_w} + R_s^4\left(\frac{1}{\mu_o} - \frac{1}{\mu_w}\right)\right]} \quad (3)$$

where $\Delta P/L$ is the pressure drop of the centred core-annular flow (Pa/m), Q is the total flow rate (m^3/s), R is the radius of the pipe (m), R_s is the core radius (m), and μ_w and μ_o are the dynamic viscosity of water and oil, respectively (Pa s).

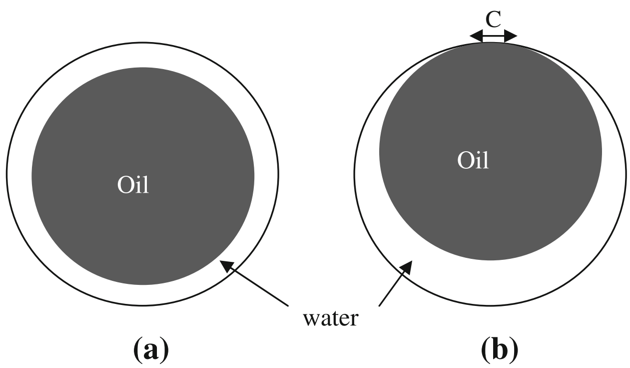

Fig. 8 Radial position of the oil core: **a** perfect core-annular flow and **b** with density difference. *C* is the contact perimeter between the oil phase (core) and the pipe wall

In situ upgrading

The increasing exploitation of vast heavy oil and bitumen resources to meet global energy demand and the concern for the environment have led to the incorporation of in situ upgrading with enhanced oil recovery. In situ upgrading is achievable during thermal recovery methods such as ISC, SAGD, CSS and subsequently the novel THAI and its add-on catalytic upgrading process in situ (CAPRI), collectively called THAI–CAPRI™ (Greaves and Xia 2004; Hart 2012; Hart et al. 2013). These processes rely on the reduction of heavy crude oil viscosity by heat to improve its flow from the oil reservoir to the production well. The upgrading is due to the heavy molecules splitting into smaller molecules thermally. This thermal cracking reactions in situ reduces the viscosity of the heavy oil and bitumen to a high order of magnitude, thereby improving flow and production. However, of all these processes, the THAI–CAPRI process integrates a catalytic upgrading process into the recovery. Details of the above-mentioned technologies for in situ upgrading during heavy oil recovery can be found in a review paper on novel techniques for heavy oil and bitumen extraction and upgrading by Shah et al. (2010).

Conclusions

For the increasing exploitation of heavy oil and bitumen, it is necessary to develop technology to aid in their transportation through pipelines. In this review paper, the technologies used to enhance the transportation of heavy crude oil and bitumen through pipelines was explored. Each of the three categories of methods employed to reduce viscosity and pressure drop to aid pipeline transportation of heavy crude oil has been presented along with their advantages and disadvantages. The techniques employed take into consideration the properties of the oil, regional logistics between the well-head and the refining site, operational concern, transport distance, cost, environmental concerns and the legislation. However, the present strategy in the petroleum industry is to integrate in situ upgrading to thermal enhanced oil recovery methods because of the cost, environment and energy effectiveness it offers.

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