

Transportation of heavy and extra-heavy crude oil by pipeline: A review

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ABSTRACT

The transportation of heavy and extra-heavy crude oils from the head-well to the refinery is becoming important since their production is currently rising all over the world. Such oils are characterized by a low API gravity (<20) and high viscosity ($>10^3$ cP at 298.15 K) that render difficult oil flow through pipelines. Conventional technology pipelining is designed for light and medium oil crudes, but the pipelining of heavy and extra-heavy crude oils may be challenging because of their high viscosities, asphaltene and paraffin deposition, increasing content of formation water, salt content and corrosion issues. In this paper, the current and innovative technological solutions covering viscosity and friction reduction to move such crude oils from the production site to the processing facilities are thoroughly discussed.

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Contents

1. Introduction	274
2. Viscosity reduction	275
2.1. Dilution of heavy and extra-heavy crude oils	275
2.2. Formation of heavy and extra-heavy crude oil emulsions in water (O/W)	276
2.2.1. Heavy oil emulsions for transport in cold environments	278
2.3. Heating heavy and extra-heavy crude oil and heated pipelines	278
2.3.1. Electrically heated subsea pipelines	278
2.4. Pour point depressants	279
3. Reducing friction	279
3.1. Drag reducing additives	279
3.2. Annular and core flow for heavy oil pipelining	280
4. Conclusions	281
Acknowledgment	281
References	282

1. Introduction

In the last quarter of the 20th century, global demand for crude oil had a very stable yearly growth rate averaging 1%. This has changed

radically in the first years of the 21st Century due to "Emerging Countries" like China and India whose dynamic economies resulted in a remarkable 1.8% global growth in demand for crude oil in 2009 (IEA, 2010). Serious international studies still foresee that in the next 20 years, at least 80% of the world's energy requirements will come from petroleum, natural gas and coal (IEA, 2008). Consequently, oil will remain the dominant source of energy for the next half century. According to some estimates from the International Energy Agency

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(IEA), heavy oil represents at least half of the recoverable oil resources of the world. Heavy oil is defined as petroleum which has a density equal or lower than 20 API, but if petroleum has 10 API or less it is considered as extra heavy oil or bitumen, which is denser than water. The difference between bitumen and extra heavy oil is ambiguous and usually refers to the production technology, so we will include both under the term extra-heavy oil. As a framework, conventional oil such as Brent or West Texas Intermediate has a density ranging between 38 and 40 API.

Historically, demand for heavy and extra-heavy oil has been marginal because of their high viscosity and composition complexity that make them difficult and expensive to produce, transport and refine. Nowadays, Alberta in Canada and the Orinoco Belt in Venezuela are good examples of regions producing extra heavy oil. However, an increase in production of heavy and extra heavy crude oil will take place in several regions like the Gulf of Mexico and Northeastern China, as it will be needed over the next two decades to replace the declining production of conventional middle and light oil. Therefore, there is a growing interest in the use of non-conventional heavy and extra-heavy oil resources to produce fuels and petrochemicals. The incorporation of heavy oil to energy markets presents important challenges that require significant technological developments in the production chain. The transportation of heavy and extra-heavy oil presents many operational difficulties that limit their economical viability. Countries like China, Japan or the USA, with growing energy demands, promote the restructuring of its refining industries to handle this non-conventional crude. Nowadays, heavy and extra-heavy oil are cheaper than conventional petroleum and the refining margin can be bigger if properly handled with higher profits per barrel. Pipelining is the most convenient mean for transportation of crude oils and derived products continuously and economically. However, transportation of heavy and extra heavy crude oils through pipelines is difficult due to the low mobility and flowability of the crude and wax and asphaltene deposition on pipeline wall surfaces. Still, one of the technological issues regarding the access of extra heavy oil to energy markets is the problem of pipeline transportation as mentioned earlier.

The high viscosity (10^3 to 10^6 cP) and low API gravity (heavy oil less than 20 API, extra heavy oil less than 10 API) of such oils are due to the high presence of asphaltenes as well as a relative low proportion of low molecular weight compounds, which represent a lack of light ends. Heavy and extra-heavy crude oils may also have high contents of sulfur, salts and metals like nickel and vanadium (Table 1). Pipelining of heavy oil presents problems like instability of asphaltenes, paraffin precipitation and high viscosity that cause multiphase flow, clogging of pipes, high-pressure drops, and production stops.

Currently, we consider that there are three general approaches for transportation of heavy and extra heavy oil: viscosity reduction, drag minimization and *in-situ* oil upgrading. Reduction of oil's viscosity can

be accomplished by a) dilution with other substances; b) formation of an oil-in-water emulsion, c) increasing and/or conserving oil's temperature and/or d) depressing crude oil's pour point. The second alternative consists to reduce friction between the pipeline and the heavy oil through a) the addition of substances that reduce drag inside the pipeline (drag reducing additives) and/or b) developing a different type of flow (annular, slurry). Finally, physicochemical upgrading of heavy oil produces a synthetic fuel or syncrude with higher API gravity, minor viscosity and less content of pollutants as sulfur and nitrogen. The combination of two or more of these approaches may be used to resolve or improve pipelining of heavy and extra-heavy crude oil since there are not unique technological solutions. We consider in this work the first two options since oil upgrading has been recently reviewed (Rana et al., 2007). This article provides a survey of innovations regarding pipeline transportation of heavy and extra-heavy crude oils.

2. Viscosity reduction

2.1. Dilution of heavy and extra-heavy crude oils

Dilution is one of the oldest and preferred methods for reducing the viscosity of heavy oils. Since the 1930s, dilution consists in the addition to heavy oil of lighter liquid hydrocarbons, typically condensates from natural gas production, but lighter crude oils are also used. This is an effective option to reduce oil viscosity and facilitate its mobility in the pipeline since a ratio of 20–30% of solvent is often enough to avoid high-pressure drops or the need for high temperatures. Also, diluting the crude may facilitate certain operations such as dehydration and desalting. Such technology is the most widely used solution where condensates or lighter crude oil is available to transport heavy and extra-heavy oils by pipeline but it may require substantial investments in pumping and pipelines due to the increase of the transport volume and the need to separate at some point the solvent, processes it and subsequently returns it to the oil production site.

Moreover, the dilution option has some challenges since any change in oil's composition may affect the required oil/solvent ratio. Then, it is important to predetermine the ratio of solvent to heavy oil since simple mixing rules do not directly apply and careful attention should be paid to the reliable measurement of crude oil and mixtures' viscosity and compatibility. Also, experience has shown that in order to meet pipeline viscosity specifications, more diluent is used than necessary to meet the API gravity specification. Special attention must be accorded to asphaltene and paraffins stability, since condensate or light oil addition may cause precipitation and pipeline clogging (Zahan et al., 2004). Yaghi and Al-Bemani (2002) found that a mixture of extra heavy and light oils (7:3) possesses a viscosity of around 1000 and 300 cP at 303 or 323 K, respectively; when compared to the original heavy oil (15,000 cP at 293 K). Here, the dilution using a light crude oil (29 API) and the need for heating to 323 K may make this approach rather expensive. In our experience, heavy oil dilution indeed reduces viscosity but other issues remain unsolved or become more important like asphaltene and paraffin deposition.

Van den Bosch and Schrijvers (2006) present a combined dilution-upgrading method based in the *in situ* production of the solvent by separation, distillation and thermal cracking of a part of the heavy oil feed to produce one or more light fractions and one or more heavy fractions. The feed of heavy oil is split in two, one part is sent to the aforementioned process and the other is diluted with the mix of all light fractions of the processed heavy oil while the obtained heavy fractions are used to generate heat and/or power. Thus a pipeline-transportable syncrude is formed which is easier to refine and presents less stability problems than completely upgraded syncrudes. The same principle of partial upgrading is also suggested by Myers et al. (2000). Here, the hydroconversion of crude oil allows to reach a viscosity of 60 to 250 cP at

Table 1
Properties and composition of medium, heavy and extra-heavy Mexican crude oil. Adapted from Murillo-Hernández et al. (2009) and Castro and Vázquez (2009).

Parameter	Mexican crude oils		
	Medium	Heavy	Extra-heavy
API gravity	21.27	11.90	9.17
Molecular weight (g/mol)	314.8	486	507.8
Sulfur content (%)	3.40	5.02	4.80
Water content (%)	1.80	0.05	<0.05
SARA analysis			
Saturates	26.53	7.94	15.00
Aromatics	14.74	5.28	19.11
Resins	47.60	70.93	46.78
Asphaltenes (from n-C7)	11.13	15.85	19.11

313 K and further dilution with naphtha or condensate minimizes viscosity to 40–50 cP. Nevertheless, such approach is limited by place and the need for refining infrastructure in off-shore platforms. Iqbal et al. (2006) present a variety of schemes that can allow the transport and process of heavy oils with different salt and water contents, acidity and API gravity less than 15. The authors propose an integrated approach to the dilution–upgrading–transportation process thus reducing initial capital requirements and operating costs. First, the dilution of the heavy oil is done with a light liquid hydrocarbon in 1:10 ratio; the mix is then transported via pipeline to a solvent deasphalting unit which can be at a remote location. The deasphalting process produces an asphaltene fraction, a deasphalted oil fraction essentially free of asphaltenes that is ready for further refining, and the solvent fraction that can be recovered and recycled as the extraction solvent or returned for heavy oil dilution. In the same way, a simple alternative transport method for heavy oils was developed by Argillier et al. (2006). Here, asphaltenes are precipitated by n-alkanes and reincorporate to the oil to obtain a slurry, i.e. a suspension of non-colloidal particles with low viscosity that fluidizes the oil. Considering that the structure of heavy oils behaves like a viscous colloidal suspension, breaking the colloid system through asphaltene precipitation will have a definitive effect in its viscosity. The resulting morphology change of the crude in suspension form actually leads to a viscosity decrease.

From an economic point of view, any improvement in the efficiency of dilution will be beneficial to the process and reduce the amount of solvent necessary to obtain an acceptable viscosity that enables the transport of large quantities of heavy oil. That is the reason that research is done to find other more efficient solvents. Hénaut et al. (2007) propose the use of dimethyl ether (DME) under pressure as a solvent to adjust the viscosity and reduce the pressure drop in the pipeline. Moreover, the recovery of DME in the refinery, as opposed to other solvents, is much easier. Other solvents that are being researched are alcohols, i.e. pentanol is doubly effective in reducing the viscosity of heavy oil in comparison to kerosene, due to hydrogen bond interactions with the hydroxyl groups that feature some of the asphaltenes. Here, the higher the polarity or the hydrogen bonding parameter of the solvent, the greater the relative viscosity reduction of the diluted crude oil. Nevertheless, solvent owning high hydrogen bonding is generally more viscous than hydrocarbons. Only polar solvents with little hydrogen bonding give a significant reduction of the viscosity of the diluted crude oil (Gateau et al., 2004).

Nowadays, naphtha or light crude oils are an interesting alternative to the use of natural gas condensates, due to its high API gravity and efficiency in the dilution of heavy oil. Nevertheless, the mixture may alter asphaltene stability provoking its flocculation and precipitation which may cause blockage of pipelines. Here, more studies are needed in order to understand asphaltene aggregation and

flocculation as well as paraffin crystallization and deposition. Hence, we should also consider that the oil mixture may attain a lower selling price than the lighter fractions used as solvent since the lower quality of the heavy or extra-heavy oil and an economical evaluation are needed in order to assess the financial viability of the process.

2.2. Formation of heavy and extra-heavy crude oil emulsions in water (O/W)

Emulsions naturally occur in petroleum production and pipelining, mainly those of water-in-oil (W/O) and more complex like oil-in-water-in-oil (O/W/O) emulsions (Fig. 1). Such emulsions are detrimental for oil production since oil's viscosity raises, increment corrosion issues and are difficult to break in desalting and dehydrating units before refining. Nevertheless, emulsions or dispersions of heavy or extra-heavy crude oil in water (O/W) or in brine may be an alternative to pipeline transportation of high-viscosity crudes because of viscosity reduction (Pilehvari et al., 1988; Ashrafizadeh and Kamran, 2010). An O/W emulsion is a mixture of two immiscible liquids where oil phase is dispersed into the water continuous phase (Fig. 2). In some locations, hydrocarbon diluents or lighter crudes may be not available or limited while fresh water, sea water or even formation water may be available for emulsification. Very often O/W emulsions are deliberately produced to reduce the viscosity of highly viscous crude oils so that they can be transported easily through the pipeline (Zaki, 1997). The O/W emulsion reduces the viscosity of heavy crude oils and bitumens and may provide an alternative to the use of diluents or heat to reduce viscosity in pipelines (Langevin et al., 2004). Also, restarting a pipeline after an emergency shutdown and reemulsification of oil may not pose major problems (Simon and Poynter, 1970). The major application of an O/W emulsion is the Orimulsion® process developed by PDVSA (Petróleos de Venezuela) in the eighties and commercialized by its filial Bitumenes Orinoco S.A. (BITOR, Salager et al., 2001). Orimulsion® is a bitumen-in-water emulsion and the technology was developed to facilitate the transportation of Cerro Negro bitumen since the conventional dilution with gasoil becomes economically unattractive in the late 80s. Even better, not only the Orimulsion® was easier to transport but it also can be used directly as feedstock for heat/power generation in thermo-electrical plants and the technology is by far demonstrated by the large-scale development of the commercial product. In this niche market, the initial pricing structure competed well with coal price. This product was clearly successful till the late 90s, when oil upgrading became a reality and starts to compete for the bitumen with the emulsion. Since then, PDVSA could make more profits from Venezuelan exportations of extra-heavy oil and bitumen by selling blends or syncrude instead of Orimulsion® as well as producing fuels

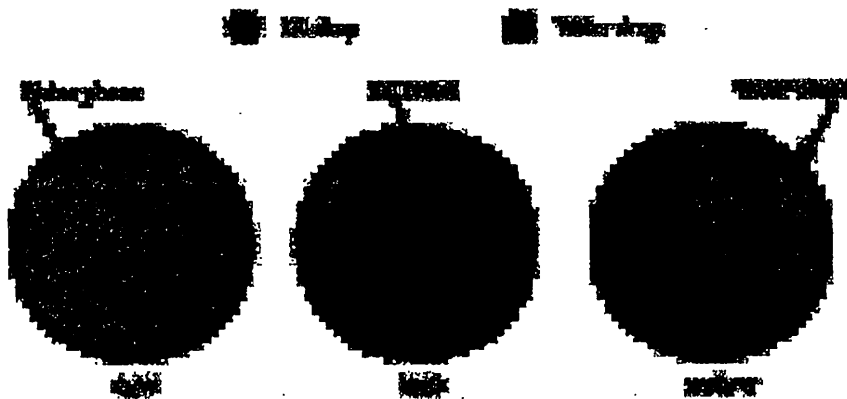


Fig. 1. Emulsions found in petroleum production and transport.

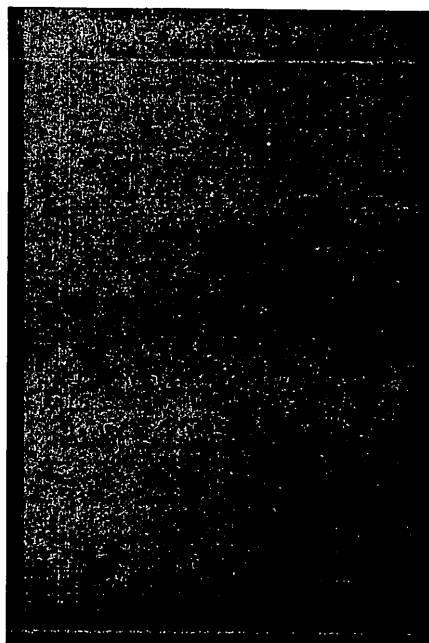


Fig. 2. Extra-heavy crude oil in water (O/W) diluted emulsion for visual purpose. A drop of the O/W emulsion (30% water) was diluted in 5 mL water (unpublished data) and the photo was taken without enlargement.

for internal consumption. Hence, PDVSA announced the closure of its filial BITOR on 2003 but also its intention to fulfill the long-term contracts with Canada, Denmark, Italy and Japan (Rodríguez, 2004). Orimulsion® is a product oriented to electricity production and would be interesting to developing countries with limited coal and gas reserves and refining capacity but the last word to reactivate emulsion production remains in PDVSA. Here, the emulsion of vacuum residue in water for heat/power generation could be an economical alternative instead of using heavy or extra-heavy oil.

An effective way to reduce the viscosity of heavy oil is the formation of oil-in-water emulsions with the help of surfactant agents. In this way, crude oil is transported in the form of fine crude oil droplets in a continuous phase consisting mainly of water or other types of aqueous solution. The O/W emulsions do not form spontaneously and need an energy input to form, which is traditionally achieved through shaking, stirring or some other kind of intensive dynamic and/or static mixing processes. In order to assure emulsion stability during pipelining, it is necessary to add surfactants (low molecular weight) to reduce oil interfacial tension and in some cases additional substances as stabilizing agents (high molecular weight) to avoid phase separation. In general, non-ionic surfactants represent a good choice because they are not affected by the salinity of the water, they are relatively cheap, and they do not produce any undesirable organic residues that affect oil properties (Rivas et al., 1998).

Typically, the use of surfactants can significantly increment the cost of an O/W emulsion but the activation of natural surfactants occurring in heavy and extra heavy crude oils is a reliable option. The ionization of acid groups present in fatty and naphthenic acids as well as asphaltenes with a strong alkali can make these surfactants more hydrophilic which allow the reduction of the interfacial tension (Langevin et al., 2004). Rivas et al. (1998) proposed the use of the natural molecules present in bitumen that when activated with amines serves as natural surfactants to form a bitumen-in-water emulsion or Orimulsion®. Some works refer to the use of the natural surfactants present in crude oil like by particles such as silica, clay,

iron oxides, etc. Moreover, more stable emulsions can be obtained if particle surface is saturated by asphaltenes (Langevin et al., 2004).

Pipelining of crude oil must transport as much oil as possible and as little water as possible for economical reasons. Nevertheless, the required viscosity for transport, typically around 400 cP at ambient temperature, may be attained only with 25–30% w/w water content. Above 70% of oil in emulsion, the viscosity may become too high or to inverse to W/O emulsion. The surfactants should allow at the same time a simple but efficient rupture of the O/W emulsion before crude oil refining and the separated water should be treated in order to comply with environmental and industrial regulations for water discharge or recycling. Then, it is necessary to develop surfactants that may form a meta-stable and easy-to-break emulsion that should require the minimum quantity of surfactant and other additives.

Bancroft's rule states that the surfactant dictates the type of the resulting emulsion and in the case of O/W emulsions, the surfactant should be soluble in the continuous phase. In consequence, pipeline-transportable heavy oil-in-water emulsions cannot be formed by directly combining the surfactant agents with the oil and subsequently mixing. The surfactant agents must be solubilized first in an aqueous solution, so premixing with water, brine, or the like, making possible the diffusion of the surfactant to the oil–water interface. The use of a dynamic mixer, like a rotor–stator mixer, may cause the formation of oil droplets having a diameter of less than 10 µm, which is detrimental to pipelining as such small oil droplets increase the viscosity of the oil-in-water emulsion, and can cause emulsion inversion to an oil continuous emulsion, with a significant increase in viscosity.

Gregoli et al. (1990, 1991, 1992, 1994) developed a process to prepare a stable oil-in-water emulsion using a static mixer consisting of baffle elements that allows the dispersion of the oil in water. Recently, an O/W emulsification technology was proposed to reduce crude oil viscosity using an eccentric cylinder mixer that allows a low energy laminar flow. The mixer's geometry allows the existence of chaotic flows that are able to mix well highly viscous fluids as Zuata and Athabasca crude oils (Fournant et al., 2008).

Zaki studied the stability and viscosity of a surfactant-stabilized O/W emulsion for pipeline transportation using an Egyptian Geisum crude oil (Zaki, 1997). The study revealed that viscosity and stability of the emulsion increases with the concentration of an anionic surfactant that reduces the O/W interfacial tension and size of dispersed droplets because of a higher coverage of surfactant molecules at the oil/water interphase. Similar results were found in a non-ionic surfactant-stabilized O/W emulsion (Yaghi and Al-Bemani, 2002). The use of anionic and non-ionic surfactants produced a synergistic effect that allows a lower viscosity and more stable O/W emulsion. Here, the use of formation water instead of fresh water resulted in a lower interfacial tension between crude oil and formation water and a more viscous O/W emulsion because of the formation of smaller crude oil droplets (Ahmed et al., 1999). Hence, the lower interfacial tension between phases allowed a larger volume fraction of the dispersed phase with an increased droplet–droplet interaction that lead to an increase in emulsion viscosity and stability.

It is known that the stability of the emulsions depends on many parameters: the composition of oil in terms of surface-active molecules, salinity and pH of water, water volume, size of the droplets and their polydispersity, temperature, type of surfactants and their concentration, energy in mixing, etc. Hayes et al. (1988) propose, in order to reduce these uncertainties, the use of "surfactant packages" containing a water-soluble chemical surfactant, or a combination of water-soluble chemical and/or biological co-surfactants, together with a bioemulsifier, surfactants of biological origins, that binds to the hydrocarbon/water interfaces. These authors state that it is possible to transport by pipeline viscous hydrocarbons through the formation of low-viscosity biosurfactant-stabilized oil-in-water emulsions, or the so-called hydrocarbolsols. Here, hydrocarbon droplets dispersed in the continuous aqueous phase are substantially stabilized from

coalescence by the presence of biosurfactants and in particular, microbial biosurfactants. The microorganisms predominantly reside at the hydrocarbon/water interface, covering the surface of the hydrocarbon droplets, protecting them from coalescence and maintaining the reduced viscosity over time. The hydrocarbons reported present viscosities reduced by at least a factor of 10 and the preferred water-soluble nonionic chemical surfactants for viscous crude oils are the commercially available ethoxylated alkyl phenols and ethoxylated alcohols; while the preferred water-soluble anionic chemical surfactants are ethoxylated alcohol sulfates. Among the preferred biosurfactants are heteropolysaccharide biopolymers produced by bacteria of the genus *Acinetobacter* and the genus *Arthrobacter*, and in particular, those produced by strains of *Acinetobacter calcoaceticus*. Still some heavy oils were not successfully emulsified with the surfactant packages studied.

Bioemulsifiers, specifically extracellular microbial polysaccharides ("emulsans") produced by different strains of the *Acinetobacter* bacteria have been extensively researched by Gutnick et al. (1983) and Gutnick and Bach (2003). These are very efficient oil-in-water emulsifiers possessing a high degree of specificity in both fresh water and sea water for emulsifying hydrocarbon substrates which contain both aliphatic and aromatic or cyclic components. Bioemulsifiers generally work by orienting themselves at the oil/water interface, avoiding the coalescence of the oil droplets and stabilizing the resulting emulsion.

Since it is not easy to produce stable heavy O/W emulsions, it is necessary to control and improve the process at every stage. In some cases, especially with extra-heavy oils, the formation of an oil-in-water emulsion will not occur. Still, there have been several scientific advances over the past 40 years, allowing for a better understanding of these complex systems. However, there are still many unresolved questions related to the peculiar behavior of these emulsions. Its complexity comes from the molecular composition of oil, which covers a wide range of chemical structures, molecular weights; to the HLB (hydrophilic–lipophilic balance) values of the surfactants, to the multiple interactions oil–water–surfactant and the possible molecular rearrangements at the oil/water interface.

2.2.1. Heavy oil emulsions for transport in cold environments

Heavy oil in cold environments can be efficiently transported through a large diameter insulated pipelines at temperatures below 273.15 K in the form of 40–70% w/w oil-in-brine emulsions containing salts dissolved in the water in amounts sufficient to prevent freezing. These operating conditions permit the insulated pipeline to be buried in the ground without causing thawing of the permafrost, which in turn can cause damage to both the environment and the pipeline. Marsden and Rose (1972) suggest that natural gas can be transported dissolved in the cold heavy oil emulsion with considerable economic advantage. It is well established that the solubility of natural gas in crude oil decreases as the temperature increases and conversely that the solubility of gas in crude oil increases as the temperature is lowered. Then the cold emulsion pipeline can also be used as a means of transporting significant quantities of dissolved natural gas. The emulsion is suggested to contain a small amount, 0.1 to 5% by weight, of a conventional surfactant to facilitate the formation and preservation of the emulsion. Natural gas in remote areas is often just disposed of through flaring. With the advent of liquefied-natural gas (LNG) markets, it is now possible to establish long-term supply contracts that would make financially feasible such technology option. The transportation feasibility of dissolved natural gas might depend on the concentration of oil in the oil-in-brine emulsion, the pressure in the pipeline, the emulsion temperature at this pressure, and the investment and operation costs of high pressure pipelines. If natural gas contains significant amounts of gases as hydrogen sulfide or carbon dioxide, these gases should be removed. Emulsions are difficult to handle in cold environments because of phase destabilization, freezing or an increase in viscosity to a level too high for pipeline transport. Gregoli and Olah (1992) propose the use of common

surfactants mix to form the emulsion and supplemented by use of the xanthan biopolymer to enhance the stability of the emulsion. The aqueous solution is suggested to be brine with a high salt content and the use of freezing point depressants like ethylene glycol in sufficient concentration to maintain the oil-in-brine emulsion in pipeline condition at 253.15 K or less, but insufficient to cause a permanent loss of the emulsion. Here, it will be necessary to consider the costs associated to emulsion rupture and further processing of produced water to discharge or reuse.

2.3. Heating heavy and extra-heavy crude oil and heated pipelines

This is the second most used method for transporting heavy oil by pipeline. The principle is to conserve the elevated temperature (<373.15 K) at which the oil is produced at the well-head through insulation of the pipelines. Nevertheless, external heating of the heavy oil is always needed because of heat losses that always occur, as a result of low flow or unused pipeline capacity. The heating method works only when oil is reheated in the pumping stations through direct-fired heaters. Insulation options include burying the pipeline to conserve heat. Also, traditional oil pipelines operate with a low vapor pressure restriction, close to ambient pressure, in order to maximize their capacity.

Ghannam and Esmail (2006) studied the thermal flow enhancement of a medium Canadian crude oil (density (ρ) = 0.929, μ = 1375 cP at 393.15 K). The viscosity at 10 s^{-1} shear rate was reduced from roughly 700 to 300 cP by heating the medium crude oil from 283 to 303 K. The effect of temperature on viscosity of the assayed crude oil was very important since it is not a very viscous crude oil as others as the Canadian Athabasca, the Venezuelan oil sands or the Mexican Ku-Maloob-Zaap or Ayatsil-Tekel crude oils. However, the authors concluded that the preheating of this kind of medium crude oil is impractical because subsequent heating is required to maintain flow (Ghannam and Esmail, 2006).

Perry (2007) discloses a novel approximation that eliminates the need for direct heating along the pumping stations where crude oil's temperature can be controlled by varying the design choices of line diameter, station spacing, operating pressure range and the viscosity specification of the transported oil at ambient temperature. The method applies when designing a new pipeline that is at least 250 kilometers (km) long, preferably 500 km with a high-pressure specification and of course, high investment cost. The fluid to be transported should be heavy oil diluted with a liquid hydrocarbon having five or fewer carbon atoms that has a high (>atmospheric) vapor pressure. The resulting expensive pipeline system may have a pressure drop of 1250 psia (86 bar) between stations, sufficient to generate a shear heating effect. Here, the temperature increases through friction in the pump as pressure augments and from the heat generated by internal shear friction of turbulent flow within the heavy oil as it flows at high velocities throughout the pipeline. Some pipeline designs can reach temperature increments of about half degree Celsius for every 15–30 km of distance, with an equilibrium temperature at 338.7 K. Rather than wait for this effect to slowly heat the oil as it travels down the pipeline, a heater is proposed at the front end of the pipeline, so that the diluted heavy oil equilibrium temperature is maintained throughout the pipeline system. The higher the oil viscosity, the greater the internal shear friction and more heat is generated, but since the system has to be designed considering shutdown conditions, diluted heavy oil is recommended. This shear heating effect is not seen with normal light and medium gravity oil, as the viscosity within the transport system is too low.

2.3.1. Electrically heated subsea pipelines

Subsea pipelines are crucial to the offshore production infrastructure but they often prove to be a weak link in certain cases where the hydrocarbon reservoir produces heavy or extra-heavy oils, which tend

to become thick and viscous at the temperature of the subsea environment. The usual solution for small distances (less than a mile) is insulating the pipelines and moving the produced well fluids as quickly as possible to minimize temperature losses. However, passive insulation becomes ineffective when longer lengths of pipeline are needed to transport the oil and higher pressures may require expensive subsea booster pumps. Supplying power for booster pumps or auxiliary heating along the pipelines is a difficult proposition for remote subsea wells and pipelines. An alternative to consider is the electrically heated subsea pipeline for the transport of heavy oils as suggested by Langner and Bass (2001). Two configurations for electrical heating are available: a single heated electrically insulated pipeline (SHIP) where electrical current flows along the pipe; and a pipe-in-pipe subsea pipeline where the oil flows through the inner electrically insulated pipe which is surrounded concentrically by an electrically conductive outer pipe. In the latter, heating is caused by a combination of electrical resistance and magnetic eddy effects associated with transmission of an alternating current through the pipeline. Also, Bass and Langner (2000) noted that AC power has several benefits over DC power, and is preferred for this application. The power and voltage requirements for direct electrical heating of the pipeline and power transmission are within conventional AC power engineering limits and are already available on platforms in standard 60-Hertz power plant configurations. Although it may be desirable to alter the frequency in certain applications, the basic power commitments for pipe lengths up to 65 km are achievable without special purpose generators. Second, DC power raises significant concerns about corrosion control for the underwater pipelines, which is not an issue with AC power. Nevertheless, the concentric pipe-in-pipe configuration is costly to deploy and operate because of the complexity of the pipeline design and the fact that it is necessary to have the whole length of the pipeline heated.

2.4. Pour point depressants

Another alternative to reduce the problems associated with the flowability of heavy or extra heavy crude oils, mainly from off-shore to ground facilities but not exclusive, is the utilization of pour point depressants (PPD). PPD, alternatively known as wax crystal modifiers, are chemical additives that affect nucleation, adsorption or solubility of waxes. The modification of wax crystallization may help to depress the crude oil's pour point, viscosity and yield stress appreciably, which facilitate the transportation of waxy crude oils (Chanda et al., 1998).

Many polymer compounds have been described as pour point depressants, the most extensively used for waxy heavy oils are highly branched poly- α -olefin (Morduchowitz and Bialy, 1977), alkyl esters of unsaturated carboxylic acid- α -olefin copolymers (Van der Meij and Bloembergen, 1973), ethylene-vinyl fatty acid ester (Qian et al., 1994; Elgamel et al., 1994; Jordan et al., 1978), vinyl acetate- α -olefin styrene maleic anhydride copolymers (Abou El-Naga et al., 1985), long-chain fatty acid amides and poly- n -alkyl acrylates (Machado et al., 2001) and methacrylate copolymers (Pedersen and Ronningsen, 2003; Da Silva et al., 2004; Song et al., 2005). The application of pour point depressants has also been described in several patents (Ahlers et al., 2007; Bloch and Martella, 2002).

A systematic study of the viscosity, pour point, and wax appearance temperature of a waxy North Sea crude oil was done with 12 different commercial pour point depressants (Pedersen and Ronningsen, 2003). These are substances capable of building into wax crystals and alter the growth and surface characteristics of the crystals, reducing the tendency to form large crystals as well as their adherence to metal surfaces such as pipe walls. They observed a large viscosity reduction (from 1000 to 10 cP) of the crude oil for temperatures between 283 and 293 K for all flow improver additives. The effect on crude oil viscosity was successfully modeled by assigning a lower melting temperature to wax molecules in the range C_{21} – C_{45} in the presence of a flow improver additive (Fig. 3).

More recently, the pour point depressant performance on the rheological properties of light and heavy Mexican crude oils was tested with various copolymers based on different combinations of vinyl acetate, styrene, and n -butylacrylate between 298 and 323 K (Castro and Vázquez, 2008). The pour point in light or heavy crude oils diminished about 20 and 10 °C with a styrene or vinyl acetate copolymers, respectively. The viscosity of the light crude oil was reduced only upon 313 K while for the heavy crude oil, the effect of the PPD on viscosity reduction was noticeable from 298 K.

3. Reducing friction

3.1. Drag reducing additives

When fluids are transported by pipeline, the force that must be overcome to drive the fluid through the pipeline is defined as the force of drag or simply drag. This drag is the result of stresses at the wall (due to fluid shearing) causing a drop in fluid pressure. Due to this pressure drop, the fluid must be transported with sufficient pressure to achieve the desired throughput. When higher flow rates are needed, fluid deformation is higher and shear stresses increase, so more pressure must be applied to maintain the flow at the same average velocity. However, specifications of pipeline design may limit the amount of pressure that can be employed or rise substantially the investment costs. The problems associated with pressure drop are more acute when fluids are transported over long distances, so drag reducing additives may be incorporated in the flowing fluid. The role of these additives is to suppress the growth of turbulent eddies by the absorption of the energy released by the breakdown of the lamellar layers, which results in higher flow rate at a constant pumping pressure. Hence, turbulent flow and therefore drag reduction are difficult with heavy and extra heavy crude oils because of the high viscosity and that flow is generally laminar. Nevertheless, we must also consider that heavy and extra heavy crude oils may be diluted or heated to assure, at least, transitional flow where the use of drag reducers may be important to delay the onset of turbulent eddies (Johnston et al., 2008).

Drag reducing agents can be divided in three main groups: surfactants, fibers, and polymers. Surfactants can reduce the surface tension of a liquid while fibers and polymers orient themselves in the main direction of the flow, limiting eddies appearance which results in drag reduction. A study suggests the formation of polymer films inside

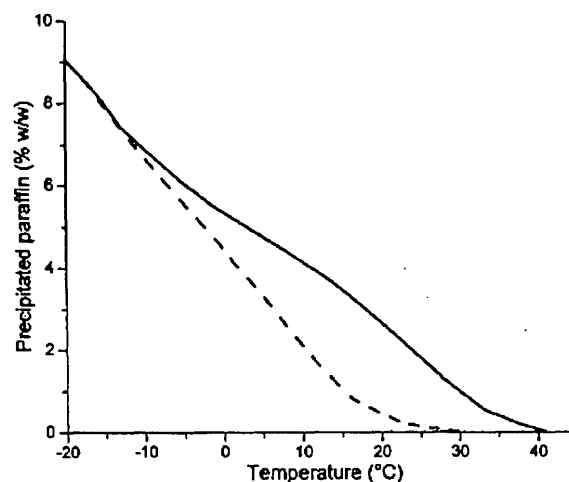


Fig. 3. Precipitated weight of paraffin from the oil with (dashed line) and without (solid line) inhibitor. Adapted from Pedersen and Ronningsen (2003).

the crude oil's matrix that lubricates it and allows an effective drag reduction (Storm, et al., 1999), but it must not be confused with another type of lubricated flow, the core annular flow (see later discussion; Peysson, et al., 2007). The most important requirement is that the drag reducing additive should be soluble in the crude oil and for the case of polymers, it is known that the following properties influence their performance: high molecular weight ($M > 1,000,000$ g/mol), shear degradation resistance, quick solubility in the fluid, and stability against heat, light, chemical and biological agents. One type of current generation of drag reducing additives for liquid hydrocarbons consists of ultra-high molecular weight polymers composed of long chain hydrocarbons that act as an intermediate layer between the fluid and the inner wall of the pipe to reduce energy loss caused by turbulence. However, commercial polymeric drag reducers, typically homopolymers or copolymers of alpha-olefins, do not perform well with heavy oils having low API gravities and/or high asphaltene content.

Milligan et al. (2008) propose the use of high molecular weight acrylate-based polymers for drag reduction consisting of latex suspensions product of an emulsion polymerization reaction. The percentage of drag reduction reported for heavy oils is in the range of 28–36% as shown in Table 2, which is a significant improvement when comparing with commercial products that attained no drag reduction with heavy oils. Here, the drag reducer is soluble in the crude oil phase and seems to form films or layers inside crude oil's matrix that allows it to slip and results in a higher flow rate at a constant pumping pressure. This phenomena has also been observed with the use of drag reducer/pentanol mixtures in extra-heavy oils (10 API; Storm, et al., 1999), and known as lubricated flow. Here, we must differentiate the latter case from core annular flow, where the lubricating ring is formed with water and a polymeric additive (see later discussion).

The relevant problem in using drag reducing latex additives is the difficulty encountered when dissolving the polymeric material contained in the latex emulsion into the hydrocarbon stream. The polymeric suspensions prepared for injection have a tendency to separate when stored in the field locations and special equipment is needed. The problem of preparing, storing and dissolving such drag reducing polymers has been addressed by forming an initial latex suspension, then modifying it by adding low HLB surfactants and solvents that enhance the dissolution rate in a hydrocarbon stream over the initial latex as suggested by Harris et al. (2006). One additional consideration when using these additives is that they are susceptible to shear degradation when dissolved in hydrocarbons. Thus, passage through a pump or severe constrictions in a pipeline can shear the polymer and reduce its effectiveness, in some cases dramatically so. Consequently, it is important that these polymers be poured into the flowing hydrocarbon stream in a form that achieves the needed flow features. The drag reduction of an Iranian crude oil in two-phase flow was studied to simulate the transport of crude oil and natural gas in horizontal pipes (Mowla and Naderi, 2006). Here, poly(isobutylene) was employed as the drag reducing additive and it was found that a dosage of 18 ppm was required to keep constant the pressure drop. Authors state that drag reduction

increased with pipes of smaller diameter and roughness of pipe's surface, i.e. where turbulent flow exists with a high Reynolds number for the same flow rate.

High molecular weight polymers are by far the most efficient drag reducers, but their susceptibility to shear degradation, limits their use. Surfactants show somewhat less drag reducing capabilities than polymers, but their advantage is that drag reduction at fluid velocities over the "critical shear stress", shear stress at which surfactant's micelles disappears, is less affected than in the presence of polymers. Indeed, surfactants have the ability to restructure its rod-like microstructures and re-assume its own drag-reducing capability when the shear stress in the flow decreases to a certain level. The orientation of the large-scale orderly rod-like micelle structures, which promote the drag reduction phenomenon, is recoverable on the order of seconds even after being disrupted (Zhou et al., 2006). Also, drag and heat transfer reduction increases with additive concentration till a maximum reduction is reached (Salem et al., 1998). Such behavior has been explained in terms of the Sublayer Model Theory of Virk that states that an elastic sublayer grows with increasing additive concentration until it eventually occupies the entire pipe diameter, reaching an asymptotic condition (Virk, 1975). By this reason, research of Akron University (Ohio, US) studied the applications of a heterogeneous surfactant formulation that is formed by a mixture of a 70% of non-ionic surfactant and 30% of anionic surfactant (Hellsten, 2002). In the same sense, the synergistic effect on drag reduction was studied for a mixture of polymer and surfactant (Matras et al., 2008). According to the authors, molecular aggregates are formed where a polymer film is formed around surfactant's micelle. Under flow, such aggregates take preferred orientation according to the minimum resistance principle and reduced drag more efficiently than the additives alone. When the Reynolds number augments and reaches a certain value, called the critical point, the drag reduction caused by the surfactant solution alone disappears, while that of polymer-micellar solution still remains.

3.2. Annular and core flow for heavy oil pipelining

Another solution for the transportation of highly viscous products by pipeline is based on developing a core annular flow (CAF) to reduce the pressure drop in the pipeline caused by friction. The main idea is that a thin film of water or aqueous solution can be located adjacent to the inner wall of the pipe, "lubricating" the inner core fluid consisting of heavy oil, thus leading to a reduced longitudinal pressure gradient and a total pressure drop similar to moving water (Bensakhria et al., 2004; Peysson et al., 2007; Ghosh et al., 2009). Annular flow is one of the regimes presented by a two-phase flow but a full and stable CAF is very rare, so a wavy flow is more likely to be present in the core fluid.

This technique has been considered for a long time, Isaacs and Speeds (1904) mentioned the possibility to pipelining viscous fluids through water lubrication. However, a commercial pipeline dedicated to transportation of heavy oil through annular flow was not in operation until the 1970s (Peysson et al., 2007; Bensakhria et al., 2004). The pipeline is operated by Shell near Bakersfield, California, claiming to have transported significant amounts of high viscosity crude oil with water lubrication. Since then, several works were dedicated to CAF regime and some reviews have been written (Joseph et al., 1997; Oliemans and Ooms, 1986). Nevertheless, the capillary instability breaks the inner core into slugs at low velocity and stratification occurs in the system.

Poettmann (1975) suggests the application of an annular ring of relatively inexpensive micellar solution to reduce drag, forming a temporary film over the interior of the pipeline. This micellar system containing surfactants, hydrocarbons, and water can either be maintained on the pipeline wall by repeated injections or permitted to be gradually absorbed into the liquids being transported. This is useful in commercial pipelines where the transport of highly viscous

Table 2
Drag reduction of heavy crude using some reported drag reducing agents (Milligan et al., 2008).

Drag reduction in heavy crude using LP 300 versus polymer A and polymer B		
Product	Concentration (ppm)	Drag reduction (%)
LP 300	187	0
Polymer A	50	28.5
	100	39.5
Polymer B	50	28.8
	100	36.7

fluids requires such drag reducing films and is followed by fluid liquids which do not require such films. The micellar solution may be either water or oil-external micellar solutions. Older pipelines which have been exposed to crude oils are generally oil-wet, so oil-external micellar solutions will tenaciously stick to the surface of the pipeline and present a smooth surface to the fluid being transported. However, water may combine with petroleum through a pump, forming a high viscosity W/O emulsion.

Chilton and Handley (1958) propose a pipeline system with water injection and extraction units and in order to minimize the water used, the injection is carried out at several points around the circumference of the pipe. They mentioned that the addition of chemicals such as sodium hexametaphosphate to the water increases the water's ability to adhere to the pipe and displace the oil films without forming an emulsion. Broussard et al. (1976) developed a solution to the problem of passage of a core-flow system through booster pumps in a pipeline without prior separation of the oil–water fluid. The alternative solution is to add more water or other less viscous liquid after the pump to enable core flow of the resulting emulsion, subsequently the emulsion is broken by applying high shearing forces by means of pipe flow through specialized pipes that restores the annular flow.

While extensive experimental and analytical studies have been carried out to demonstrate that core annular flow is a feasible method for the transport of heavy and extra-heavy crude oils and bitumen at ambient temperatures, no attention has been given to the manner in which this flow pattern is to be established in a commercial pipeline. The effectiveness of the commercial use of core flow is related to its adaptability to existing pipeline systems. Establishing annular flow involves not only technical questions but also operational methodologies to increase the flexibility of the method, in particular, the capacity to share the pipeline with other types of fluids that are not in the core flow regime. Zagustin et al. (1988a) disclose a solution by placing a spherical sealed pig within the pipeline at a desired position. A fraction of the pipeline, situated upstream of the pig, is filled with a low viscosity fluid such as water; and core flow of a viscous oil such as a heavy or extra heavy crude oil is initiated after the first fraction has been filled. The process permits the core-flow of viscous oil with a non-core-flow fluid in the same pipeline. In order to do this, a second pig is placed in the pipeline between the core-flow viscous oil and the non-core-flow fluid and a second portion of the pipeline is filled with another fluid between the second pig and the core-flow viscous oil batch.

Still, establishing annular flow for heavy oil transportation involves significant problems for commercial application as pipeline's exclusive dedication to annular flow regime, maintaining the stability over long distances, fouling and corrosion of the pipe walls, and in particular the difficulties of restarting the flow in case of unscheduled downtime. In any normal pumping operation of crude oil, we can expect interruptions in the process due to mechanical failure, power interruptions, and ruptures in the pipeline or climate concerns. When annular flow is used to transport heavy oil through a pipeline, interruptions in the operation even for relatively short periods of time can lead to the stratification of the two phases. Attempting to restore annular flow by pumping simultaneously a multiphase system with different viscosities creates peaks in the discharge pressure of pumps or along the pipeline. These large pressure peaks can cause major failures in the pipeline as they may exceed the maximum allowable pressure. A basic process for restarting core flow with heavy oils after a long standstill period was also proposed by Zagustin et al. (1988b). First, a flow of a low viscosity fluid such as water is pumped into an inlet portion of the pipeline, gradually this flow increases until reaching the critical velocity required to develop annular flow in a steady state condition (Fig. 4). Next, the flow of heavy oil is started into the inlet portion of the pipeline, and is gradually increased either by adjusting a variable speed motor to the pump or by adjusting a control valve in a viscous oil bypass line. The increase of pressure due



Fig. 4. Scheme of a pipeline design allowing core flow of heavy oils after a standstill period.

Adapted from Zagustin et al. (1988b).

to the pumping of heavy oil is much smaller than the pressure peaks observed during the low viscosity fluid build-up stage.

4. Conclusions

In this review, various technologies and methods allowing the transportation of heavy and extra-heavy crude oils from the production sites to the processing facilities were presented. The fully applicable technologies on the field as well as new method developments to move such crude oils are mainly based on the reduction of crude oil's viscosity, drag reduction in pipelining and partial upgrading of crude oils to syncrudes. Such technologies address the improvements for ease of operation, reliability, cost, size, maintainability, infrastructure and resource disponibility, type of crude oil, and improved crude oil quality. With the increasing production of heavy and extra-heavy crude oils in North America, South America and Eastern Asia, more technological innovation as well as research and development will be needed in order to generate specific solutions for crude oil transportation. Indeed, current and future responses to the transport of heavy and extra-heavy crude oils should take into consideration the composition and physicochemical properties of producing oils, regional logistics between the head-well and the exporting or refining sites, current infrastructure and operational concerns, transport distances, quality of crude oil to export or refine, associated operational and maintaining costs, strict regulations for spills, environmental awareness for water, etc. Crude oil transport by reducing viscosity will be affordable in such production areas with large disponibility of lighter crude oils, condensates or water as well as site disponibility to allocate mixing and/or emulsifying infrastructure. The characteristics and behavior of specific diluted or emulsionated crude oils should be understood in order to address a cost-effective solution to pipeliners and refiners. The needs for improved and new chemicals should boost the research and development on surfactants, flow improvers, drag reducing agents, catalysts and other valuable additives. Besides the need for fundamental research, future developments on crude oil transportation should be based on results from pilot plant and semi-industrial facilities, like instrumented loop pipelines and reactors, in order to offer to the end-users a reliable and tailor-made technology. In the near future, the technological advancements are likely to be aligned with the anticipated requirements to transport the increasing production of heavy and extra-heavy crude oils. This might require the convergence of several technologies in order to satisfy the local and specific requirements of the petroleum industry. Then, we expect that new developments will migrate from out-of-well to inside-the-reservoir technologies where, i.e. the O/W emulsion could be formed or the crude oil might be upgraded inside the reservoir itself.

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