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The Pipeline Transportation of Heavy Oils Using Water Based Dispersions

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Abstract

This paper reviews the properties of water-based formulations designed to mobilize heavy oil in transport pipelines and flowlines through the formation of low viscosity dispersions. The creation of a mobile dispersion involves blending a water based solution, containing a soluble dispersing polymer, into a heavy oil. Typically, the water content of the final dispersion would be in the range 20% to 35%, and the concentration of the dispersing polymer in solution would be in the range 0.3% to 0.5% to obtain the maximum viscosity reduction.

The preferred dispersing polymers are non-toxic and fully biodegradable. Formulations are recyclable, and the dispersions can be easily separated using conventional chemical demulsifiers, heat or gravity treatment. The polymers have been tested with brines of up to 80,000mg/l total dissolved solids, and total hardness ions of up to 2,000mg/l, and shown to be compatible. Using formulations at ratios of approximately 70:30 oil:water, the frictional pressure losses experienced in pipes can be reduced by over one order of magnitude.

Multiple field trials were designed to test the basic chemical principles behind the technology and to evaluate field handling requirements. In an example reviewed in detail, the frictional pressure losses (differential and injection pressures) along a section of infield pipeline for a heavy Newtonian oil treated with a polymer solution were determined and compared with a baseline case where no polymer solution was added. During this trial, the neat oil or dispersion fluids were injected at a constant oil rate, and temperature and pressure readings were recorded continuously at both ends of the flowline. It was observed that, once the injection of neat oil had stabilized, the injection pressure was 850psi and the differential pressure was 820psi. However, with the co-injection of the polymer formulation, the injection pressure displayed a 98% reduction to 25psi, over 2 hours. This resulted in a 43% increase in total fluid flow rate, demonstrating the potential to transport increased fluid with reduced energy. Simulations and history matching, using API RP 13D methodologies, indicated that the treated fluid had an apparent viscosity in the pipe of 350cP compared to the neat oil viscosity of approximately 60000cP.

Introduction

Two common ways of transporting petroleum on land involve the use of trucks or pipelines. Pipelines are the least expensive and most efficient option and are used to transport a high proportion of Canada's crude oil and natural gas production. However moving bitumen and heavy oil by pipeline is problematic because of the high frictional pressure losses associated with the flow of viscous fluids. To overcome this problem, producers commonly reduce the viscosity of bitumen or heavy oils by diluting them with low viscosity petroleum, naphtha or condensate. Bitumen and heavy oils may require between 5% and 50% dilution in order to reduce the viscosity enough to facilitate flow. Surfactant based emulsions may also be used to achieve similar rheological effects[10].

The approach described herein, involving water based formulations[11], was developed in order to overcome the operational complexities and environmental concerns over the use of surfactants, diluents and trucks.

The Polymeric Dispersing Agents

Using the approach herein, increased oil mobility is achieved by blending a field strength polymer solution into a heavy oil, at an oil to polymer solution ratio of approximately 70:30. A typical field strength formulation contains up to 0.5% polymer by weight in brine or fresh water. The full salinity boundaries are still under investigation.

Physical Properties of Polymer

It is convenient to refer to the polymer as a vinyl acetate co-polymer. In a preferred alternative, the polymer tacticity as well as the proportions of acetate, hydroxyl and alkyl groups, have been optimized to enhance dispersion formation and dispersion separation. The rest of this paper concerns the properties of the preferred alternative.

The viscosity of any brine used to prepare a polymer solution is not modified by the presence of the dissolved polymer since the polymer does not associate or self-assemble. The viscosities of formulations containing 0.5% polymer are no more than 0.5cP higher than those of the mix water at any corresponding temperature (Table 1). This limited impact on viscosity implies that there will be no deleterious effects on pumping equipment designed for low viscosity fluids.

Temp' C	Pure Water cP	Water + 0.5% Polymer cP	Water + 1% Polymer cP
20	1	1.30	1.61
25	0.9	1.19	1.50
30	0.8	1.09	1.41
35	0.74	1.02	1.31
40	0.66	0.94	1.25

Table 1: Viscosities of Preferred Polymer Solutions

Data in table 1 was collected using a Bohlin Gemini 150 rheometer with a double gap sensor.

The physical properties of the preferred polymer are:

- White granular powder
- Solids density: 1300kg/1000 litres
- Bulk density 700 to 800kg/1000 litres
- Maximum solubility in brine: 30% by weight
- Shelf life: Indefinite if kept dry
- pH: 6.5 to 7.5 at all concentrations in brine

Toxicity and biodegradation tests were performed with the preferred polymer. These included LD50 tests on multiple marine organisms. On the basis of these results, the dispersing polymer was assigned to the OSPAR gold band (CEFAS product registration number 5699) in accordance with its measured HQ value. Preliminary third party tests showed that the preferred polymer is compatible with generic scale inhibitors, corrosion inhibitors, wax inhibitors, pump elastomers and demulsifiers.

Dispersion Formation

Once blended with oil, the field strength formulation containing the polymer interacts with oil surfaces spontaneously to break-up the oil into mobile deformable droplets (Figure 1). These separated oil droplets are encapsulated by a molecular layer of the polymer. The outcome is that the oil droplets can slip and roll over each other, and also slip over surfaces to which they would ordinarily be bound. Oil droplets are therefore mobilized in environments where they would otherwise be immobile. Minimal agitation is required to achieve this effect, and the properties of the oil in the droplets remain unchanged by polymer solution. Given time, and zero agitation, these droplets coalesce since they are not stabilized through tight emulsion formation. If dispersions are subjected to increasing shear energy, the oil droplet sizes decrease, they become increasingly more stable and their rheology can be determined more reproducibly. However, it has been demonstrated that the rheological properties of dispersions, regardless of the amount of shear used during mixing, are largely indistinguishable within the limits of experimental error.

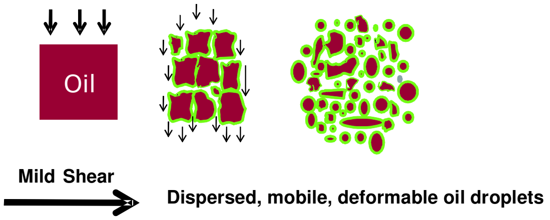

Figure 1: Dispersion Creation

Required Rheological Properties of Oil

For Newtonian heavy oils, the rheology of the dispersions are largely independent of the oil type. Equivalent Newtonian viscosities for dispersions in cylindrical pipeline geometries are commonly in the range 100cP to 300cP. In this sense, and to a first approximation, the water standardizes the mobility of heavy oils (Figure 2). Typically, oils that have viscosities of less than 100,000cP at 25^{o}C, and asphaltene contents of less than 20% conform to this rule

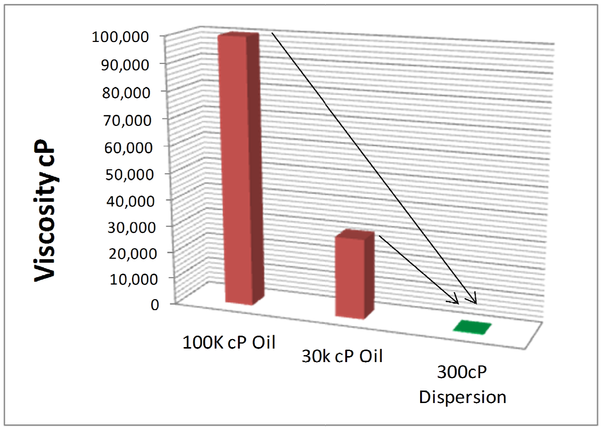

Figure 2: Required Oil Viscosity and Viscosity Reduction

Figure 3 shows the temperature dependence of the viscosities of three Newtonian heavy oils selected for testing, with data for a lighter oil for comparison. All oils originated from either Colombia or North America. Viscosity data was collected, at a shear rate of $10s^{-1}$, using an Anton PAAR MCR 300 rotational viscometer equipped with a cone and plate sensor. API gravites were measured using an RDA Automatic Density Meter DDM 2911. We note that the viscosities of Heavy Oil 1, Heavy oil 2, Heavy Oil 3 and the light oil are 145,000cP, 39,000cP, 19,700cP and 2,700cP respectively at 20^{o}C. All oils were shown to be Newtonian to within the limits of experimental error.

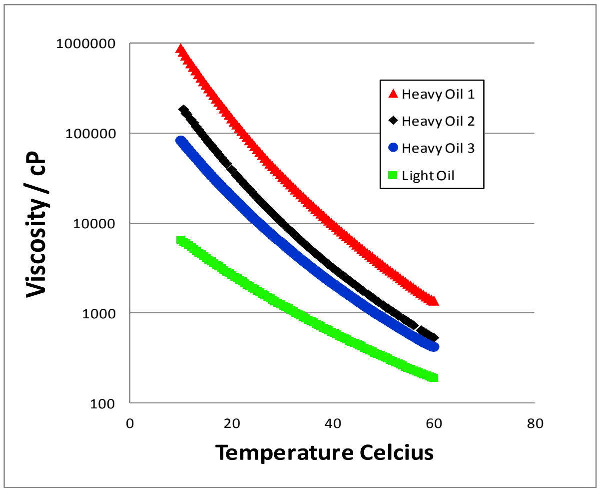

Figure 3: Heavy Oil Viscosities *vs* Temperature

Rheological Properties of Dispersions

At a more detailed level, dispersions exhibit pseudo-plastic rheology that is best described using temperature dependent consistency indices and power law coefficients[4].

Figure 4 shows the flow curves of the corresponding dispersions made from each oil in figure 3, at 20^{o}C. Dispersion rheologies were collected using an Anton PAAR MCR 300 rotational viscometer equipped with a parallel plate sensor with a gap size of 1mm. All dispersions contained 70% by weight of oil and the concentration of the active polymer in the water phase was 0.5%. The water phase was tap water. Dispersions were created by blending the respective components in a glass vessel and shaking vigorously by hand for 60 seconds (low shear mixing). We note that the flow curves for the dispersions have collapsed on to a single line that is best described with the expression:

$$\log \mu\ (\gamma) = \log K - (1\text{-}n) \log \gamma$$

.... Equation (1)

where $\mu(\gamma)$ is the viscosity in cP, at a wall shear rate of $\gamma\, s^{-1}$. The coefficient K is a temperature dependent consistency index, that takes a value of 915 mPa.s^{n} at 20^{o}C, and n is a dimensionless fluid flow coefficient that is to a first approximation independent of temperature and has the value 0.55. Both K and n were determined by regression using data from figure 4.

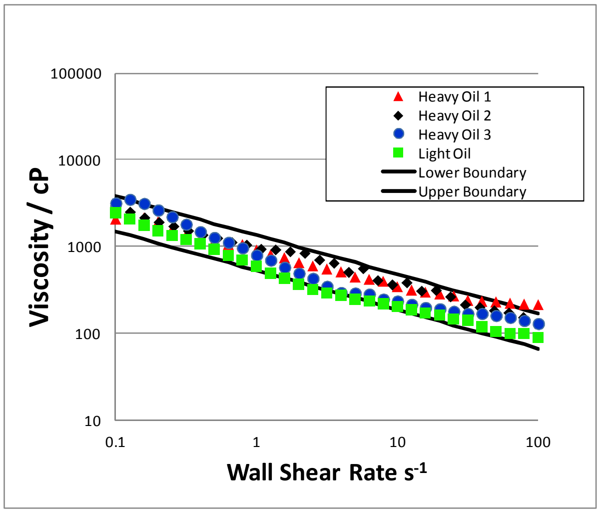

Figure 4: Flow Curves at 20^{o}C for Heavy Oil Dispersions

More extensive data, described elsewhere[1], shows that this behaviour is representative of many other heavy oils. These data[1] suggest that the experimental uncertainty on each viscosity point is approximately ± 25%.

An additional rheological feature of the dispersions is that the temperature dependence of the flow curves is less than that for the neat oils themselves. This can be seen by comparing data in figures 3 and 5. Figure 5 shows temperature dependence of the consistency indices, as per equation 1, for the dispersions made using all four oils under examination. Figure 5 also shows the temperature profile for Heavy Oil 2 for comparison. These comparisons indicate that the greatest contrast between the apparent viscosity of the dispersion and its corresponding oil occurs at temperatures below 50^{o}C.

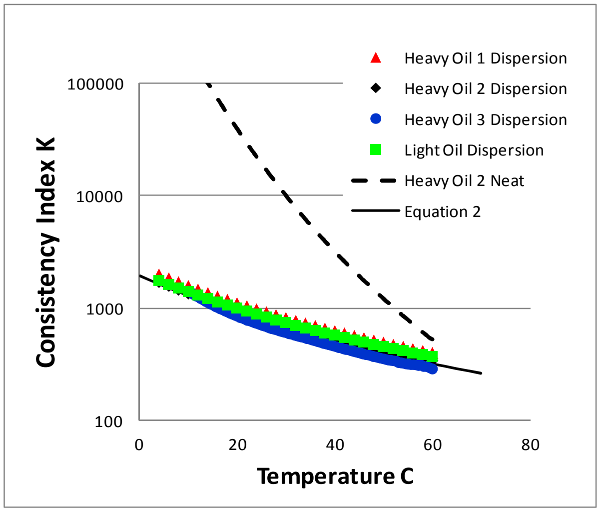

Figure 5: Consistency Indices K (mPa.s^{n}) for Heavy Oil Dispersions *vs* Temperature

The temperature dependence of the consistency indices for all dispersions is best described with the expression:

K(T) = 6 x10^(330/(142-Tk))

…............ Equation (2)

where K(T) is the consistency index K at a temperature T in Celsius, and Tk is the corresponding absolute temperature in Kelvin. Equation 2 was determined by regression using data in figure 5.

Interfacial Properties of Dispersions

Structural Considerations

The dispersing polymer differs from conventional surfactants in a number of ways. Primarily, surfactants stabilize oil dispersions *via* the formation of tight emulsions that lead to the formation of small, rigid, oil droplets[2,3]. In contrast, the polymer solutions lead to the formation of large unstable, deformable, droplets. Consequently, oil droplets in polymer dispersions can be an order of magnitude greater in size than those found in surfactant stabilized emulsions. This is demonstrated in figure 6, which shows droplet size distributions for dispersions made with a heavy oil (6,000cP at 25°C) using either the preferred polymer at 5000 mg/l or the surfactant Triton X-100 at the same concentration. All dispersions had an Oil:Solution ratio of 70:30 and were made by first mixing the oil and the water phases by hand and shaking for 100 seconds (low shear mixing), and then blending further using an Ultra Turrax mixer, with a 25mm head, at 6,000RPM for 15 minutes (high shear mixing). Droplet size distributions were measured using Laser Light Scattering (Malvern Mastersizer 2000).

Figure 6 also demonstrates that a dispersion made with the polymer can be made using minimal shear and that further shearing leads to a reduction in mean oil droplet size. In the case of the Triton X-100 dispersion, compared with the polymer dispersion, the droplets size is reduced significantly using the same amount of shear energy leading to stable emulsions[2,3].

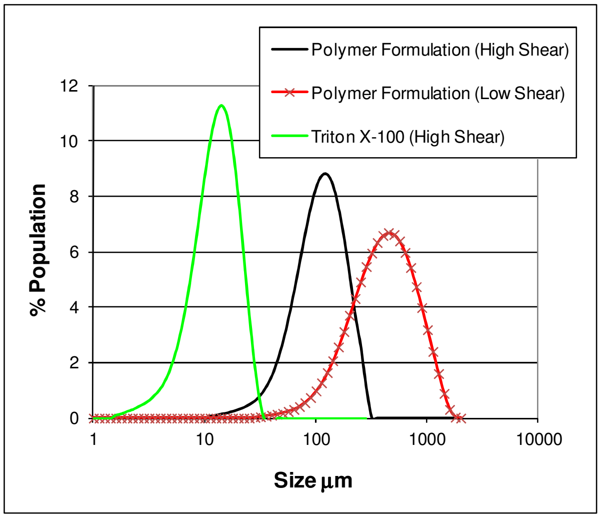

Figure 6: Droplet Size Distributions for Comparable Systems

Interfacial Tension

In addition to the formation of larger oil droplets, air/water and water/oil interfacial tensions (IFT) are reduced less by the polymer than by surfactants (Figure 7). IFT data was determined using drop shape analysis, employing a Kruss DSA 100 equipped with a 'J' needle[12]. Figure 7 shows an expected IFT for heavy oil/water of 24.5mN/m, and an oil/water IFT with a typical dispersing surfactant of <0.1mN/m. In contrast, the IFT determined for the polymer solution has fallen to only 40% of the original oil/water value. We interpret this intermediate IFT value as leading to weaker, and less structured interfaces, and being a critical part to the formation of large mobile deformable droplets, as opposed to the formation of tight, stable, emulsions that have smaller droplet sizes[2,3,8].

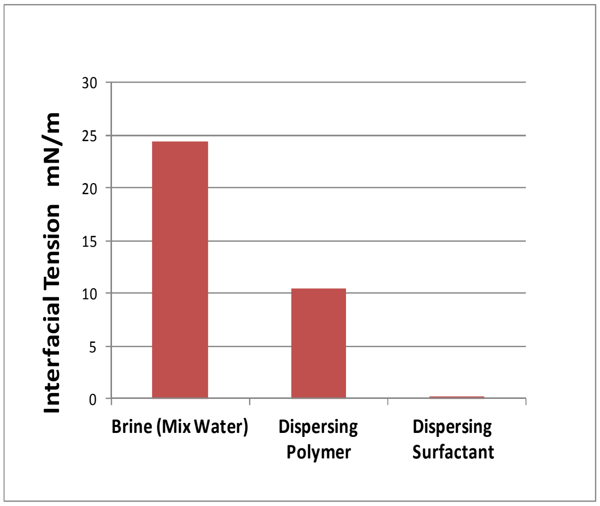

Figure 7: Oil/Water Interfacial Tensions

Dispersion Separation and Recycle

The colloidal and interfacial chemistry of the oil dispersions are such that stable, high viscosity, emulsions are not formed. In reality, the ease of separation will vary on an oil-by-oil basis. However, in house studies and field trials of the polymer chemistry, in pipeline and pump applications, have confirmed the ease of separation.

Laboratory Studies

To emphasize this point, the ability of a dispersion, made with Heavy Oil 2 (Figure 3), to separate was evaluated by first preparing a dispersion (70 parts of oil to 30 parts of mix water) and then incubating the dispersion at 80°C for 16 hours. Figure 8 shows photographs of the separated dispersion, along with the mix water and the unseparated dispersion.

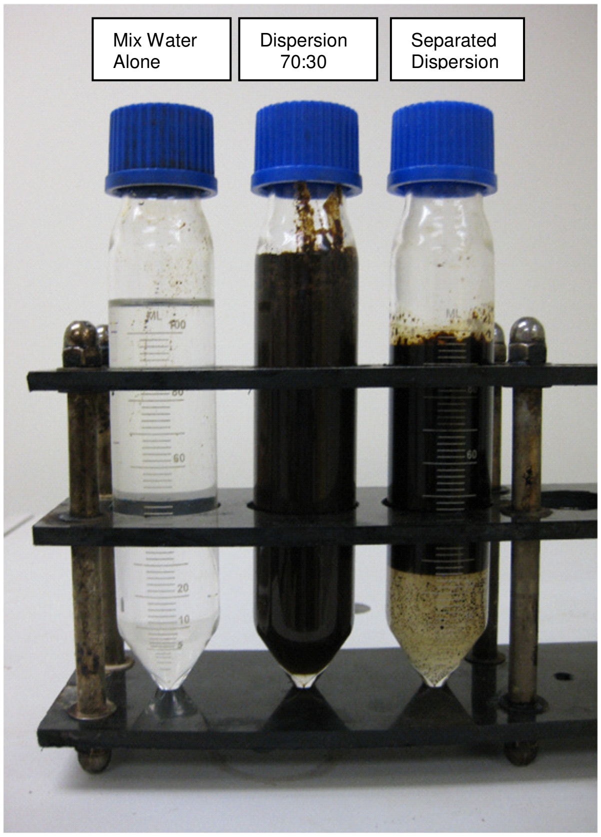

Figure 8: Photographs of Separation Tests with Heavy Oil 2.

Spectroscopic analyses of separated water phases confirmed that, once separated, >99% of the polymer remains in the water phase in an active form. This makes the separated water phases suitable for reuse.

General Comments

We attribute the bulk rheological behaviour of dispersions, and the tendency of the dispersions to separate easily, to the rheological characteristics of the polymer layer at the oil water interface[2,3,8,9]. In particular, the structure and rigidity of the interface should be high enough to resist rupturing, thus preventing the re-formation of two immiscible fluids, but be flexible enough to allow the maintenance of deformable oil droplets in the continuous water phase.

Dispersion Brine Tolerance

To evaluate the effect of brine salinity on dispersion rheology, dispersions were made from four heavy oils using synthetic brines of different ionic compositions at 25^{o}C. Brines were made to represent the compositions of production waters encountered in Northern Alberta and the North Sea. Their compositions range from as little as 257.8ppm TDS up to 78,720ppm TDS and 1,900ppm total hardness (Table 2). Dispersions were prepared following the procedures used to prepare those with Heavy Oils 1 to 3 (see figure 4).

Species	Tap Water	Brine 1	Brine 2	Brine 3	Brine 4	Brine 5
Na	1.3	361	10,200	11,700	19,030	28,750
K	0.5	11.2	78.7	32.5	187	0
Ca	40	5.5	20.1	600	663	1200
Mg	12	1.2	87.2	265	993	720
Total CO3	150	5.5	3	150	435	0
SO4	48.9	4.3	1.3	50	2.2	480
Cl	4.1	500	15,995	22,149	34,046	47570
TDS	257.8	888.7	26,385	39,946	55,357	78,720

Table 2: Brine Compositions

Figure 9 shows the flow curves for the oils and the dispersions at 25^{o}C, and indicates the relevant oil/brine combinations. The oil viscosities at 25^{o}C varied between 6,700cP and 82,000cP. As with data in figure 4, the dispersion rheologies fall on a single line that is closely approximated by equation 1, regardless of brine composition.

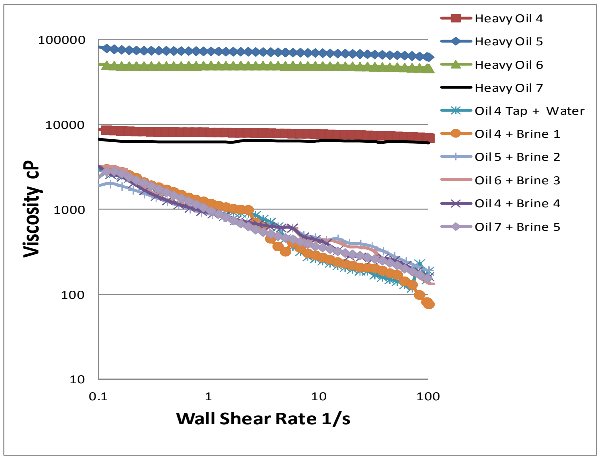

Figure 9: Oil and Dispersion Rheologies in Brines at 25^{o}C

Hydraulic Simulations

The primary role of the OSI in house simulator is to predict frictional and hydrostatic pressure losses for the flow of Newtonian and Non-Newtonian fluids in single transport pipelines. The methodology selected is based on the steady state approximations in API RP 13D[4] for laminar or turbulent flow patterns. The rheological model is limited to pseudo-single phase 'power law' fluids flowing in elevated or flat cylindrical pipes[4,5]. The user provides the geometry of the pipeline (ID, length and end-to-end elevation), the viscosity of the baseline oil or diluent blend, the power law coefficients of the dispersion (equations 1 and 2), the volumetric flow rate of the oil and the proportion of the polymer solution in the dispersion. The model then predicts frictional pressure losses, hydrostatic pressure losses, power consumption and other relevant fluid and mechanical characteristics.

The model limitations arise from the assumption of pseudo-singe-phase behavior in a single pipe. In this sense the model is not comparable with dynamic multi-phase computational fluid dynamics calculations[6,7] or steady state multi-pipe calculations. Despite the model's simplicity, it can be used to generate information for preliminary hydraulic analysis, history matching, job optimization and planning.

Field Trials

A number of field trials were conducted in Albania and Colombia. Each trial was conducted with the intention of assessing the fluid performance, with different oils, in different pipe geometries (Table 3).

	Oil API	Oil Viscosity cP at 25C	ID in	Pipe Length m	Objective of Trial
1	9	80,100	4	100	Evaluate field handling needs and assess basic performance.
2	15.5	550	3	2800	Demonstrate product QC in field and assess basic performance
3	15.5	550	3	2800	Demonstrate basic performance on a fully instrumented pipeline and assess accuracy of OSI steady state simulator
4	10.1	~60,000	4	600	Demonstrate basic performance and assess accuracy of OSI steady state simulator
5	11.9	11,500	3	2800	Demonstrate basic performance and assess accuracy of OSI steady state simulator

Table 3: Field Trial Summary

Trial 1 was the first attempt by OSI to take the technology out of the laboratory into a field environment. Trials 4 and 5, reported below, represent more challenging environments with higher viscosity oils.

Trial 4

This trial involved comparing the frictional pressure losses for an oil, treated with the polymer solution, with a baseline case where no polymer solution was added. The oil was Heavy Oil number 1 in figure 3 and the corresponding dispersion flow curve is seen in figure 4. Figure 10 shows the pipeline configuration. Injection and differential pressures were recorded using analogue recorders at both ends of the pipeline. The baseline oil was first injected, displacing an ill defined fluid originally in the pipe, until the injection pressure stabilized. At this point the, polymer solution was co-injected for a period of 4 hours. Fluid delivery rates were controlled using the OSI pilot scale pump assembly.

Pipeline Conditions (Figure 10)	
Length	600 m
ID	4inch
Differential elevation (flat)	+3 m
Ambient Temperature	25°C

Oil Properties - Clean Dead Oil	
Viscosity (25°C)	~60,000cP
API	10.1
BS&W	<0.4%
Sand	<0.02%

Baseline Conditions (Zero Polymer Solution)	
Oil Flow Rate	220BPD
Injection pressure	**850psi**

Results with Polymer Solution	
Oil Flow Rate	220BPD
Polymer solution flow rate	94BPD
Oil: Solution Ratio	70:30
Polymer Concentration	0.5%
Injection pressure	**25psi**

With the untreated oil, the injection pressure was approximately 850psi, the differential pressure along the pipe was approximately 820psi and the residence time in the pipe was approximately 2 hours. Figure 11 shows the evolution of the fluid injection pressure as a polymer solution was subsequently injected into the flow stream of the dry oil. Over a period of approximately 2 hours the injection pressure fell from 850psi to around 25psi. This 98% reduction in injection pressure was achieved with a 43% increase in total fluid flow rate (220BPD to 220+94 BPD), demonstrating the potential to transport increased fluid with reduced energy. The undulations in the pressure trends in Figure 10 are not interpreted here and may be measurement noise or measurement artifacts.

Computer simulations, using the OSI steady state pipeline simulator and equation 1, predicted the measured frictional pressure losses to within 5%. Using the simulator to history match the trial data indicated that the treated fluid had an apparent viscosity in the pipe of 350cP compared with the neat oil viscosity that fell in the range 55,000cP to 65,000cP**.**

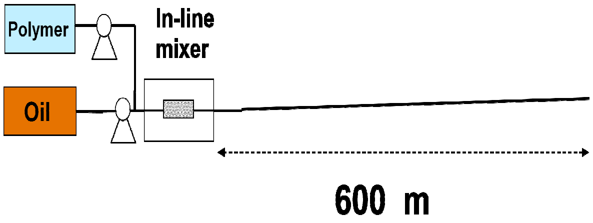

Figure 10: Pipeline Configuration (Trial 4)

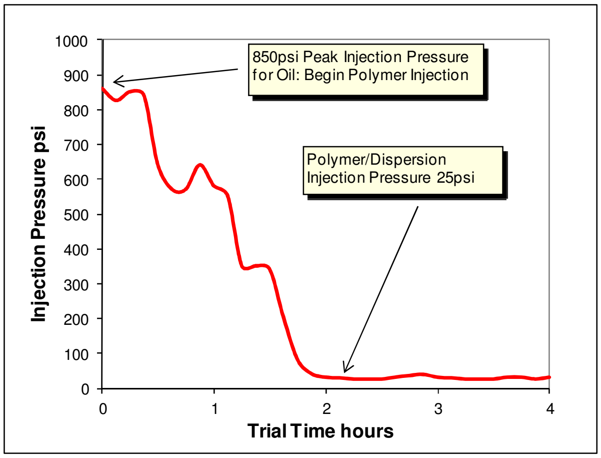

Figure 11: Injection Pressure Measurements (Trial 4)

Trial 5

This trial involved determining the frictional pressure losses (both differential pressures and injection pressures) along a section of infield pipeline for an oil treated with the polymer formulation. Figure 12 shows the pipeline configuration. The oil was Heavy Oil number 3 in figure 3. The volume of oil made available for the trial was insufficient to complete both an oil baseline and also a test with a dispersion. Consequently, friction losses for the baseline case were estimated using the OSI pipeline hydraulics simulator and the trial involved only measurements on a dispersion. Injection and differential pressures were recorded using analogue recorders at both ends of the pipeline as well as at the mid-point. In contrast to trial 4, where an untreated oil baseline was collected, the oil and the polymer solution were co-injected from the start of the trial, and pressures recorded continually for a period of 8 hours. This two phase fluid initially displaced a lighter oil initially residing in the pipeline. Fluid delivery rates were controlled using the OSI pilot scale pump assembly. The residence time in the pipe was calculated to be 6 hours.

Pipeline Conditions (Figure 12)

Length	2800 m
ID	3inch
Differential elevation	+2.5 m
Ambient Temperature	24°C

The pipeline reached a minimum elevation of -60.7 metres at the mid-point.

Oil Properties - Clean Dead Oil

Viscosity (24°C)	12,500cP
API	12.9
BS&W	<0.5%
Sand	<0.01%

Baseline Conditions (Simulated, Zero Polymer Solution)

Oil Flow Rate	220BPD
Injection pressure	**2036psi**

Results with Polymer Solution

Oil Flow Rate	220BPD
Polymer solution flow rate	94BPD
Oil: Solution Ratio	70:30
Polymer Concentration	0.5%
Injection pressure	**67psi**

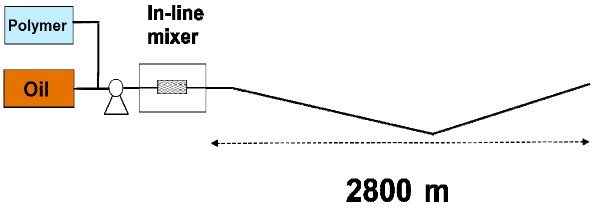

Figure 12: Pipeline Configuration (Trial 5)

Over a period of approximately 5-6 hours the injection pressure fell to around 67psi compared to the simulated 2036psi for the untreated Heavy Oil. This 97% reduction in injection pressure was achieved with a 43% increase in total fluid flow rate, once more demonstrating the potential to transport increased fluid with reduced energy. Computer simulations, using the OSI steady state pipeline simulator, predicted the measured frictional pressure losses to within 5%. The simulations indicated that the treated fluid had an apparent viscosity in the pipe of 195cP. This was consistent with a viscosity reading taken at the time of the trial.

Studies with Ultra Heavy Oils

Neat Ultra Heavy Oils

Two oils from Northern Alberta were made available for testing with the viscosity reducing polymer formulation. Both were tested with the objectives of determining whether or not the polymer formulation can be used to form mobile, separable, dispersions when mixed with the oils. Prior to rheological testing, both oils were dehydrated at 70°C to minimize residual water and sand content. Figure 13 shows the temperature dependence on the oil viscosities, measured at a wall shear rate of $10s^{-1}$ using an Anton PAAR MCR 300 rotational viscometer equipped with a cone and plate sensor. Both oils were Newtonian in the temperature range 20°C to 60°C. Ultra Heavy Oils 1 and 2 had viscosities of 1.4million cP and 200,000cP at 25°C, and API gravities of 7 and 9.5 respectively.

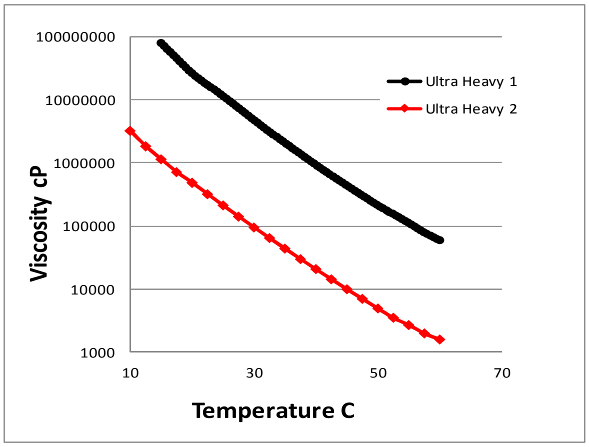

Figure 13: Viscosities of Ultra Heavy Oils *vs* Temperature

Dispersions with Ultra Heavy Oils

Dispersions with Ultra Heavy Oils were made using the low shear mixing procedure used with the Heavy Oils, and their rheological properties collected using an Anton PAAR MCR 300 rotational viscometer equipped with a parallel plate sensor and a gap size of 1mm. All dispersions contained 70% by weight of oil and the concentration of the active polymer in the water phase was 0.5%. In contrast to the ease of mixing observed with the heavy oils, it was not possible to disperse the Ultra Heavy oils at 25°C. With these Ultra Heavy Oils it was necessary to increase the mixing temperature to either 50°C or 70°C to facilitate dispersion formation. Figures 14 and 15 show the flow curves for dispersions made with both oils. In all cases, mixing was at the higher temperature indicated, but the flow curves were collected at 25°C after cooling. The flow curves for the untreated Ultra Heavy Oils are also presented, along with the theoretical flow curves from Equation 1, for comparison.

Ultra Heavy Oil 1 (Viscosity 1.4million cP at 25°C)

The flow curves in figure 14 indicate that the mobility of a dispersion made with Ultra Heavy Oil 1 will be much greater than that of the untreated oil itself. However, neither mixing at 50°C or 70°C lead to flow curves that fell on top of equation 1 for Heavy Oils at 25°C. Also, dispersion separation tests, as described for Heavy Oil (Example - Figure 8), lead to the conclusion that dispersions made with Ultra Heavy Oil 1 did separate rapidly at 80°C, but the water quality was very poor.

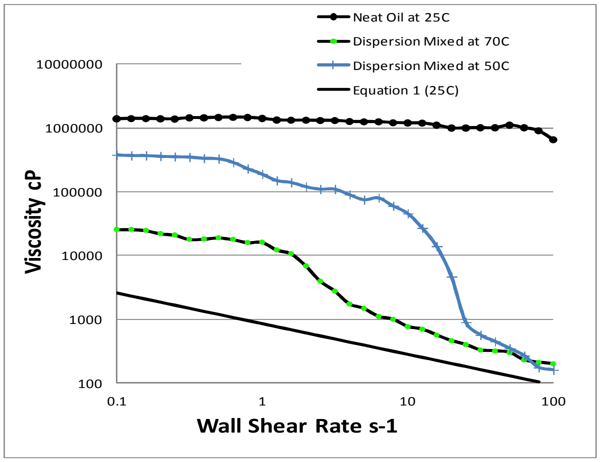

Figure 14: Flow Curves at 25°C for Dispersions with Ultra Heavy Oil 1

Ultra Heavy Oil 2 (Viscosity 200,000cP at 25°C)

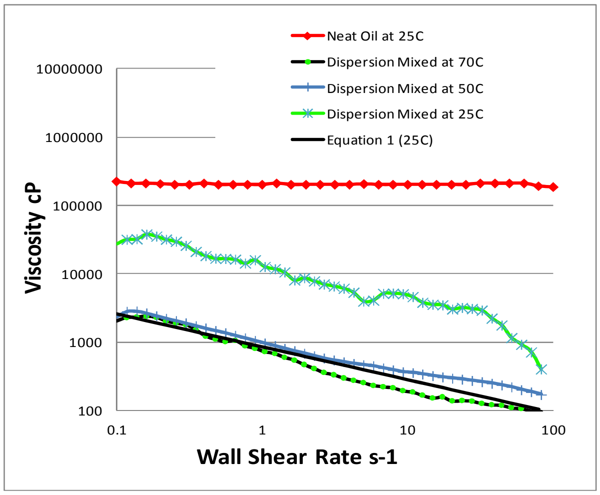

Figure 15: Flow Curves at 25°C for Dispersions with Ultra Heavy Oil 2

The flow curves in Figure 15 indicate that the mobility of the dispersion made with Ultra Heavy Oil 2 will be much greater than that of the untreated oil itself and, in contrast to the observations made with Ultra Heavy Oil 1, the flow curves made by mixing at 50°C and 70°C fell close to equation 1 for Heavy Oils. If the dispersion was blended at the lower temperature (25°C), the dispersion flow curve did not match Equation 1. In view of the limited availability of oil, separation tests with Ultra Heavy Oil 2 were not attempted.

More work is needed to understand the behavior of the formulations with Ultra Heavy Oils, in particular the oil-to-oil dependence, methods for rheological optimization, blending requirements and the resulting formulation boundaries.

Conclusions

- The polymer technology described herein involves a water based formulation designed to mobilize heavy oil in transport pipelines and flowlines. The methodology involves blending a polymer solution into a heavy oil, at an oil to solution ratio of approximately 70:30. Typically, the concentration of the polymer in the formulation is below 0.5%. The outcome of blending is that a mobile dispersion of oil droplets in an aqueous external phase is formed.

- The dispersion characteristics are attributed to rheological characteristics of the polymer layer at the oil water interface. In particular, the structure and rigidity of the interface should be high enough to resist rupturing, thus preventing the rapid re-formation of two immiscible fluids, but flexible enough to allow the maintenance of deformable oil droplets in the continuous water phase. These interfacial characteristics differentiate the polymer performance from that of surfactants.

- The active component in the formulation is non-toxic and fully biodegradable and was assigned to the OSPAR gold band in accordance with its measured HQ value.

- The preferred polymer is compatible with generic scale inhibitors, corrosion inhibitors, wax inhibitors, pump elastomers and demulsifiers.

- The dispersing polymer has a minimal effect on the viscosity of mix waters and will not adversely affect the injection and production facilities through viscosity changes.

- For Newtonian oils with viscosities below 100,000cP at 25°C the following rules, or observations, apply:
    - The dispersion viscosities can be reduced to around 300cP at the wall shear rates typically encountered in transport pipelines. This 300cP is close to common viscosity requirement for oil/diluent blends in transport pipelines.
    - The formulation standardizes the dispersion rheology, i.e., regardless of the original oil viscosity, the dispersion viscosities are identical within an uncertainly of ±25%.

  - Frictional pressure losses in pipes can be reduced by over one order of magnitude depending on the oil and the pipeline geometry
  - The water phase of the dispersion can be removed using regular chemical demulsifiers, or heat and gravity alone. The active component remains entirely within the separated water phase, which makes formulations recyclable.
  - In field trials, frictional pressure losses were simulated using methodology in API RP 13D[4] to within 5%.
  - The preferred polymer has been tested with brines of up to 80,000mg/l total dissolved solids, and total hardness ions of up to 2,000mg/l, and shown to be compatible and effective.

- A limited number of experiments were performed with Newtonian oils that had viscosities between 100,000cP and 1.4 million cP at 25°C. With these oils, mobile dispersions could be formed, but temperatures of up to 70C were needed in order to achieve adequate mixing. For such Ultra Heavy oils, dispersion viscosities are expected to be highly oil-to-oil dependent. More work is needed to understand the behaviour of the formulations with such oils.

- Ongoing work involves the evaluation of factors such as corrosion, erosion, sand deposition and stop/start characteristics, and is employing flow loop studies and simulations based on computational fluid dynamics (CFD).

- Currently, several commercial applications of the viscosity reducing formulation are ongoing in Northern Alberta.

Nomenclature

ppm = Concentration, mg/l
γ = Wall shear rate, s^{-1}
psi = Pressure, 6.895 kPa
cP = Dynamic viscosity, mPa.s
n = Dimensionless power law coefficient
K = Consistency Index, mPa.s^n , or cP at a wall shear rate of 1 s^{-1}.
T = Temperature in Celsius
Tk = Absolute Temperature in Kelvin
Flow curves = Plots of apparent dynamic viscosity *vs* wall shear rate.
TDS = Total dissolved solids, ppm
m = length in metres
in = length in inches
ID = Internal pipe diameter
API = Oil density in units of degrees API.
Heavy Oils = Oils with viscosities in the range 200cP to 100,000cP at 25°C
Ultra Heavy Oils = Oils with viscosities >100,000cP at 25°C

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