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Lubricated Pipe Transport of Heavy Crude Oils

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Abstract: Optimal conditions for lubricated transport of very heavy crude oils in a horizontal pipeline are established. A central core annular flow is obtained using water as the lubricating fluid and heavy oil as the core of the flow. The pressure drop along the pipe using lubricated transport is 50 times less than the pressure drop required to transport the heavy oil without lubrication. When the conditions of temperature, viscosity, and pressure at the injection nozzle are maintained within a certain range, the lubricated transport, with 70% heavy oil in the center and 30% water in the outer annulus, remains stable regardless of the pipe wall temperature.

Keywords: core annular flow, heavy oil, lubricated-pipe transport, oil-water flow

INTRODUCTION

It is of practical knowledge that in order to transport highly viscous heavy crude oils it becomes necessary to reduce the oil viscosity; this is usually achieved by raising its temperature, diluting it with a solvent, or emulsifying the oil in water (Jubran et al., 2005; Mamdouh et al., 2006). The disadvantages of the above methods are obvious. Heating the oil to a temperature high enough to lower its viscosity to a value feasible for pumping often calls for special materials in the manufacturing of the pump. Dilution with a miscible solvent is expensive and often inadmissible, and forming an emulsion in water will require breakage of the emulsion after transportation, which is not an easy matter. A much easier alternative is to use a very low viscosity fluid, such as water, to provide a lubricating thin layer adjacent to the inner wall of the pipe.

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This will lower the viscous stresses at the wall and the resulting pressure gradient along the pipe will be lowered substantially, thus rendering the pumping a more feasible matter. This process is known as lubricated transport. Whenever two immiscible fluids are flowing inside a pipe, the less viscous fluid will be displaced toward the region of higher shear stresses. Therefore, if the flow is inside a pipe of circular cross-section, the less viscous fluid will be displaced toward the wall of the pipe, while the more viscous fluid will flow down the center, forming what is called a "central annular flow" or central core flow (Joseph and Renardy, 1993). There are various flow regimes in lubricated pipe flow (Bai et al., 1992; Joseph et al., 1997; Guevara et al., 1998) other than central core flow, but we are interested in the latter as the obvious application to lubricated transport of very heavy crude oil residues, using water as the less viscous lubricating fluid. Since the pumping pressures are directly related to the viscous stresses at the pipe wall, and these, in turn, are related to the viscosity of the outer fluid (in this case water), the total pumping pressure gradient necessary to transport a very heavy viscous oil in central core flow will be determined by the pressure gradient due to the lubricating fluid, rather than the heavy oil. Typically, the energy saved using lubricated transport is of the order of the viscosity ratio between the heavy oil and that of water (Joseph et al., 1997; Bensakhria et al., 2004). In practice, the volume fraction of water in lubricated transport is between 10–30% and the viscosity ratio will be of several orders of magnitude (Saniere et al., 2004). There are, however, several difficulties in employing this technique, such as plugging or fowling due to adhesion of the heavy oil to the pipe wall, initiated by flow instabilities (Oliemans and Ooms, 1986; Prezioki, et al. 1989; Bai et al., 1992; Li and Renardy, 1998; Joseph et al., 1999), but these may be easily overcome as we shall see below.

LUBRICATED TRANSPORT THEORY

As described above, consider a pipe of circular cross-section with radius R_2 with a liquid film of density ρ_2 and viscosity μ_2 acting as the lubricating film in the outer annular region between the pipe wall and the inner fluid region. The latter consists of a fluid of density ρ_1 and viscosity μ_1 flowing in the central core of the pipe with a radius R_1 (see Figure 1).

The total friction loss h_f in a pipe of length l of circular cross-section is given by the Darcy-Weisbach equation:

$$h_f = f \frac{l}{d} \frac{v^2}{2g} \tag{1}$$

where f is the friction factor, l and d are, respectively, the length and diameter of the pipe, v is the average velocity of the lubricating fluid, and g is the acceleration of gravity.

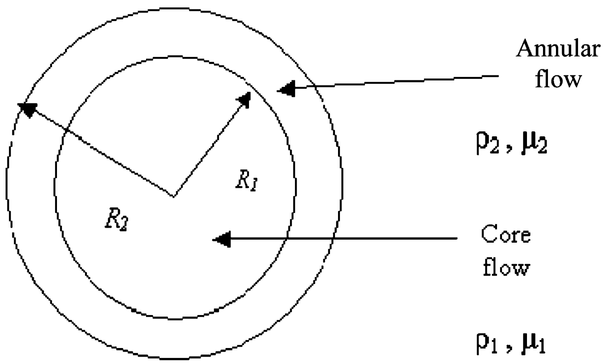

Figure 1. Schematic representation of a lubricated pipe flow in a pipe of circular cross section.

Assuming a turbulent flow regime for the lubricated transport, the friction factor f is given by Blasius's equation:

$$f = \frac{0.316}{\mathrm{Re}^{0.25}} \tag{2}$$

Here, the Reynolds number, R_e, is defined as a function of the average radius R_1 of the central oil core flow, the inner radius of the pipe R_2, the fluid physical properties, and the global velocity of the lubricating flow, as

$$\mathrm{Re} = \frac{2\rho_c R_2 U}{\mu_w}[1 - \eta^4(m-1)] \tag{3}$$

where ρ_c is the average density of both fluids involved, $\eta = \mathrm{R_1/R_2}$ is the ratio between the radii, $\mathrm{m} = \mu_\mathrm{w}/\mu_\mathrm{o}$ is the viscosity ratio between the lubricating fluid (water) and the oil, and U is the global surface velocity defined as

$$\mathrm{U} = (\mathrm{V_w} + \mathrm{V_{Oil}})/\pi \mathrm{R}_2^2 \tag{4}$$

where $\mathrm{V_w}$ and $\mathrm{V_{Oil}}$ are, respectively, the average velocity of the water phase and of the oil phase, both based upon the volumetric flow rate $\mathrm{Q_w}$ and $\mathrm{Q_{Oil}}$ corresponding to each phase as

$$V_{Oil} = Q_{Oil}/\pi R_1^2 \text{ and } V_W = Q_w/\pi(R_2^2 - R_1^2) \tag{5}$$

EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown in Figure 2. It consists of a stainless steel pipe with a circular cross-section of 1.27 cm inner diameter and a total

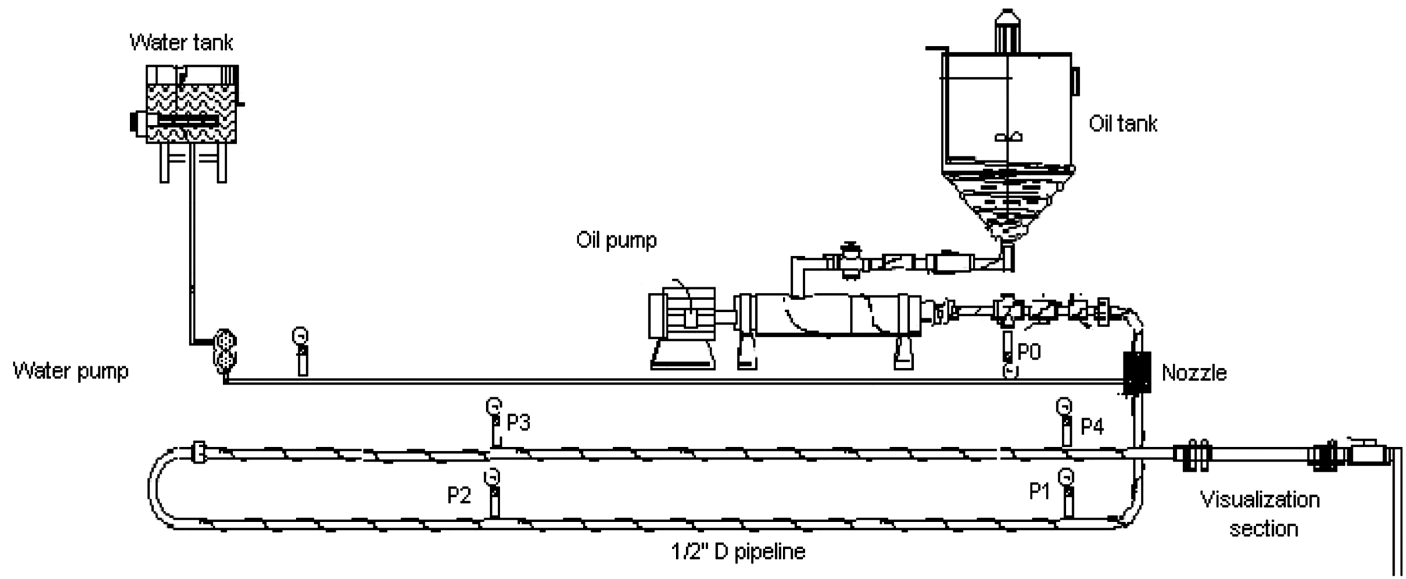

Figure 2. Schematic diagram of the experimental arrangement.

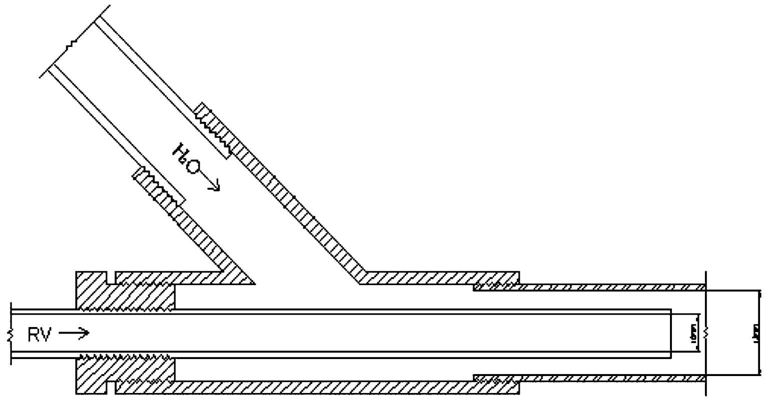

Figure 3. Heavy oil injection nozzle.

length of 12 m. The pipe is kept at a constant wall temperature with the aid of electrical resistances located along the total length of the pipe. The heavy oil is injected into an established water flow rate using an injector nozzle system as shown in Figure 3.

This injector nozzle establishes the initial condition for lubricated transport to be achieved. Both fluids are pumped into the system using positive displacement gear pumps, and both fluids are kept in reservoirs at constant regulated temperature.

The volumetric flow rate for both fluids is accurately controlled with precision using a servo controlled pumping system. Figures 4 and 5 show the calibration curve for both pumps. The linearity between flow rate and pump frequency is evident.

The pressure drop along the pipe is measured using pressure transducers and manometers located at various points of the experimental loop and separated a distance of 4 m between each transducer. Towards the end of the test section, there is a flow visualization zone. It consists of a glass tube of the same diameter as the loop. This visualization zone allows for observation and filming of the flow patterns as well as providing relative velocity measurements between the oil and the water for all the different flow conditions.

EXPERIMENTS

Experimental Fluids

Heavy oils originating from various PEMEX (Petróleos Mexicanos) refineries were used throughout the experiments. These are essentially the oil residues or remainders after refining; they are basically asphaltenes and heavy organic

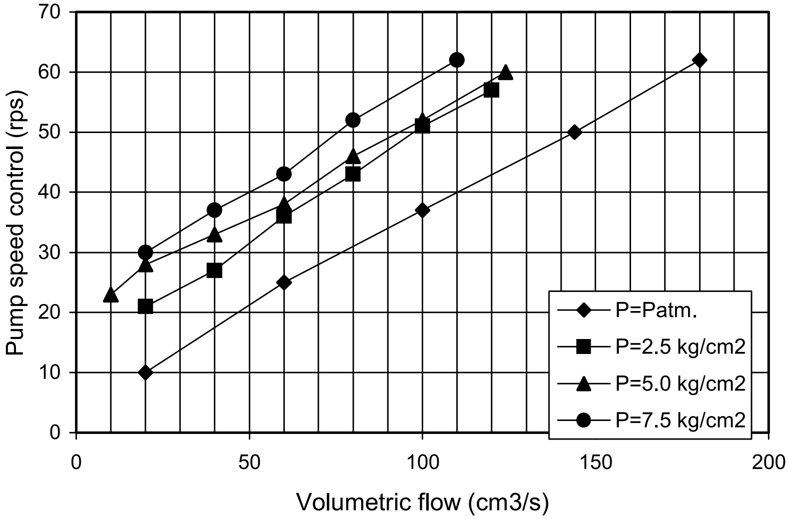

Figure 4. Water pump calibration.

residues that remain after the aromatics and light oils have been removed. These oil residues may be emulsified in water and used as a viable and much cheaper alternative fuel to be burned in thermoelectric plants instead of the commonly used heavy fuel oil. Currently they are used in Venezuela (Orimulsion) and a suitable emulsion has been developed in Mexico by the Instituto de Investigaciones Eléctricas (Peralta et al., 2001; Sánchez et al., 2006). In any case, the heavy oil residues provide a useful material to be

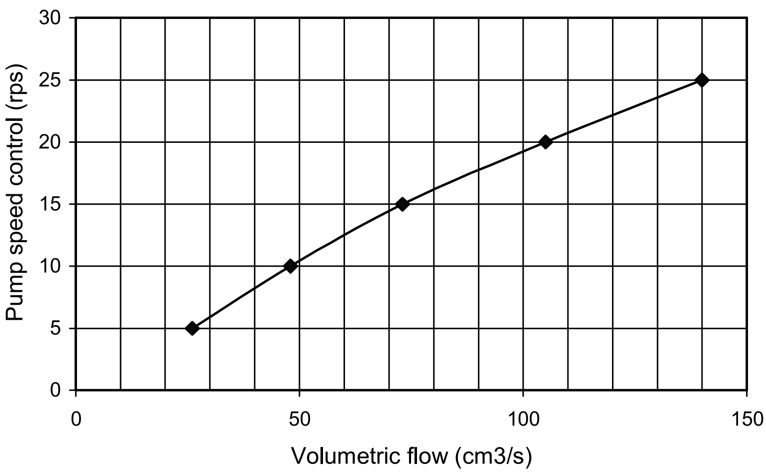

Figure 5. Oil pump calibration.

pumped and tested using lubricated pipe transport. These are rheologically complex fluids whose properties are not easily measured. They are highly temperature dependent, as well as shear dependent. They are basically solid or have solid like behavior at room temperature and up to 80°C with viscosities of several hundred Pascal-sec. It is only above 90°C that they may be pumped and, even so, with great difficulty. The use of an Ares rheometer (parallel plate and concentric cylinder geometries) as well as a Controlled Stress Rheometer showed that the oil residues have basically Newtonian behavior (showing negligible normal stresses and very little shear dependent viscosity) with a high dependence on temperature.

Experimental Procedure

The experimental loop was kept at a constant temperature of 70°C with the aid of temperature controlled electric coils located along the length of the pipe. The water used as lubricating fluid was also kept at 70°C in the feeding reservoir, and a small amount (10 ppm) of surfactant was added in order to inhibit the oil adherence to the pipe wall in order to prevent fouling. The surfactant used was of the noniphenil alcohol type, but virtually any water soluble surfactant may be used. The oil residue was kept in a reservoir at a temperature slightly above 90°C since at that temperature its viscosity is around 10 Pa.s permitting it to be fed by gravity into the pump and then into the loop. Figure 6 shows the viscosity curve as a function of temperature at two different shear rates for the oil residue used in the experiments.

Initially, the system was filled with the water-surfactant solution at a flow rate of 95 cm^3/s with a measured pressure gradient of 250.1 Pa m^{-1}. Once the flow was established, the oil residue was fed into the system using

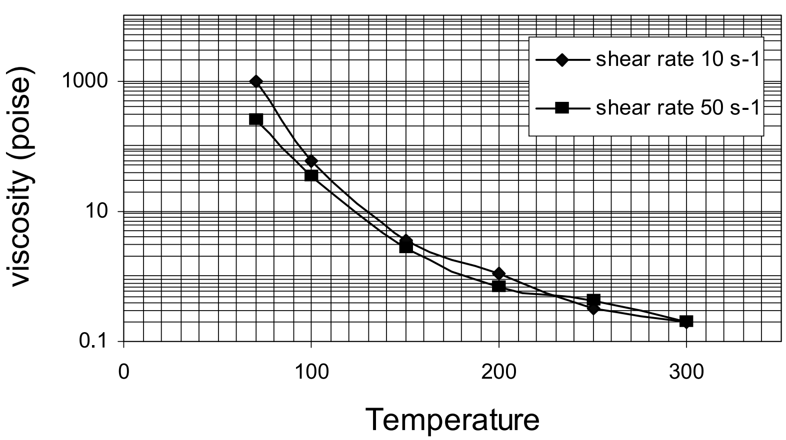

Figure 6. Heavy oil viscosity as a function of temperature for two values of the shear rate.

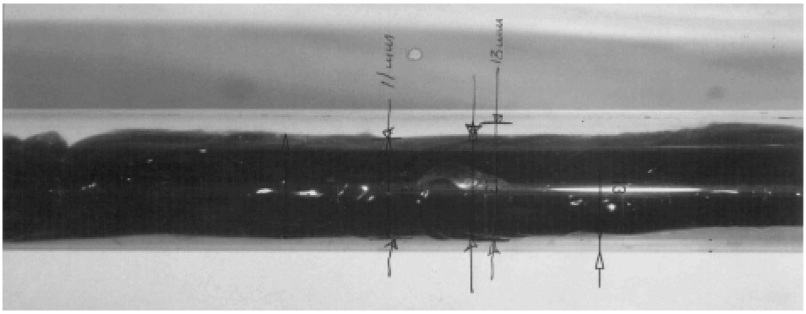

Figure 7. Photograph of the core annular flow in the visualization zone.

the specially designed injection nozzle shown in Figure 3. The smallest flow rate of oil residue was 28.0 cm^3/s, and it was increased periodically, always allowing for the pressure gradient to become stable. At that point the flow visualization zone would show a stable continuous core flow of oil residue surrounded by an annular flow of water, as shown in Figure 7. Once this permanent flow situation was achieved, the flow rate of oil was increased, and the corresponding pressure reading taken. The lubricating water flow rate was kept constant (95 cm^3/s) at all times. The flow pattern was filmed using a high-speed video camera and the experimental data were stored in a computerized data system. Once a set of experiments was finished, the mixture of oil residue and water was collected at the exit. Each batch was then analysed for water concentration, chemical balance, and so on. It was observed that a total separation of the oil residue was possible and that it would have the same characteristics as the original sample. This ascertains that the oil residue can be transported using lubricated transport, without affecting its properties and characteristics.

EXPERIMENTAL RESULTS

Tables 1 and 2 show experimental data for the lubricated transport of the heavy Pemex oil residue corresponding to the rheological characterization of

Table 1. Pressure gradient as function of the flow rate

$\Delta P_{EXPER}/\Delta L$ (Pa m^{-1})	250	417	500	667	1000	1334	1668	2001	2566
Q_{Oil} (cm^3/s)	0.0	28.0	50.0	73.0	105.0	140.0	160.0	190.0	219.0
$QRV = Q_{Oil} = (Q_{Oil}/(Q_W + Q_{Oil})) * 100\%$	0.0	22.7	34.5	43.4	52.5	59.6	62.7	66.7	69.7

Table 2. Theoretical and experimental pressure gradient as a function of Reynolds number

Twall (°C)	T_{Oil} (°C)	T_W (°C)	m_W (g/s)	m_{Oil} (g/s)	m_{Oil} (%)	T_{bexp} (°C)	T_{global} (°C)	Flow conditions
70	90	70	17.1	32.0	65.2	71.3	79.4	Lubricated flow
65	90	65	16.9	31.1	64.8	70.7	76.7	Lubricated flow
60	90	60	16.1	31.3	66.0	70.4	74.4	Lubricated flow
55	90	55	15.4	31.7	67.0	67.3	72.4	Lubricated flow
55	110	55	17.3	31.9	64.8	69.7	80.7	Lubricated flow
50	90	50	16.8	29.8	x	x	68.3	Fouling
50	100	50	16.7	30.8	x	x	73.6	Fouling
50	110	50	16.9	30.8	x	x	77.9	Fouling
50	130	50	17.4	31.5	x	x	87.1	Flow instabilities and Fouling
40	90	40	17.7	31.1	x	x	62.8	Fouling
40	120	40	18.3	30.8	x	x	75.6	Fouling
40	130	40	16.8	30.8	x	x	79.6	Fouling

Figure 6. Table 1 shows values of the pressure gradient $\Delta P_{EXPER}/\Delta L_{OBTAINED}$ for a constant water-surfactant flow rate of $Q_W = 95$ cm^3/s, while the flow rate of heavy oil residue, as well as the total percentage of oil in the total volume flow in the pipe, was being increased.

Flow visualization was possible for all of the cases in Table 1 (see Figure 8). From the photographs and videos, the central core diameter and the water film thickness were measured, and average velocities and Reynolds numbers (Re_{Oil} and Re_W) were obtained for each case.

The first two rows of Table 2 shows a comparison between the theoretical pressure gradient using Blasius expression $\Delta P_{BLASIUS}/\Delta L$ and the experimental pressure gradient obtained $\Delta P_{EXPER}/\Delta L$. It may be seen that as the percentage of heavy oil in the pipe is increased, the agreement between both values becomes better. This is due to the fact that the lubricating film of water becomes thinner, the turbulence increases, and the friction factor value becomes closer to the Blasius expression.

We may observe that when approximately 70% (69.7%) of heavy oil residue is transported with approximately 30% (30.3%) of water, the pressure gradient needed to transport the mixture (2566.0 Pa m^{-1}) is increased one order of magnitude with respect to the pressure gradient necessary for pumping water only. On the other hand, this value is approximately 50 times less than the pressure gradient needed to transport the heavy crude oil on its own (1.3×10^5 Pa m^{-1}). In other words, all other things being equal, lubricated transport of heavy oil residues may be affected with pressure gradients, which are at least one order of magnitude smaller than without the use of lubrication.

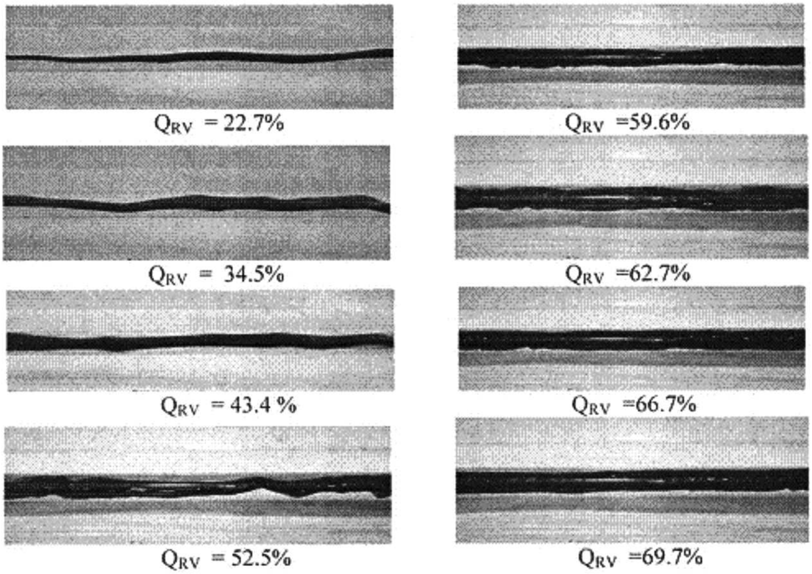

Figure 8. Photograph sequence corresponding to Table 1.

Another interesting observation that emerges from Table 2 is that when the amount of oil residue is increased, the velocity of the oil phase V_{Oil} is not drastically affected. This is in contrast to the water phase velocity V_W, which may increase to approximately 300%. Calculations of the Reynolds number for both phases shows that in all cases, the oil residue flow is laminar while the water flow is in a turbulent regime.

It is also of interest to compare the experimental values of the pressure gradient with the theoretical values of the Blasius equation as obtained in Table 2 for the various experimental conditions of lubricated transport. This is shown in Figure 9 where values of the friction factor f are plotted as a function of the Reynolds number Re_W for the experiments reported here.

In order to examine the conditions for which lubricated transport could be achieved, further tests were conducted using a straight pipe of stainless steel with 0.55 cm of interior diameter and a total length of 4 m. This pipe was easy to clean if fouling occurred. Furthermore, in order to analyze in detail the temperature relation between the oil residue and the water lubricant for central core flow to occur, heat exchangers were installed for both fluids. Immediately after the oil injection through the nozzle, the lubricated transport conditions are established under a constant wall temperature condition. Throughout the experiments, the minimum oil temperature was 90°C, at which the oil could be pumped by the gear pump with a viscosity of approximately 10 Pa.s. The maximum temperature would be 130°C, at which the viscosity was reduced to 0.5 Pa.s, a value that has been reported by other authors as

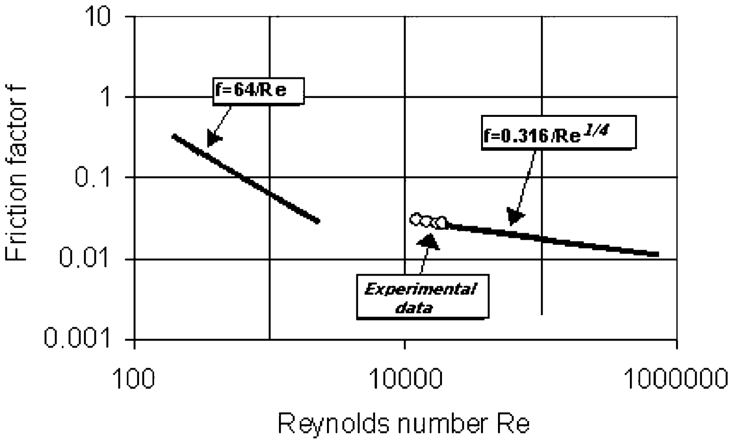

Figure 9. Friction factor f as a function of Reynolds number, Re, ◊ Experimental data.

the minimum viscosity for lubricated transport before fouling occurs. The water temperature range covered was from room temperature (25°C) to 70°C, after which evaporation effects started to appear and flow rate in the pump became difficult to control. For all cases reported below in Table 3, the mass flow rate of water m_W and the mass flow of oil residue m_{Oil} were kept constant. The objective was to control the wall temperature of the pipe T_{wall}, the oil temperature T_{Oil} and the water temperature T_W, so that the central core annular flow would develop inside the pipe and reach equilibrium state at the value of the wall temperature. In some cases, if the temperature difference between the oil residue and the water was large, fouling would occur; the oil residue would freeze and clog the pipe. However, when the temperature gradient between water and oil was kept between certain limits, central core flow could be achieved. Whenever the lubricated transport was established, the bulk temperature T_{bexp} was measured at the exit of the pipe;

Table 3. Experimental values averaged from several experimental runs

$\Delta P_{BLASIUS}/\Delta L$ (Pa m^{-1})	701	821	1006	1388	1545	1909	2189	2566
$\Delta P_{EXPER}/L$ (Pa m^{-1})	417	500	667	1000	1334	1668	2001	2501
Q_{Oil} (cm^3/s)	28.0	50.0	73.0	105.0	140.0	160.0	190.0	219.0
% Q_{Oil}	22.7	34.5	43.4	52.5	59.6	62.7	66.7	69.7
V_{Oil} (cm/s)	199.2	272.9	234.9	219.2	264.4	257.8	282.1	235.1
Re_{Oil}	0.84	1.31	1.5	1.7	2.2	2.3	2.6	2.6
V_W (cm/s)	75.8	83.0	93.4	112.0	119.1	134.4	145.3	240.0
Re_W	9854	10790	12142	14560	15483	17472	18889	31200

simultaneously, flow samples were taken at 5 min intervals to verify the mass flow rates of oil and water provided by the calibrated pumps. In order to have a qualitative idea of the average temperature of the center core flow in the injection section as well as its corresponding value of viscosity in the nozzle, we may calculate a global temperature T_{global} corresponding to the oil water mixture as

$$T_{global} = \frac{m_W C_W T_W + m_{Oil} C_{Oil} T_{Oil}}{m_W C_W + m_{Oil} C_{Oil}} \tag{6}$$

where C_W and C_{Oil} are the corresponding values of the specific heat coefficients of the water and oil, respectively. Table 3 shows the measured experimental values averaged from several experimental runs.

The following observations emerge from the above data:

1. Lubricated transport could not be attained at wall temperatures below 55°C; the corresponding viscosity value of the oil residue being around 10^2 Pa.s.
2. The average temperature at the exit of the pipe was greater than the wall temperature for all the cases considered. This implies that flow required to attain such a regime was not a thermally developed flow; a longer pipe would be required for this situation. At the exit temperature, the corresponding oil residue viscosity would be of the order of 30–40 Pa.s.
3. The temperature difference between the injection of the oil residue and the lubricating water-surfactant mixture must be kept within 20°C and 55°C.
4. The global conditions to be maintained in order to achieve a central core annular flow of lubricated transport for heavy oils may be summarized as follows: (a) the lubricating fluid temperature T_W must be kept between 55°C and 70°C, and (b) the heavy oil residue should be pumped at the temperature which is closest to the water temperature but allows for the fluid to be pumped without difficulty. In the case at hand, the minimum oil temperature T_{Oil} was 90°C.

In order to further examine the thermally developed flow of point 2 above, another set of experiments was taken without heating the pipe wall and using a pipe length of 32 m. It was observed that although it was necessary to keep the conditions for temperature difference between the oil and the water in the nozzle, once the flow was established, it would remain stable, regardless of the wall temperature. So for practical applications if the conditions at the nozzle are controlled, the lubricated transport of heavy oil residues is feasible with up to 70% oil and 30% water. The pressure gradient required is approximately ten times more than the one required for pumping only water through the pipe, but 50 times less than the one required to pump the oil residue on its own. This results in an enormous energy saving.

CONCLUSIONS

In lubricated transport, the pressure gradient needed to transport a mixture of approximately 70% of heavy oil and 30% of water is one order of magnitude less than the pressure gradient necessary to transport the heavy oil on its own. The flow regime obtained in all cases was a core annular flow and it remained stable provided that the water temperature at the injection nozzle was kept between 55 and 70°C, and oil temperature injection between 90°C and 110°C. For practical applications, if the conditions at the nozzle are controlled, the lubricated transport of heavy oil residues remains stable, regardless of the pipe wall temperature. The huge reduction of friction in the pipe enhances the interest in the use of the lubricated technique to transport heavy crude oil. Stopping and restarting operations have to be studied to guarantee the complete feasibility at an industrial scale.

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