Isothermal and non-isothermal water and oil two-phase flow (core-flow) in curved pipes

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ABSTRACT
The occurrence of heavy oils in the world has increased substantially and points favorable to investment in exploration of mineral deposits and consequently, for the development of new technologies. Heavy oil has a high viscosity that varies from 100 to 10,000 times greater than the viscosity of water. The high pressure due to friction and viscous effects during the transport of heavy oil has been a major challenge, for itself to be economically viable for production or transportation. The core annular flow technique is a more recent technology favorable the explotation and transportation of heavy oils that provides a considerable reduction of pressure drop during the flow of these oils type. In this sense, this paper presents a 3D numerical study involving the heavy oil transportation in curved pipes, using the core-flow technique by CFD (ANSYS CFX® 12.0). Results of pressure, velocity, volume fraction and temperature distribution of the heavy oil are presented and analysed.

Keywords: Heavy oil, Transportation, Numerical simulation, CFD, CFX

1. INTRODUCTION

To generate projects which provide significant volume recovery from reservoirs and improve existing projects, is of fundamental importance to develop new production technologies focused on heavy oils, especially in the scenario of offshore fields. However, heavy oils present high viscosity which ranges from 100 to 10000 times greater than the viscosity of water, which makes it difficult, expensive and often unfeasible to transport these oils from the reservoir to new destination through pipelines, for example.

The core-flow technique basically consists of injecting small quantities of water at a flow rate lower than the oil causing the heavy oil to be surrounded by a layer of water and flowing in the center of the pipe without touching the inner wall of the pipe, thereby establishing an annular pattern. The core-flow technique does not alter the oil viscosity, but transforms the flow pattern and reduces friction during transport of very viscous products, such as heavy oils. This flow pattern is characterized by a water pellicle that is formed close or adjacent to the inner wall of the pipe, functioning as a lubricant. The oil flows in the center of the pipe causing a reduction in longitudinal pressure drop [8].

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It has been noted in the literature, studies concerning the use of this technique in order to improve the transportation of heavy oils using water as a lubricant [3, 4, 6, 8, 10, 13, 14, 15, 18, 19, 21, 22, 24]. Prada et al. [22] have noticed that the pressure drop by friction in lubricated flow by water is of 750 to 2000 times lower when compared to single-phase flow of the heavy oil on the same pipe and same volumetric flow rate.

Bannwart [6] proposed a theory for the stabilization of the annular pattern when two liquids of different viscosities and densities flows in a horizontal pipe. The theory is based on the analysis of the linear momentum equation in a transverse section of the pipe considering the effect of interfacial tension. This theory enabled the accomplishment of an interesting analogy between the peripheral flow and the flow bypassing a rising bubble, subsequently, observed by [16] and [23]. In this study Bannwart [6] implies that the viscous and inertial forces on the annular flow can be combined into a single drag force alike the one observed in the bubbly flow.

Ooms and Poesio [21] examined the annular flow in a stationary regime on a horizontal pipe and suggested a theoretical framework based on the theory of hydrodynamic lubrication. According to this model, we observed a harmonic motion in annular flow, i.e., the more viscous fluid (oil) moved on a corrugated form in the center of the horizontal pipe; such behavior is known as Wavy Core- Annular Flow (WCAF).

Miesen et al. [18] used a 0.2% solution of sodium silicate to avoid buildup of oil in the inner wall of the pipe. Bannwart [9] investigated the behavior of horizontal annular flow modifying the inner surface of the pipe and proposed two correlations: the first is used to calculate the pressure gradient using the core-flow technique in a horizontal pipe with an inner oleophobic surface and the second is used to calculate the pressure gradient using the core-flow technique in a horizontal pipe with an inner oleophilic surface.

Brauner [9] proposed an analytical model to predict the holdup and pressure drop *in situ* for a two-phase flow in a horizontal pipe and obtained the power saving factor as a function of the viscosity ratio. The author observed that in the case of laminar flow of two fluids, the energy saving factor is independent for the properties of fluids and turbulent flow, this factor increases with the decrease of density difference between the phases.

Ooms et al. [21] investigated theoretically the hydrodynamic counterbalancing of a drag force of the oil core flowing in the pipe, taking into account the difference in density between the two fluids. During the study it was assumed that the fluid which forms the core consists of a solid surrounded by a layer of a low viscosity fluid. The theory of hydrodynamic lubrication used takes into consideration the flow of an annular layer of a liquid of low viscosity and in the center a liquid layer of high viscosity, thus, the development of interfacial waves between the fluids was calculated. The authors imposed the wavy shape of the interface, but have not found the form of the waves.

Andrade et al. [1] presented a study of the core-flow technique by numerical simulation using the ANSYS CFX® 10.0 software. The viscosity of the oil used was 12 Pa.s, flowing in a pipe of 15 m length and 20 cm diameter. The flow was considered two-dimensional and transient. The mathematical approach used was the inhomogeneous Eulerian-Eulerian, admitting laminar flow for the oil phase and turbulent flow for the water phase (k-ε model). The authors noted that a continuous water pellicle was formed in the pipe wall, and the oil core kept flowing in the center of the pipe, thus characterizing the annular flow or core-flow. Further, the authors noted that the reduction in pressure drop was approximately 59 times when compared with that obtained when the heavy oil flows alone in the pipe, for velocities of 0.4 m/s and 0.8 m/s for oil and water, respectively. One reduction in pressure drop of approximately 98% during the flow was found.

Faced with these challenges, mainly, due to the shortage of numerical work in three dimensions available in the literature, this paper aims to make a contribution in this area of transportation of heavy and highly viscous oils using the computational fluid dynamics technique. Then, study aims to evaluate the flow pattern of the core annular flow in curved connections and consequently the pressure drop due to friction.

2. METHODOLOGY

2.1. PHYSICAL PROBLEM DESCRIPTION

The physical problem evaluated in this work consists in a two-phase flow (water and heavy oil) in a curved pipe of 6 meters length and 0.15 m diameter. Figures 1 and 2 illustrate the representation of the curved pipe as well as details of geometry and mesh respectively, used to study two-phase flow of water and highly viscous oil.

In present day, the Computational Fluid Dynamics (CFD) has been increasingly used in diverse industry segments (automotive, aerospace, chemical processing, power generation, metallurgy, oil companies, etc.) for various purposes. Herein, mesh with 946484 control volume was created in module ANSYS ICEM CFD® Release 12.0. This domain of study was created by defining points, curves, surfaces and solids describing its size and shape. In this mesh we can observe the main details near the wall of the curved pipe and in the regions of interface, where the velocity gradients are most relevant. A further refinement of this region was done and compared to the central region of the mesh in the search to get results closer to reality where they have a well-defined interface.

It is through the interface that exists heat exchange, dissolution, drag, etc, i.e., the interface is the region of space where the different phases exchange information, and also where occurs transfer of heat, mass, and momentum.

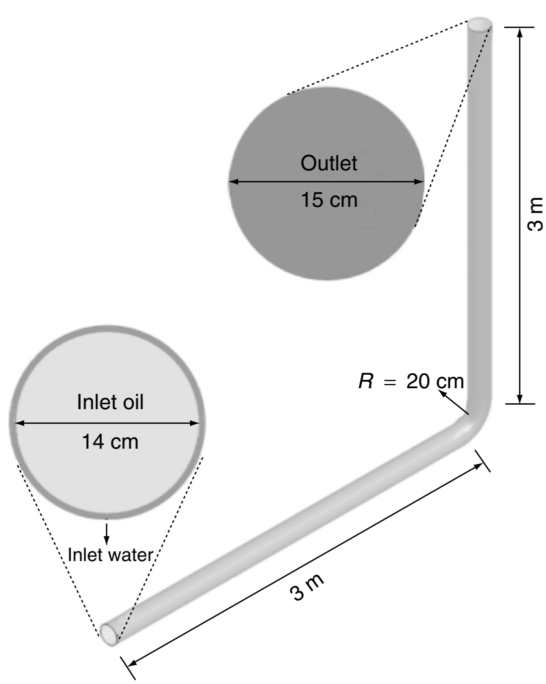

Figure 1 Domain of study with details the inlet and outlet of fluids in curved pipe.

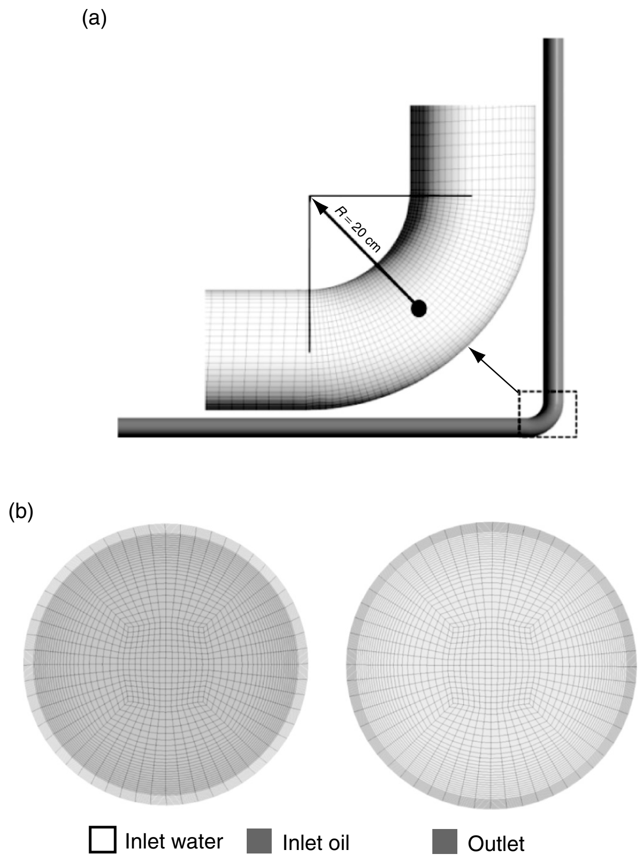

Figure 2 (a) The computational grid and (b) Details of the Inlet and outlet of fluids.

2.2. MULTIPHASE MATHEMATICAL MODELING

The modeling procedure consists in the mathematical description of the physical problem to be analyzed. In the case of fluid flow, the mathematical model consists of conservation equations (mass, energy and momentum), initial and boundary conditions, and constitutive equations establishing the relationship between the stress and velocity in flow, among others. From the viewpoint of engineering, these models correspond to a set of data and abstract ideas that allow the engineer, or researcher, to propose an explanation for the phenomenon that is being studied.

To model the multiphase flow, the following equations can be used [2]:

2.2.1. Mass conservation equation

This equation is given as follows:

$$\frac{\partial}{\partial t}(f_\alpha \rho_\alpha) + \nabla \bullet (f_\alpha \rho_\alpha \vec{U}_\alpha) = S_{MS\alpha} + \sum_{\beta=1}^{N_p} \Gamma_{\alpha\beta} \tag{1}$$

When the terms of mass source S_{MSa} and the term of mass diffusivity $\Gamma_{\alpha\beta}$ are neglected, we can write the Equation 1 as:

$$\frac{\partial}{\partial t}(f_\alpha \rho_\alpha) + \nabla \bullet (f_\alpha \rho_\alpha \vec{U}_\alpha) = 0 \tag{2}$$

2.2.2. Momentum equation

This equation is given as follows:

$$\frac{\partial}{\partial t}(f_\alpha \rho_\alpha \vec{U}_\alpha) + \nabla \bullet \left[f_\alpha (\rho_\alpha \vec{U}_\alpha \otimes \vec{U}_\alpha) \right] = -f_\alpha \nabla p_\alpha + \nabla \bullet \left\{ f_\alpha \mu_\alpha \left[\nabla \vec{U}_\alpha + (\nabla \vec{U}_\alpha)^T \right] \right\} + \sum_{\beta=1}^{N_P} (\Gamma^+_{\alpha\beta} \vec{U}_\beta - \Gamma^+_{\beta\alpha} \vec{U}_\alpha) + \vec{S}_{M\alpha} + \vec{M}_\alpha \tag{3}$$

In the Equations (1), (2) and (3), the sub-index α is the phase indicator on the two-phase water-heavy oil flow; f, ρ, μ and $\vec{U}$ are the volume fraction, density, dynamic viscosity and velocity vector, respectively; p is pressure and $\vec{S}_{M\alpha}$ represents the term of external forces which act on the system per unit volume. In the term regarding momentum transfer induced by interfacial mass transfer (third term on the right side of equality) the sub-indexes α and β correspond the phases involved, water and heavy oil. $\Gamma^+_{\alpha\beta}$ corresponds to the mass flow rate per unit volume of phase α to phase β and vice-versa; $\vec{M}_\alpha$ describes the total force per unit volume (interfacial drag force, lift force, wall lubrication force, virtual mass force and turbulent dispersion force) on the α phase due to interaction with β phase.

The interfacial mass transfer term was not taken into account because the interfacial mass transfer in the momentum equation is used for disperse solid phase representing an additional force due to collisions between particles [2]. Thus, Equation(3) reduces to:

$$\frac{\partial}{\partial t}(f_\alpha \rho_\alpha \vec{U}_\alpha) + \nabla \bullet \left[f_\alpha (\rho_\alpha \vec{U}_\alpha \otimes \vec{U}_\alpha) \right] = -f_\alpha \nabla p_\alpha + \nabla \bullet \left\{ f_\alpha \mu_\alpha \left[\nabla \vec{U}_\alpha + (\nabla \vec{U}_\alpha)^T \right] \right\} + M_\alpha \tag{4}$$

2.2.3. Energy equation

The energy conservation equation is given by:

$$\frac{\partial}{\partial t}\left(f_\alpha \rho h\alpha\right) + \nabla \bullet \left[f_\alpha (\rho_\alpha \vec{U}_\alpha h_\alpha - \lambda_\alpha T_\alpha) \right] = \sum_{\beta=1}^{N_P} \left(\Gamma^+_{\alpha\beta} h_{\beta S} - \Gamma^+_{\beta\alpha} h_{\alpha S} \right) + Q_\alpha + S_\alpha \tag{5}$$

were h_α, λ_α, and T_α, denote the static enthalpy, thermal conductivity and temperature of phase α, respectively; S_α describes external heat sources, Q_α denotes interphase heat transfer to phase at α the interfaces with other phases. The term $(\Gamma^+_{\alpha\beta} h_{\beta S} - \Gamma^+_{\beta\alpha} h_{\alpha S})$ represents heat transfer induced by interphase mass transfer.

2.2.4. Turbulence model

The turbulence model used for the water phase was the k-ε model. In this model, it is assumed that Reynolds tensors are proportional to the average velocity gradients, with the constant of proportionality being characterized by turbulent viscosity (idealization known as Boussinesq hypothesis). The characteristic of this type of model is that two transport equations modeled, separately, are solved for the turbulent length and time scale or for which either two combinations are linearly independent. The transport equations for the turbulent kinetic energy, k, and turbulent dissipation rate, ε, are respectively:

$$\frac{\partial(\rho_\alpha f_\alpha k_\alpha)}{\partial t} + \nabla \bullet \left\{ f_\alpha \left[\rho_\alpha \vec{U}_\alpha k_\alpha - \left(\mu + \frac{\mu_{t\alpha}}{\sigma_k} \right) \nabla k_\alpha \right] \right\} = f_\alpha \left(G_\alpha - \rho_\alpha \varepsilon_\alpha \right) \tag{6}$$

$$\frac{\partial(\rho_\alpha f_\alpha \varepsilon_\alpha)}{\partial t} + \nabla \bullet \left\{ f_\alpha \rho_\alpha \vec{U}_\alpha \varepsilon_\alpha - \left(\mu + \frac{\mu_{t\alpha}}{\sigma_\varepsilon} \right) \nabla \varepsilon_\alpha \right\} = f_\alpha \frac{\varepsilon_\alpha}{k_\alpha} \left(C_1 G_\alpha - C_2 \rho_\alpha \varepsilon_\alpha \right) \tag{7}$$

where G_α is the production of turbulent kinetic energy within the phase α; C_1 and C_2 are empirical constants. Although on these equations, the dissipation rate of turbulent kinetic energy and turbulent kinetic energy for phase α, are defined by:

$$\varepsilon_\alpha = \frac{c_\mu q_\alpha^3}{l_\alpha} \tag{8}$$

$$k_\alpha = \frac{q_\alpha^2}{2} \tag{9}$$

where l_α is the length of spatial scale, q_α is the velocity range and c_μ is an empirical constant, given by:

$$c_\mu = 4c_\alpha^2 \tag{10}$$

where c_α is also an empirical constant. The turbulent viscosity $\mu_{t\alpha}$ is given as follows:

$$\mu_{t\alpha} = c_\mu \rho_\alpha \frac{k_\alpha^2}{\varepsilon_\alpha} \tag{11}$$

The constants used on previous equations are: $C_1 = 1.44$; $C_2 = 1.92$; $C_\mu = 0.09$; $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.3$.

2.2.5. Mixture model (constitutive equations)

For this work we adopted the Eulerian model of mixing, for the analysis of water-heavy oiltwo-phase flow in pipes with curved connections. This model can present more complex formulations, however, is suitable for the modeling of liquid-liquid two-phase flow, where is calculated all forces acting on the interface between the fluid phases. In this model was considered only the total drag force exerted by the phase β under the phase α per unit volume, given by:

$$\vec{M}_\alpha = C_D \rho_{\alpha\beta} A_{\alpha\beta} \left| \vec{U}_\beta - \vec{U}_\alpha \right| \left(\vec{U}_\beta - \vec{U}_\alpha \right) \tag{12}$$

where C_D is the drag coefficient in which was assumed a value equal to 0.44. The density and viscosity of the mixture are given respectively by:

$$\rho_{\alpha\beta} = f_\alpha \rho_\alpha + f_\beta \rho_\beta \tag{13}$$

$$\mu_{\alpha\beta} = f_\alpha \mu_\alpha + f_\beta \mu_\beta \tag{14}$$

The mixture model treats both phases α and β symmetrically. The surface area per unit volume is given by:

$$A_{\alpha\beta} = \frac{f_\alpha f_\beta}{d_{\alpha\beta}} \tag{15}$$

where $d_{\alpha\beta}$= 1 mm is an interfacial length scale which must be specified.

The dimensionless transfer coefficient between the phases (Reynolds number of the mixture) is given by:

$$\mathrm{Re}_{\alpha\beta} = \frac{\rho_{\alpha\beta}\left|\vec{U}_\beta - \vec{U}_\alpha\right| d_{\alpha\beta}}{\mu_{\alpha\beta}} \tag{16}$$

2.3. BOUNDARY CONDITIONS

In the inlet section for oil was used a prescribed value for the velocity component U_o = 1.0 m/s and oil volume fraction f_0 = 1.0:

a) $u = v = 0$ and $w = U_o$ in $z = 0$ to $\forall$ (x, y);

b) T_o = 303.15 K to 380.15 K

c) Laminar flow.

In the annular section for the inlet of water we use a prescribed value for the velocity component U_w = 1.8 m/s and water volume fraction f_w = 1.0. Further,

a) $u = v = 0$ and $w = U_w$ in z = 0 to$\forall$ (x, y);

b) T_w = 273.15 K;

c) Turbulent flow.

In the wall of the pipe was used not slip condition and a roughness 45 µm. Further,

a) $u = v = w = 0$ at the wall pipe;

b) T_{wall} = 288.15 K.

Table 1 reports the thermal physical properties of the fluids used in all simulation.

Table1 The thermal-physical properties of the water and oil used.

Physicals properties	**Water**	**Heavy oil**
Density (kg/m^3)	997	989
Dynamic viscosity (Pa.s)	8.89×10^{-4}	10.0
Temperature (K)	273.15	303.15 to 380.15
Heat capacity (J/kg K)	4181.7	1800
Thermal conductivity (W/ m K)	0.58	0.147
Surface tension (N/m)	0.072	

3. RESULTS AND DISCUSSIONS

Aiming to validate the multiphase model and mesh, a simulation was made with two identical fluids (heavy oil-heavy oil), which similar to single phase flow of heavy oil.

Figure 3 shows the comparison between the numerical and analytical results of heavy oil velocity as a function of the radial position in z = 2 m. We can see a good agreement between the results. A good trend matching between analytical and simulation signifies that the simulation is capable of capturing the physics of phenomena. According to literature the velocity profile has a parabolic behavior for a fully developed laminar flow and a hydrodynamic entry length given by L = 0.06 ReD [12]. For the case studied here L = 0.0374 m. Therefore, the data presented in Figure 3 were taken at Z = 2 m, on the horizontal region of the curved pipe. Moreover, the maximum velocity is twice the average velocity which for this study, the most recent was 0.52 m/s, in accordance to literature.

Further it is yet compared the pressure drop along the horizontal pipe. Table 2 shows this comparison; we can see that a good agreement was obtained.

Figure 4 illustrates the pressure field by friction along the curved pipe.We can verify that there is a higher pressure in the initial region of the pipe which decreases along the pipe, thus

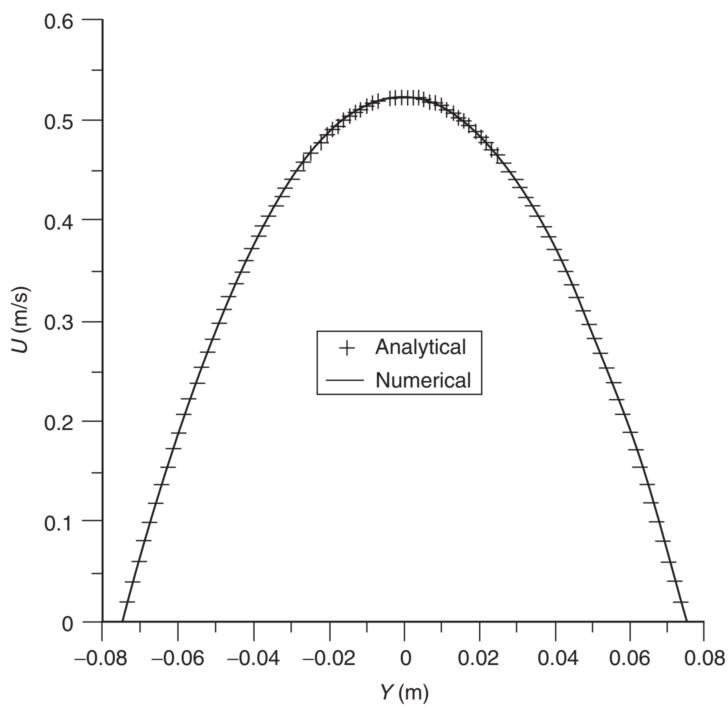

Figure 3 Comparison between numerical and analytical results of the axial velocity component at z = 2 m.

Table 2 Pressure drop from pipe inlet to position z = 2.0 m.

	Analytical	Numerical
ΔP (Pa)	7432.53	7480.00

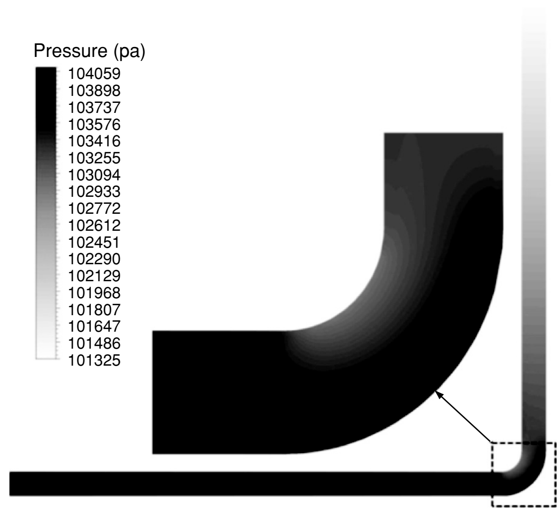

Figure 4 Pressure field in the pipe T_o = 298.15 K.

favoring the flow. Further, is noted that in the lower region of the curvature the pressure is greater than in the upper region of the curvature.This is due to the fact that fluids, both water and oil, by inertia, tend to continue in the same or horizontal direction causing the pressure to increase in this region.

Figures 5 to 7 show the heavy oil volumetric fraction distribution along the pipe at different moments.

We can see the presence of a water pellicle near the pipe wall, where in this region the oil volumetric fraction is zero. This occurs throughout the pipe, including the curved region, where the flow is more complex. Thus, the core annular flow pattern can be kept in curved connections, depending on flow conditions.

At a time of 2.7 seconds, the heavy oil begins to approach the bend of the pipe with a curvature radius of 20 cm. After 3.18 seconds, the heavy oil has already passed the entire

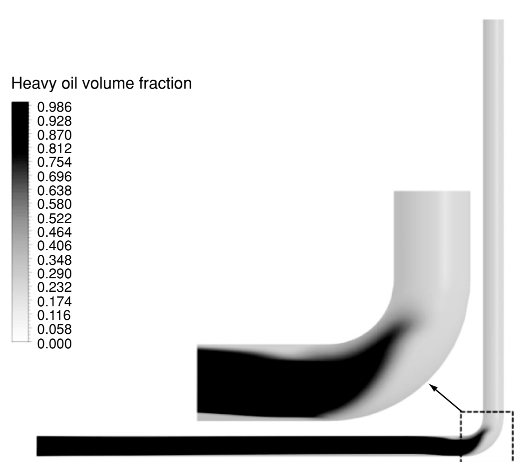

Figure 5 Heavy oil volume fraction in the pipe at t = 2.7s (T_o = 298.15 K).

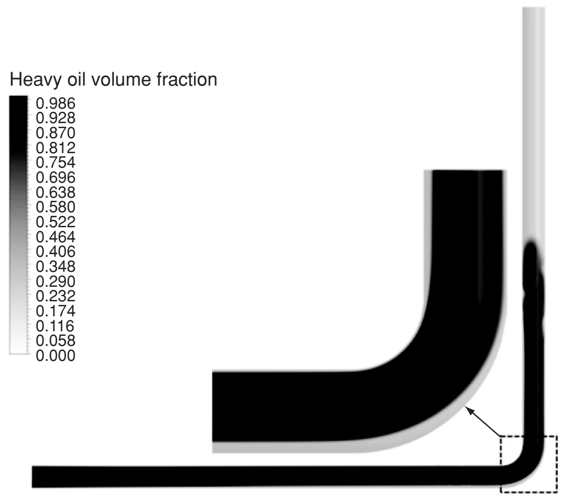

Figure 6 Heavy oil volume fraction at $t = 4$s ($T_o = 298.15$ K).

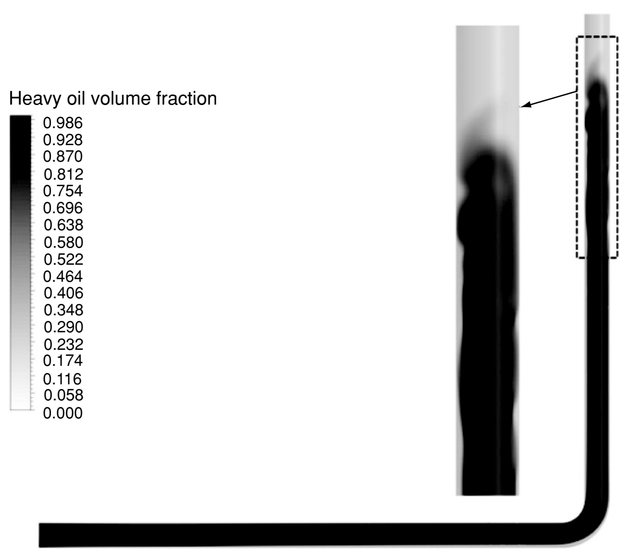

Figure 7 Heavy oil volume fraction at $t = 5$s ($T_0 = 298.15$ K).

perimeter of curvature practically not touching of the wall of the curved connection retaining the annular pattern. This phenomenon can be seen in Figure 6.

At the time of approximately 5 seconds (see Figure 7) the flow of heavy oil already starts to increase at the outlet of the curved pipe. At this moment is notable the presence of undulations in the interface region of heavy oil-water, this event approaches well to experimental results available in the literature [6, 7, 18, 14, 24].

According to these authors, the core-flow technique used in vertical pipes is more favored because the center of gravity is the same for the two fluids. However, in horizontal pipes the phenomenon becomes a little more complicated due to the density difference between the fluids. In this case, the fluids of lower density tend to touch the upper wall of the pipe.

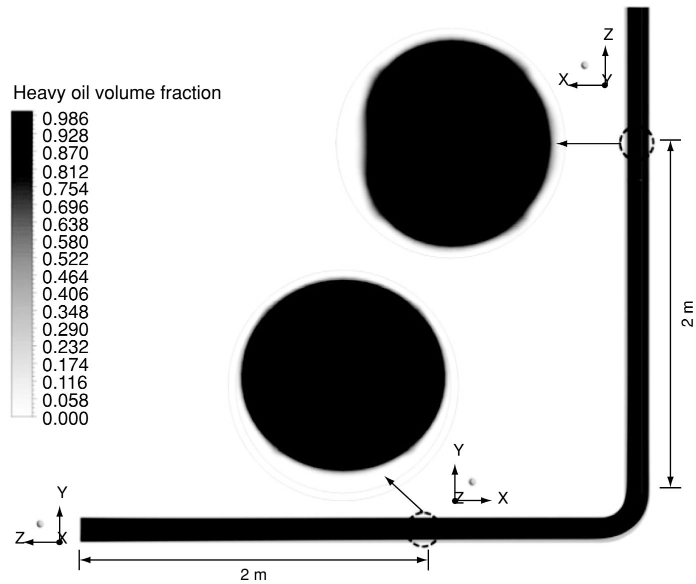

Figure 8 Heavy oil volume fraction in the horizontal and vertical extension of the pipe at $t = 13$s ($T_o = 298.15$ K).

This phenomenon can be seen in Figure 8 where the heavy oil core is not centered (z-axis) on horizontal line of the curved pipe. However, for the flow in vertical ascending direction, the eccentricity of the oil core is relatively much smaller compared with the flow in the horizontal region of the pipe.

Bensakhria et al. [8] evaluated the radial position of oil core in the annular flow and showed that this position depends solely on the ratio of the perimeter of contact between the pipe wall, the fluid which forms the core (heavy oil) and the circumference of the pipe. This ratio depends on the density difference between the fluids to be transported and the lubrication, as well as the amount of water injected into the pipe. Some authors state that ideal amount of water for water-heavy oil annular flow should be around 20% of the total mass flow rate, however, in this study, this amount is around 21%, i.e., 4.0779 kg/s of water.

Figure 9 illustrates the volume fraction of heavy oil along the entire perimeter of curvature in the total simulation time (t = 13 s).We can note that the heavy oil does not touch the walls in this region. Thus, the transportation of heavy oils using the core flow technique can be performed in pipes with curved connections as long as the radius of curvature is not too small.

The superficial velocity field of heavy oil is shown in Figure 10, where it can be seen that the axial variation of superficial velocity of heavy oil is very small. In the enlarged detail of the curvature region of Figure 10, there is a variation of the superficial velocity which is more pronounced at the top of the curvature. This suggests that there is a hydrodynamic lubrication force exerted by the annular fluid (water), tending to push the oil core to the central axis of the curvature, however, the oil phase does not touch this region, where the superficial velocity of heavy oil is practically null. During projects with curved connection pipes, the radius of curvature of these should be thoroughly analyzed, for the purpose of avoiding recirculation zones in the regions of curvature. These recirculation zones may cause an increase in pressure drop during the transport of heavy oils; therefore, the flow pattern would undergo a core-flow perturbation in a way that the pattern is transformed in another, for example, a totally eccentric stratified pattern with a concave interface.

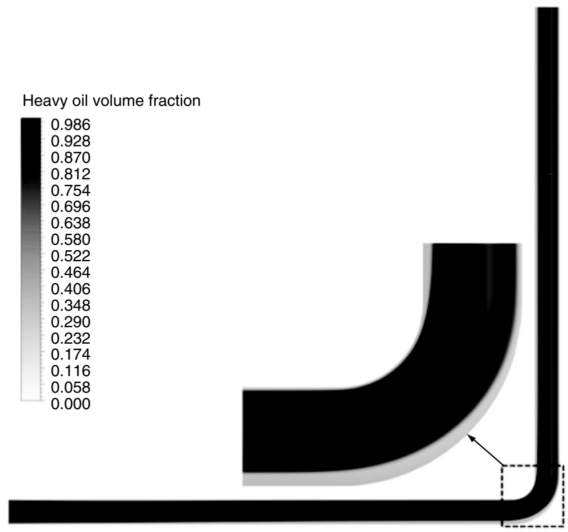

Figure 9 Heavy oil volume fraction at $t = 13$ s ($T_o = 298.15$ K).

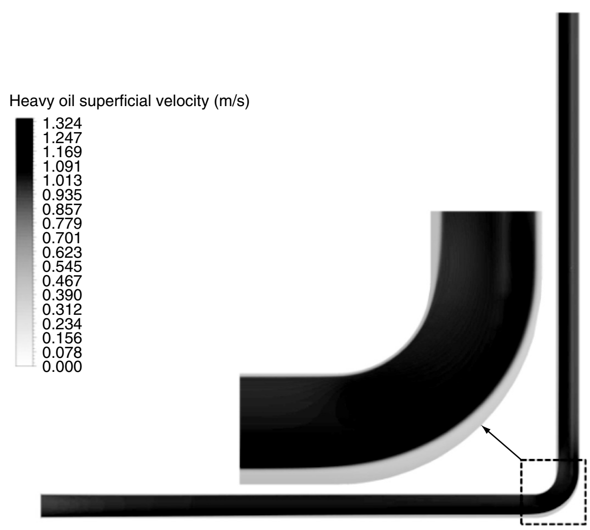

Figure 10 Heavy oil superficial velocity at $t = 13$ s ($T_o = 298.15$ K).

In order to evaluate the efficiency of core-flow technique in terms of pressure drop, it is necessary to make a comparison with the single phase flow for both heavy oil and water, separately. Thus, it is possible to quantify the reduction of pressure drop when using the core annular flow technique. Then, the single phase flow simulations were performed under the same conditions of mass flow rate of water-heavy oil two-phase flow, in the same pipe, using the same fabric and the same simulation time (13 seconds).

Figure 11 illustrates a comparison of the pressure drop by friction of a single phase flow of water and heavy oil, and the pressure drop by friction using the core flow technique.

By observing this figure, it can be seen that the technique used to transport heavy oil significantly reduced the frictional pressure drop when compared to single phase flow of oil,

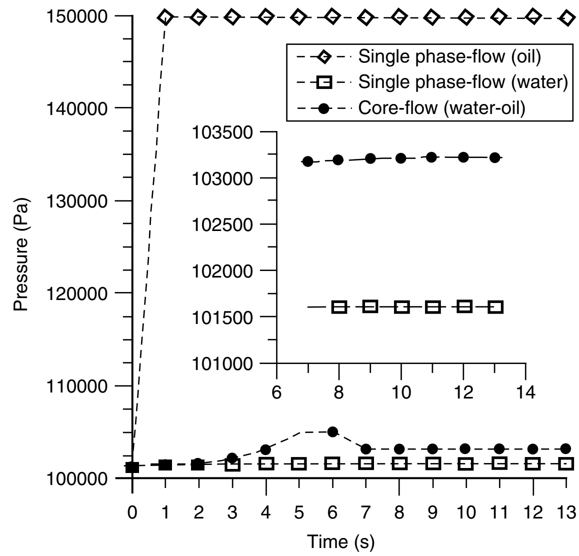

Figure 11 Average pressure at longitudinal plane of the pipe as a function of the time (T_o = 298.15 K).

presenting a reduction of 96%, changing from 48449 Pa to 1908 Pa. Compared with the single-phase flow of water one can say that the pressure drop using the core flow technique approaches the pressure drop of the single-phase flow of water.

Figure 12 shows the variation of the heavy oil viscosity as a function of the temperature. Is verified that there is a significant decrease in the viscosity of the heavy oil as the temperature increases, this fact occurs with most fluids.

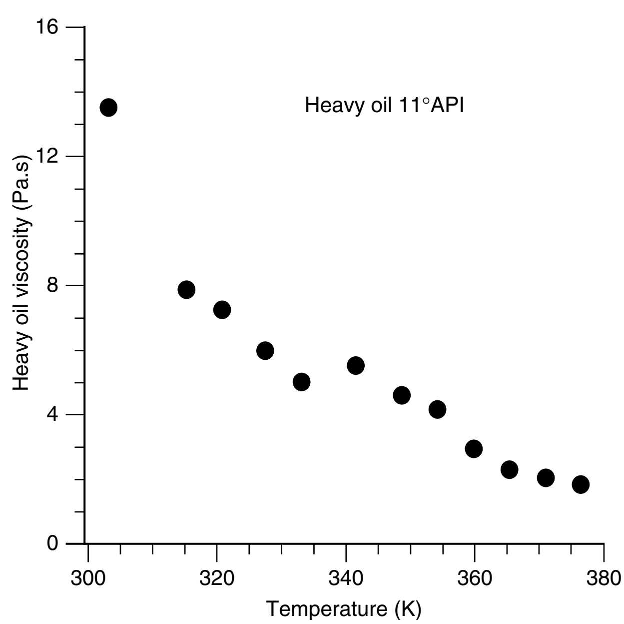

Figure 12 Oil viscosity as a function of the temperature.

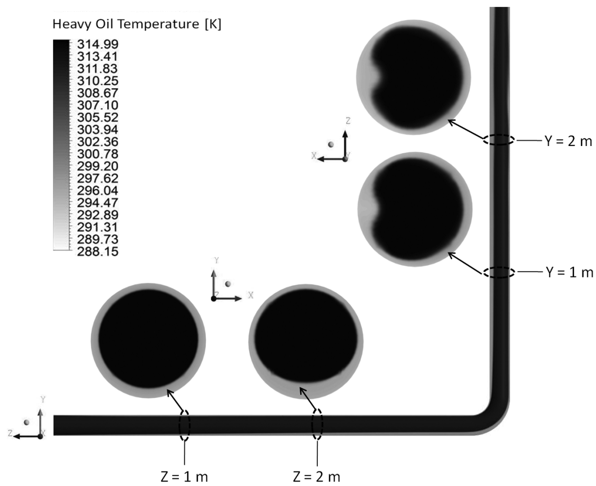

Figure 13 Heavy oil temperature field throughout of the pipe (T_o = 315 K).

Figure 13 shows the field of heavy oil temperature. From the analysis of this figure, it is possible to see that the temperature increases from the periphery to the center axis of the curved pipe. In this figure there is a temperature gradient between the wall of the pipe and the interfacial area between the fluids, remembering that was used as a boundary condition a temperature of 288 K on the wall of the curved pipe.

4. CONCLUSIONS

This study aims to analyze the horizontal and upward flow of heavy oil and water through the curved tube using the core annular flow technique. For this, a 3D model was developed using ANSYS CFX® Release 12.0. From the study the following conclusions can be made:

1. The mathematical model employed using the software ANSYS CFX® Release 12.0 represented well the physics of annular flow (type core-flow) for the transport of heavy oils. It was found that the utilization of this technique provides significant reduction in pressure drop, which is very useful for the oil industry, since oil reserves of the type Brent are becoming smaller.
2. It was possible to observe that in horizontal annular flow due to density difference between the fluids, the oil core tends to occupy a position eccentric to the axis of the tube.
3. The water injection of 4.0779 kg/s around 21% of the overall mass flow rate was sufficient to maintain the annular flow thus reducing pressure drop by friction.
4. The use of core-flow technique may be executed in curved connections, provided that the radius of curvature is sufficient to keep the annular flow pattern. However, these connections should preferably have smooth curves, ensuring a flow with lower pressure drop.
5. The energy saving during the use of core-flow technique may be used as a replacement to the conventional techniques of petroleum transportation.

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