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Multiphase Flow and Heat Transfer in Risers

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Abstract. Multiphase flows commonly occur in the production and transportation of oil, natural gas and water. In this type of flow, the phases can flow in different spatial configurations disposed inside the pipe, so called multiphase flow patterns. The identification of flow patterns and the determination of the pressure drop along the pipe lines for different volumetric flows are important parameters for management and control of production. In this sense, this work proposes to numerically investigate the non-isothermal multiphase flow of a stream of ultraviscous heavy oils containing water and natural gas in submerged risers (catenary) via numerical simulation (ANSYS CFX 11.0). Results of the pressure, volumetric fractions and temperature distributions are presented and analyzed. Numerical results show that the heat transfer was more pronounced when using the largest volume fraction of gas phases.

Introduction

Considered of great importance in the oil industry, heavy oils constitute an important reserve to be exploited and produced. The heavy oil reserves in the world are estimated at three trillion barrels representing 15% of all world reserves. Given the enormous potential and reduction of conventional oil, commercial exploitation of accumulations of heavy oils in deep water represents a major technological and economic challenge for the oil companies, due to the high American Petroleum Institute gravity index, ºAPI, (range 10° - 20°) and high viscosity (range 10^2 cP – 10^4 cP). All of these factors have an important effect on production and transportation, mainly of ultraviscous heavy oils in offshores. Multiphase flows are commonly encountered in the production and transportation of oil, natural gas and water. In this type of flow, the phases present can be arranged in different spatial configurations within the duct, called multiphase flow patterns [1]. The identification of flow patterns is essential for issues that are closely related to the economic return from the field as well as to determination of the pressure drop along the flow lines, measurement of volumetric flow rate transported, management and supervision of production [2]. These aspects are critical in conditions of offshore production, where large distances and high costs are involved. The study of the three-phase flow of heavy oil and water containing free gas presents as useful due to the high complexity and large number of flow patterns that can occur [3, 4].

In this sense, this study proposes to numerically investigate the non-isothermal multiphase flow of a stream of ultraviscous heavy oils containing water and natural gas in submerged risers (catenary type).

Geometry and Mesh

Figure 1 illustrates the three-dimensional structured mesh (800, 240 tetrahedral elements) generated in ICEM CFD, representing the physical domain of study. In this figure we can see refinement regions due to recirculation zones and the greater heat transfer in the vicinity of the walls.

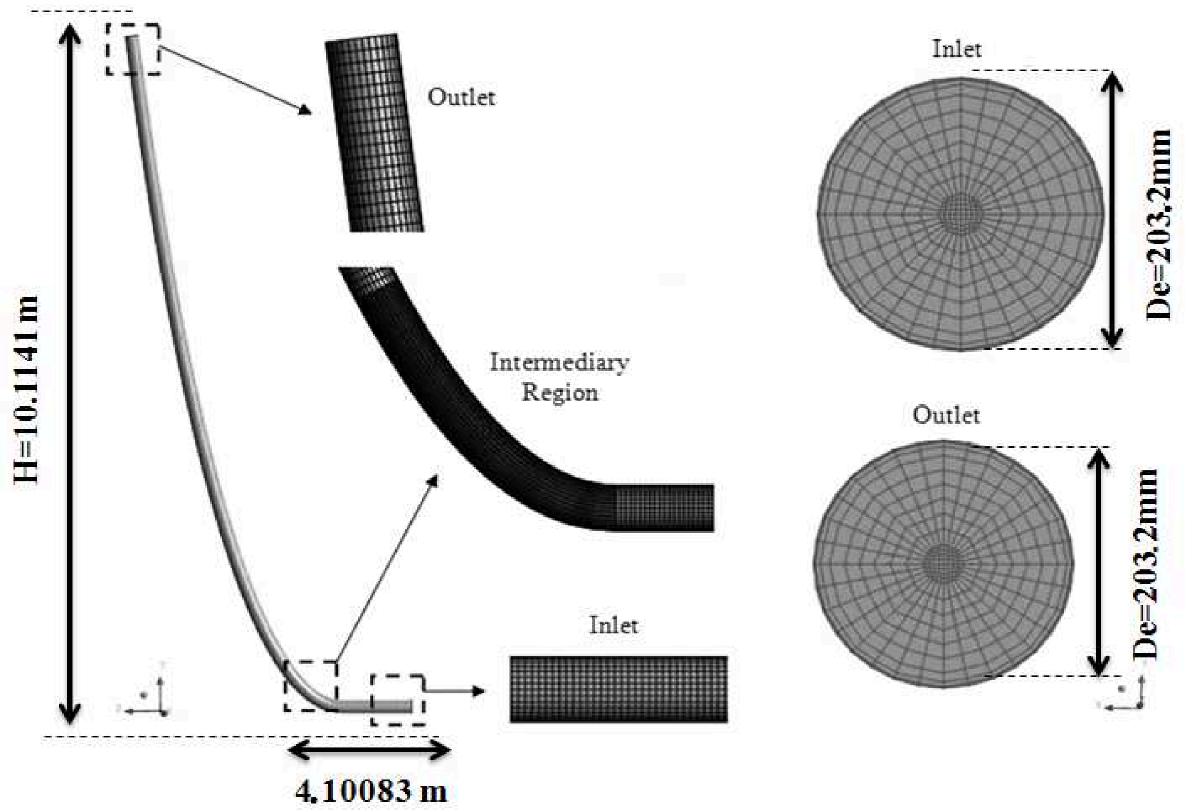


Figure 1. Geometrical parameters of the riser.

Mathematical Modeling

The following equations of the thermo-hydrodynamic of the multiphase flow were used.

Mass conservation equation:

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

Momentum conservation equation:

$$\frac{\partial}{\partial t}\left(f_\alpha \rho_\alpha \vec{U}_\alpha\right) + \nabla \bullet \left[f_\alpha\left(\rho_\alpha \vec{U}_\alpha \otimes \vec{U}_\alpha\right)\right] = -f_\alpha \nabla p_\alpha + \nabla \bullet \left\{f_\alpha \mu_\alpha \left[\nabla \vec{U}_\alpha + \left(\nabla \vec{U}_\alpha\right)^T\right]\right\} + \\ + \sum_{\beta=1}^{N_P}\left(\Gamma^+_{\alpha\beta}\vec{U}_\beta - \Gamma^+_{\beta\alpha}\vec{U}_\alpha\right) + \overrightarrow{S_{M\alpha}} + \overrightarrow{M_\alpha} \quad (2)$$

where α an β denote the involved phases (water, oil and natural gas), t is the time, f is the volumetric fraction, ρ is the density, $\vec{U}$ is the velocity vector, N_P is the number of phases, p is the pressure and μ is the dynamic viscosity.

Energy conservation equation:

$$\frac{\partial}{\partial}(r_\alpha \rho h_\alpha) + \nabla \bullet \left[r_\alpha\left(\rho_\alpha \vec{U}_\alpha h_\alpha - \lambda_\alpha \nabla T_\alpha\right)\right] = \sum_{\beta=1}^{Np}\left(\Gamma^+_{\alpha\beta} h_\beta - \Gamma^+_{\beta\alpha} h_\alpha\right) + Q_\alpha + S_\alpha \quad (3)$$

where h_α denotes the static enthalpy, λ_α is the thermal conductivity, T_α is the temperature of phase α and S_α describes external heat sources, and Q_α is the interphase heat transfer to phase α across 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. Further, in this research we use the *k*-*ε* turbulence model.

Initial and Boundary Conditions. The properties of the fluids used in the simulation are presented in Table 1.

Table 1. Parameters of the fluids a boundary conditions.

Parameters	Water (Disperse)	Heavy oil (Continuous)	*Natural gas (Disperse)
ρ [kg/m^3]	997	989	766
bubble diameter [mm]	8	-	3
T [K]	333	333	333
k [W/m.K]	0.6069	0.147	0.809
μ [Pa.s]	$\mu_w = 0,00002414x10^{\left(\frac{247.8}{T-140}\right)}$	$\mu_o = 5,187.e\left[-2,3935.\left(\frac{T-273}{573-273}\right)\right]$	$\mu_g = 0,0744x10^{\left(\frac{T}{177-140}\right)}$
σ [N/m]	0.045 (water/heavy oil)		
	0.015 (natural gas/heavy oil)		
h [W/m^2.K]	30		
inlet velocity [m/s]	2		
Boundary Contours	Values		
	f_w	f_g	f_o
Case 1	0.4	0.1	$1-(f_w+f_g)$
Case 2	0.1	0.4	$1-(f_w+f_g)$

*Natural Gas (Natural Gas Composition: CH_4=0.90; C_2H_6=0.05; C_3H_8=0.025; C_4H_{10}=0.025)

Results and Discussion

Pressure Drop. Fig. 2 shows the pressure drop at the longitudinal center of the catenary as a function of *Z*, where it senses a total pressure drop for *z* between 1 and 4 m.

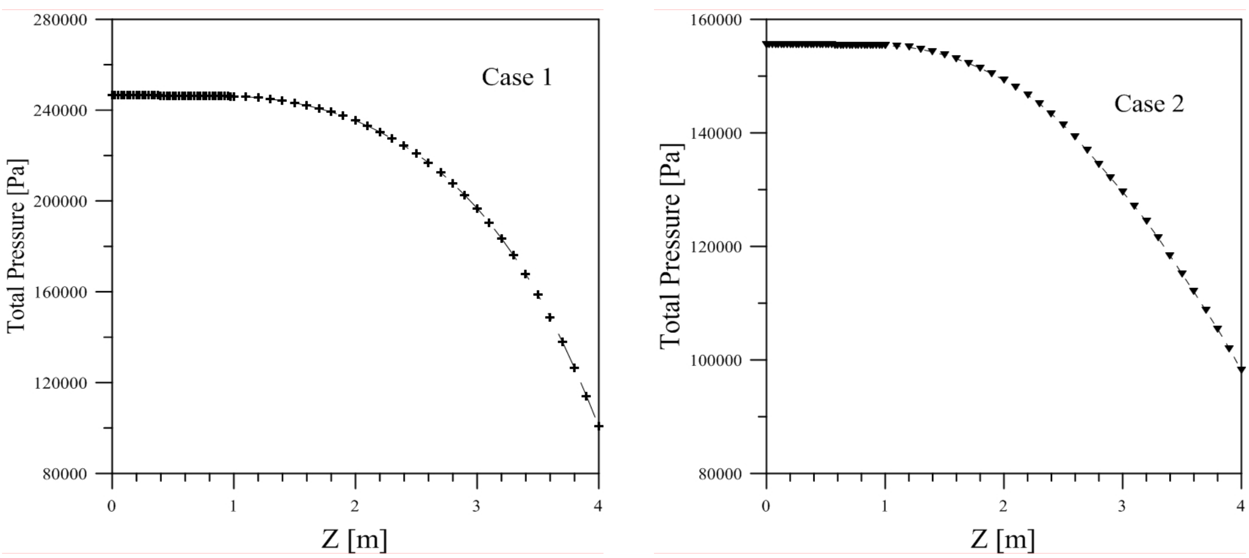


Figure 2. Pressure drop in the center riser.

It can be seen that the total pressure drop is more pronounced for the case where the gas fraction is smaller (Case 1). This is because the smaller amount of gas increases the density of the mixture and pressure losses through friction. Fig. 2 shows the maximum pressure inlet and minimum pressure outlet for two cases. For Case 1 was required a pressure differential = 149900 Pa, and in Case 2 was required a pressure differential = 58900 Pa to drain the three phases. This difference is the barrier needed to transport and lift the heavy oil and ultraviscous water and natural gas.

Analysis of the Volumetric Fraction Fields and temperature. Fig. 3 shows the volume fraction in a ZY-plane for the phases involved. The heavy oil is at the center of the pipe while the other phases more close to the walls.

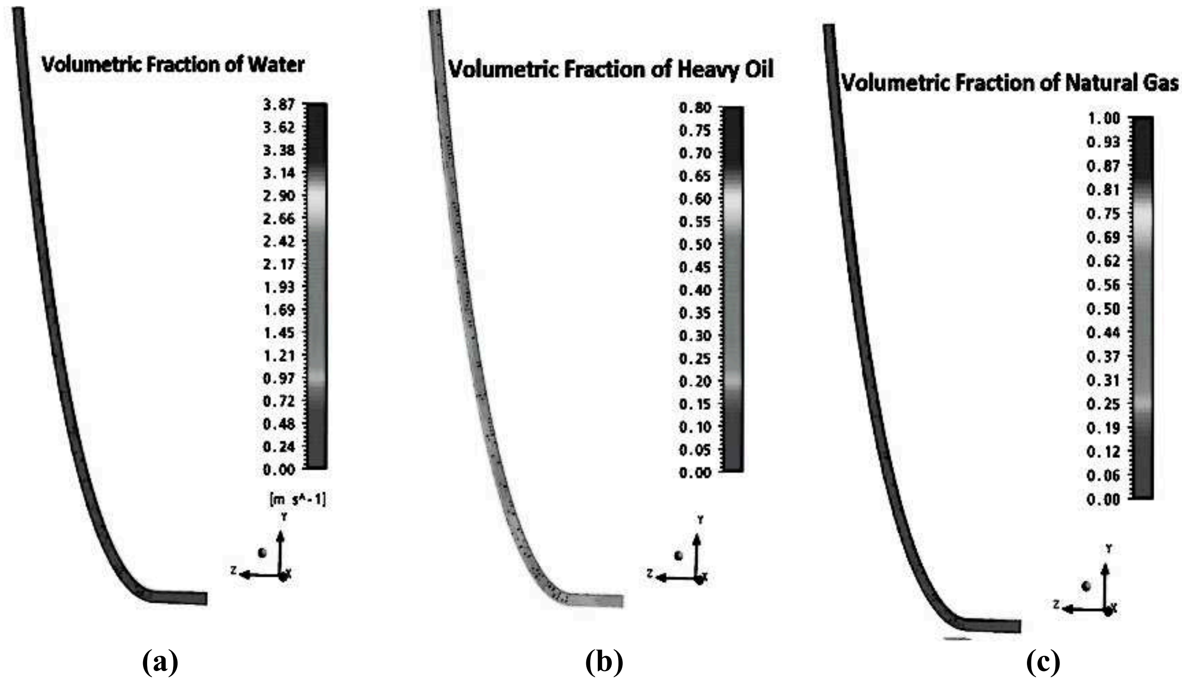
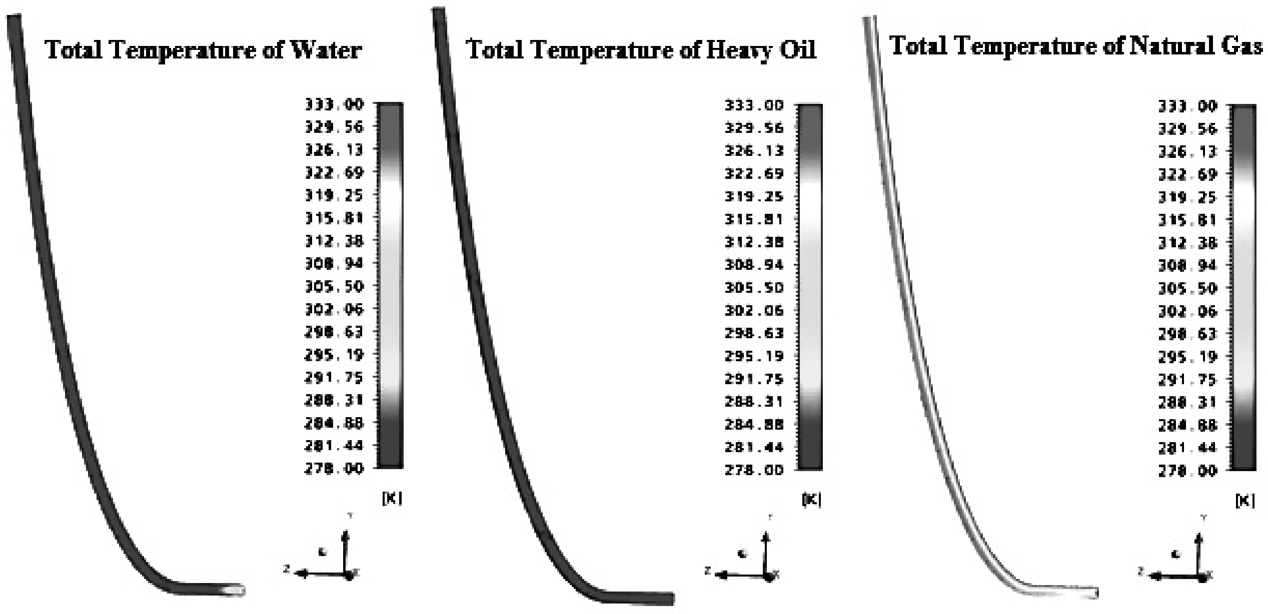


Figure 3. Volume fractions of the phases for the case 1, $f_g = 0.1$.

Fig. 4 (a) shows the rapid growth of the thermal boundary layer of water that occurs due to the low Prandtl number, Fig. 4 (b) there isn't an increase in the apparent thermal boundary layer due to the high Prandtl number of the oil. In Fig. 4 (c) there is an increase in the thermal boundary layer due to the low Prandtl number.

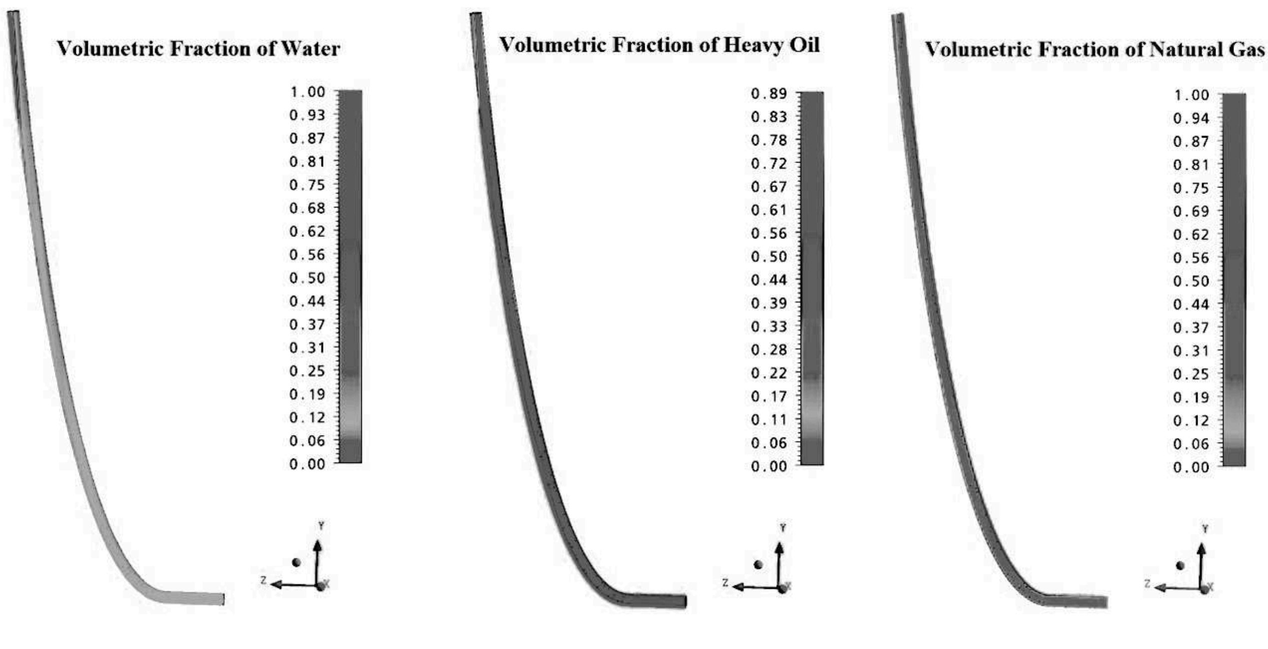
Analogously to Fig. 3, Fig. 5 shows the volume fraction in the *ZY* plan to phases involved, where heavy oil has a preferred way through the central pipe and other phases have a preferred way for the periphery of the pipe. However there is a greater mixing region due to turbulence caused by the gas.

Fig. 6 (a) shows the rapid growth of the thermal boundary layer of water that occurs due to the low Prandtl number, in Fig.6 (b) there is a thermal boundary layer growth visible due to increased turbulence caused by gas causing a rise of the oil temperature. In Fig. 6 (c) there is an increase in the thermal boundary layer due to the low Prandtl number.



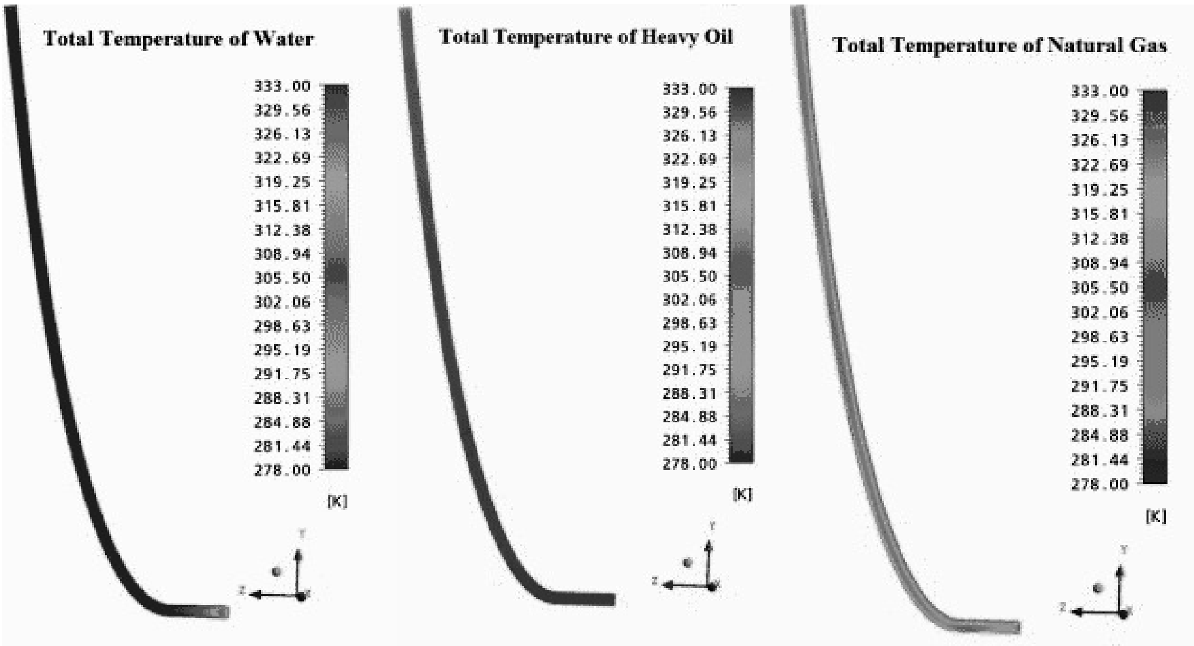
(a) (b) (c)

Figure 4. Temperature of the phases for the case 1, $f_g = 0.1$.



(a) (b) (c)

Figure 5. Volume fractions of the phases for the case 2, $f_g = 0.4$.



(a) **(b)** **(c)**

Figure 6. Temperature of the phases for the case 2, $f_g = 0.4$.

Conclusions

From the results presented and discussed, it can be concluded that the pressure loss in the flow using higher fraction of natural gas is lower than when using lower gas fraction, due to the lower density. The results of the simulation showed that the heavy oil has a preferred way through the center of the pipe and the other phases have a preferred way for the periphery of the pipe. Although we found that the heat transfer was more pronounced when using the higher volume fraction of gas.

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