23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

THREE-PHASE FLOW IN CIRCULAR CYLINDRICAL DUCT WITH LEAK: A NUMERICAL STUDY BY CFD

Wanessa Raphaella Gomes dos Santos
Federal University of Campina Grande, Department of Mechanical Engineering, Post-graduate in Process Engineering, Av. Aprígio Veloso, 882, Bodocongó – Campina Grande – PB, Brazil, CEP: 58429-900.
wanessa.raphaella@yahoo.com.br

Helton Gomes Alves
Federal University of Campina Grande, Department of Chemical Engineering, Post-graduate in Chemical Engineering
helton.02@hotmail.com

Boniek Evangelista Leite
Federal University of Campina Grande, Department of Mechanical Engineering, Post-graduate in Process Engineering
boniek3@gmail.com

Severino Rodrigues de Farias Neto
Federal University of Campina Grande
fariasn@deq.ufcg.edu.br

Antonio Gilson Barbosa de Lima
Federal University of Campina Grande
antonio.gilson@ufcg.edu.br

Abstract. *Pipeline is a conventional, efficient and economic way for oil transportation. However, operation in pipelines is subject to failure because the action of physicochemical nature agents that eventually deteriorate part of the duct (corrosion, disruptions). Leakage monitoring systems must be capable to detect and locate a leak in few minutes, reducing risks of environmental and socioeconomics impacts. The use of a good system for detecting and locating leaks in pipeline contribute significantly to operational safety and cost saving in petroleum industry.*
When a leak occurs, a pressure wave will propagate through the pipeline depending on the position and shape of the leak. For an efficient detection, we must determine and understand the hydrodynamics of flow inside the duct in each moment after the occurrence of a leak. In this sense, the aim of this research is to study the fluid dynamic of the three-phase flow in a vertical pipe with and without leakage by CFD (ANSYS CFX ®). Results of the pressure, velocity and volume fraction of the phases (oil, water and gas) are present and analyzed.

Keywords: *three-phase flow, leak, numerical simulation, Ansys CFX*

1. INTRODUCTION

The most economical and safe means of handling the oil industry fluids are pipelines, so these are the efficient means of transportation of production from producing regions, platforms, refineries, marine terminals, storage parks and consumer centers. The analysis of transport's costs indicates significant economic advantage, permitting reduction of costs on freight that influence the final price of the product, besides minimizing the truck traffic and increased urban's safety roads. On the other hand this type of transport has as a disadvantage the occurrence of leakage caused due to the sudden change in pressure, action of corrosion, wear or improper maintenance, where a small percentage of loss generates events with significant socio-economic and environmental impacts. The leak detection by the use of computational methods has had little success due to difficulties in determining experimentally the real characteristics of the fluid, which carries great generation of false alarms. To make safer decisions on the fluid transport process and greater reliability of hydrodynamic system projects is essential more broad solutions and consequently greater detail of the three-dimensional multiphase flow behavior.

From this theme some projects were developed for the purpose of describe the behavior fluid dynamics of flow in pipelines, for example, Szalinski *et al.* (2010), Santos *et al.* (2013), Sousa *et al.* (2013), Santos *et al.* (2014), Sarmento *et al.* (2014) and Tavares *et al.* (2014).

Szalinski *et al.* (2010) conducted a comparative experimental study between the two-phase flow (gas/oil and gas/water) in a vertical pipe with 6 meters length and 67 mm in diameter. To this, there was made a three-dimensional analysis where radial profiles of the gas volumetric fraction including bubble size distributions were transformed in data for a given sensor. This sensor is operated with an electronic system of conductivity measurement (to flow gas-water) and measuring the permittivity (to flow gas-oil). From these data obtained by the sensor, it has generated different patterns of two-phase flow.

Santos *et al.* (2013) studied the hydrodynamics of isothermal and multiphase flow in vertical duct (15 meters in length) with leak where it was examined the influence of different diameters (2 mm, 6 mm and 10 mm) of circular section leakage located in the middle of the pipe. The author identified the influence of the leak diameter in disturbance that it cause and difficulties of perception of minimum diameters leaks showing the importance of obtaining knowledge of the hydrodynamic flow.

Sousa *et al.* (2013) studied the isothermal flow of heavy oil and water in the vertical duct with a length of 3.5 meters in the presence of leakage through simulation software (CFX - 3D). In this study, the authors noted that the fluctuation in the total pressure drop is higher than the volume fraction of water in the mixture or flow velocity thereof.

Santos *et al.* (2014) evaluated the fluid dynamic of the three-phase flow (water, oil and gas) in a vertical pipe with and without leakage where the pipe had 8 meters in length, circular cross-section with 25 cm in diameter were numerically solved using ANSYS CFX software, in which the Eulerian-Eulerian model and the RNG κ-ε turbulence model were applied. The author concluded that in the leakage region, there is an increase in volume fraction of oil and water and a decrease in gas volume fraction probably due to its low viscosity and low density. The superficial velocity of the oil is about eight times greater than the water and twenty seven times greater than the natural gas due to its higher volumetric fraction used in the studied case.

Sarmento *et al.* (2014) studied the hydrodynamic behavior of the two-phase oil-water flow with leakage using CFD techniques where evaluated the influence of leak (square-shaped side 1 mm) in the flow behavior of a pipe 2 meters long, and clearly established the influence of the same pressure gradient.

Tavares *et al.* (2014) studied a three-phase flow (oil, water and gas) in a horizontal tube (10 meters long) which was analyzed the influence of a leak (leak diameter = 16 mm) in different positions (top, side and bottom) in the center of the pipe. The authors have concluded that the pressure drop behavior is influenced by the leak positioning.

Thus, this study aims to analyze the influence of inlet temperature in the non-isothermal, transient and three-phase flow (water-oil-gas) in a vertical duct with leakage.

2. METHODOLOGY

2.1 Mathematical Modeling

The mathematical model utilized in this research uses an Eulerian-Eulerian approach (because it is the most widely used method for solving multiphase flows) where each phase has its own flow field and there solutions for each phase separately, with interactions between them through terms of interfacial transfer. According to Andrade (2013), this technique is especially useful and computationally profitable when the interaction between the phases performs a significant part in determining the hydrodynamic system. For the continuous phase (oil) was used the κ-ε standard turbulence model, while for the dispersed phase (water and gas) was used the particle model.

Based on the considerations, Equations (1) to (7) below represent the physics of the problem and were resolved using software ANSYS CFX. The conservation equations of mass (Equation 1), moment (Equation 2) and energy (Equation 3) are:

$$\frac{\partial}{\partial t}(f_i\rho_i)+\nabla\cdot(f_i\rho_i\vec{U}_i)=0 \tag{1}$$

$$\frac{\partial(f_i\rho_i\vec{U}_i)}{\partial t}+\nabla\cdot[f_i(\rho_i\vec{U}_i\otimes\vec{U}_i)]-f_i\nabla p_i+\nabla\cdot\{f_i\mu_i[\nabla\vec{U}_i+(\nabla\vec{U}_i)^T]\}=\vec{S}_{Mi}+\vec{M}_i \tag{2}$$

$$\frac{\partial(f_i\rho_i h_{tot_i})}{\partial t}+\nabla\cdot[f_i(\rho_i\vec{U}_i h_{tot_i}-\lambda_i T_i)]=\sum_{\beta=1}^{N_p}(\Gamma^+{}_{i\beta}h_\beta-\Gamma^+{}_{\beta i}h_i)+Q_i+S_i \tag{3}$$

The drag force ($\vec{M}_i$) between two phases α and β can be determined by:

$$\vec{M}_i=\frac{1}{8}C_D\rho_\alpha A\left|\vec{U}_\beta-\vec{U}_\alpha\right|(\vec{U}_\beta-\vec{U}_\alpha) \tag{4}$$

where C_D represent drag coefficient and A the interfacial area density.

For the continuous phase (oil) was used the κ-ε standard turbulence model whose turbulent kinetic energy equation is given by:

$$\frac{\partial(\rho_i k)}{\partial t} + \nabla(\rho_i \vec{U}_i k) = \nabla\left[\left(\mu_i + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] + P_k - \rho_i \varepsilon \tag{5}$$

where σ_k is an empirical constant with value 1.

The equation of turbulent viscous dissipation rate is given as follows:

$$\frac{\partial(\rho_i \varepsilon)}{\partial t} + \nabla(\rho_i \vec{U}_i \varepsilon) = \nabla\left[\left(\mu_i + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla \varepsilon\right] + \frac{\varepsilon}{k}(C_{\varepsilon 1} P_k - C_{\varepsilon 2} \rho_i \varepsilon) \tag{6}$$

where σ_ε, $C_{\varepsilon 1}$ and $C_{\varepsilon 2}$ are empirical constants with the following values: 1.3; 1.44 and 1.92, respectively.

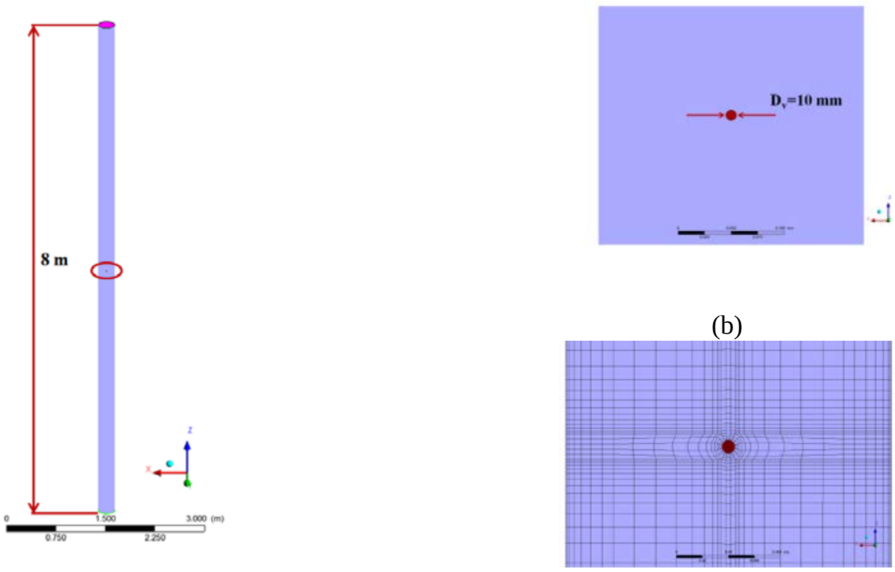
For the dispersed phase (water and gas) was used the particle model (Zero dispersed phases equation moldel). In this model, it is assumed that the eddy viscosity of the dispersed phase, $\mu_{t,d}$, is proportional the eddy viscosity of the continuous phase, $\mu_{t,c}$, as follows:

$$\mu_{t,d} = \left(\frac{\rho_d}{\rho_c}\right)\frac{\mu_{t,c}}{\Pr_t} \tag{7}$$

where $\Pr_t$ is a turbulent Prandtl number which relates the turbulent kinematic viscosity of the dispersed phase ($v_{t,d}$) with the turbulent kinematic viscosity of the continuous phase ($v_{t,c}$), ρ_d density of the dispersed phase and ρ_c represent the density of the continuous phase.

2.2 The physical problem and geometry

The studied geometry consists of a vertical pipe 8 meters in length with circular cross section 25 cm in diameter, where all cases studied the pipe contains a leak located in its central axial position with a circular shape and diameter of 10 mm, as shown in Figure 1.



(a) (b) (c)

Figure 1. Geometry used to evaluate the influence of the feed temperature (a), detail of leak (b) and mesh close to leakage (c)

Construction of the mesh was set to meet the problem to be treated without increasing excessively the computational time required. Various mesh tests were conducted to verify the convergence of the results, where they are not presented due to lack of space in the article. The mesh used to evaluate the influence of temperature inlet in the fluid flow inside the pipe contains 411656 hexahedral elements. The hexahedral mesh was used because of the historical research group's results because it was found that it brings better results in this area as well as lower numerical diffusions.

2.3 Initial and boundary conditions and properties fluids

The flow considered is the three-phase (gas-water-oil) with oil as the continuous phase, and the gas and water being dispersed phases. It considered the following gas composition: 90% CH_4, 5% C_2H_6, 2.5% C_3H_8 and 2.5% C_4H_{10}.

The initial and boundary conditions and physical of fluids properties used in the simulations are shown in Tables 1 and 2. In the wall of pipe was used no-slip condition and T_{wall} = 300 K.

Table 1. Boundary and initial conditions used in the simulation

Location	Volumetric flow rate (m^3/h)	Pressure (atm)	Volume fraction		
			Oil	Water	Gas
Inlet	500	-	0.9	0.08	0.02
Outlet	-	0.981	-	-	-
Leak	-	0.981	-	-	-

Table 2. Physical properties and geometric parameters of the fluids used in the simulation

Parameters	Phase		
	Oil	Water	Gas
Particle diameter (mm)	-	0.8	0.3
ρ (kg/m^3)	989	997	CFX
μ (mPa.s)	$\mu_0 = 10^{-3}\exp\{\exp[11.29983 - 2.099\ln(1.8T - 459.67) - 1.015\}$	$\mu_w = 0.00002414x10^{\left(\frac{N_1}{T-N_2}\right)}$	CFX
κ (W/m.K)	0.165	0.61825	CFX
σ (mN/m)	45 (water/oil)		
	15 (gas natural / oil)		
h (W/m^2.K)	30		

The viscosity of the water was based on the work of Babadagli and Al-Bemami (2007), where N_1=247.8 K and N_2= 140 K. The oil viscosity equation used was based on the work of Cunha (2010). The values of natural gas properties were calculated internally in CFX defined as a blend component. The cases studied are described in Table 3.

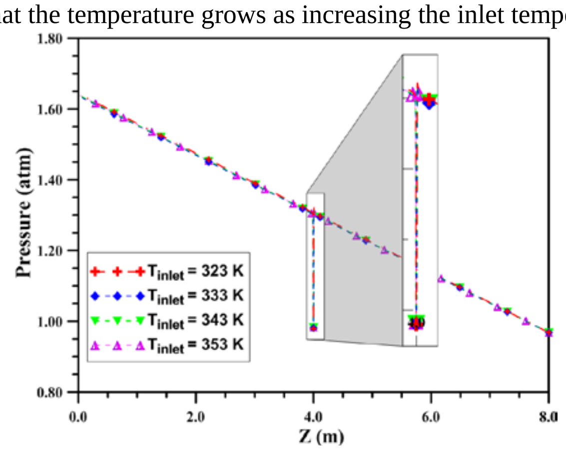
Table 3. General characteristics of the cases studied.

Case	L (m)	D_v (mm)	T_{inlet} (K)	Roughness of the pipe (mm)	Thermal conditions
1	8	10	323	Without roughness	Non-isothermal, transient, three-phase.
2	8	10	333		
3	8	10	343		
4	8	10	353		

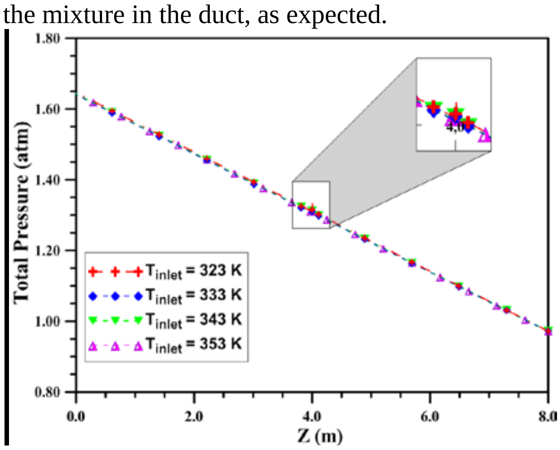
3. RESULTS AND DISCUSSION

The cases were studied in the Computational Laboratory of Fluids and Thermal in the Federal University of Campina Grande. The computer used in the simulations was PC Intel, Quad Core 3.2 GHz, 8 Gb RAM and 1 Terabyte in HD. Since this is an unpublished work, still there are no experimental data available for comparative analysis.

To analyze the influence of inlet fluid temperature (cases 1, 2, 3 and 4) was used the same initial and boundary conditions and properties of the fluids except for the feed temperature ranging, respectively, as follows: 323 K, 333 K, 343 K and 353 K. The analyses were made in a time of 10 s. The computational time spent for each simulation was an average 5 days. Figure 2 shows the pressure distribution and total pressure along the length of the pipe closed to the leak region. Observed for all cases that there was a significant pressure drop at the hole area (in Z = 4 m) (Figure 2a). This variation in pressure is not observed in the graph of the total pressure along the pipe length (Figure 2b). It is seen that the variation of the pressure (Figure 2a) in the hole for the four cases analyzed is similar, demonstrating that there is no significant influence of feed temperature of the mixture in this parameter. Is worth mentioning that the Pressure it is defined only as the static pressure, while the Total Pressure considers the static pressure and influences of gravitational, friction and drag forces. The average pressure drop in the pipe for the cases 1, 2, 3 and 4 were respectively 0.672923 atm, 0.67143 atm, 0.670052 and 0.676039 atm. These results show that until the case 3, the higher the temperature, the lower the pressure drop in the pipe, which can be explained by the lower viscosity of oil (biggest phase volume fraction) and water, with increasing feed temperature. Figure 3 illustrates the phases dynamic viscosity over the length of the pipe (1 mm hole). It is seen that the dynamic viscosity of the oil and water at 1 mm from leak along the pipe length varies according to the inlet temperature and the higher feed temperature the lower the dynamic viscosity of the oil and water phases. The influence the feed temperature of the mixture was not observed in the gas dynamic viscosity. Figure 4 shows the temperature distribution for the cases 1, 2, 3 and 4 near the bore region. The temperature of the pipe wall was defined as boundary condition being T_{wall}= 300 K for all cases, therefore near the pipe wall, the lower temperature of flow for each phase that composes it are found. The temperatures of the gas and water phases vary with the inlet temperature of the fluid. As the inlet temperature is increased from case 1 to case 4, the temperature of the dispersed phases (gas and water) grow to the same extent. Thus, it is observed that the gas and water remain coupled to the continuous phase, having influence the thermodynamic conditions and properties of the oil phase. Distribution of oil temperature for the cases 1, 2, 3 and 4 in longitudinal section, near the leak is show in Figure 5. We can see that the temperature variation is greater near the pipe wall and it is uniform for a certain distance from it. Furthermore, it is seen that the temperature grows as increasing the inlet temperature of the mixture in the duct, as expected.

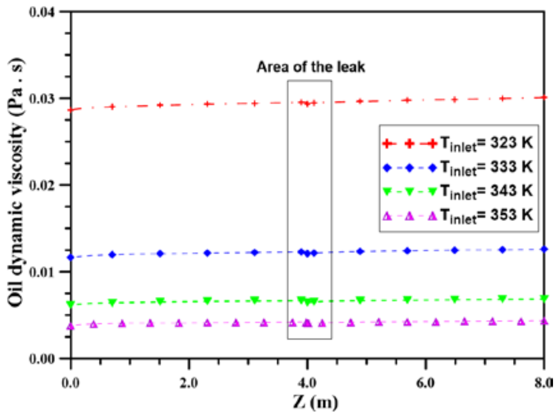


(a)

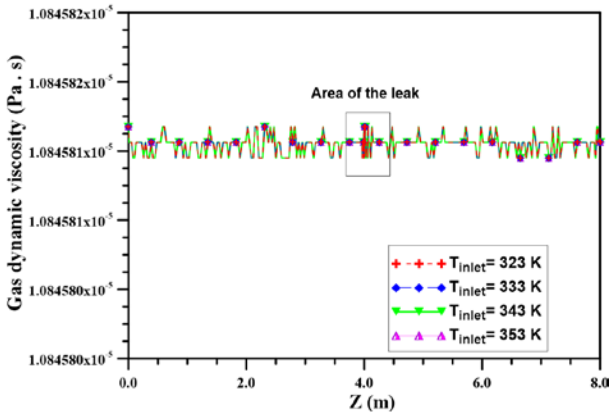


(b)

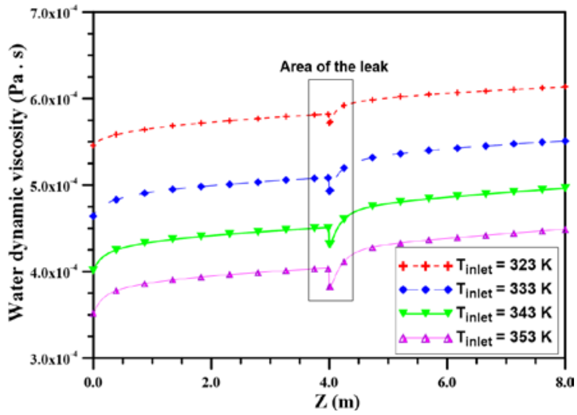
Figure 2. Pressure (a) and total pressure (b) along the length of pipe near to the leakage area (1 mm hole)



(a)



(b)



(c)

Figure 3. The dynamic viscosity of a) oil, b) gas and c) water along the pipe length near to the leak region (1 mm hole)

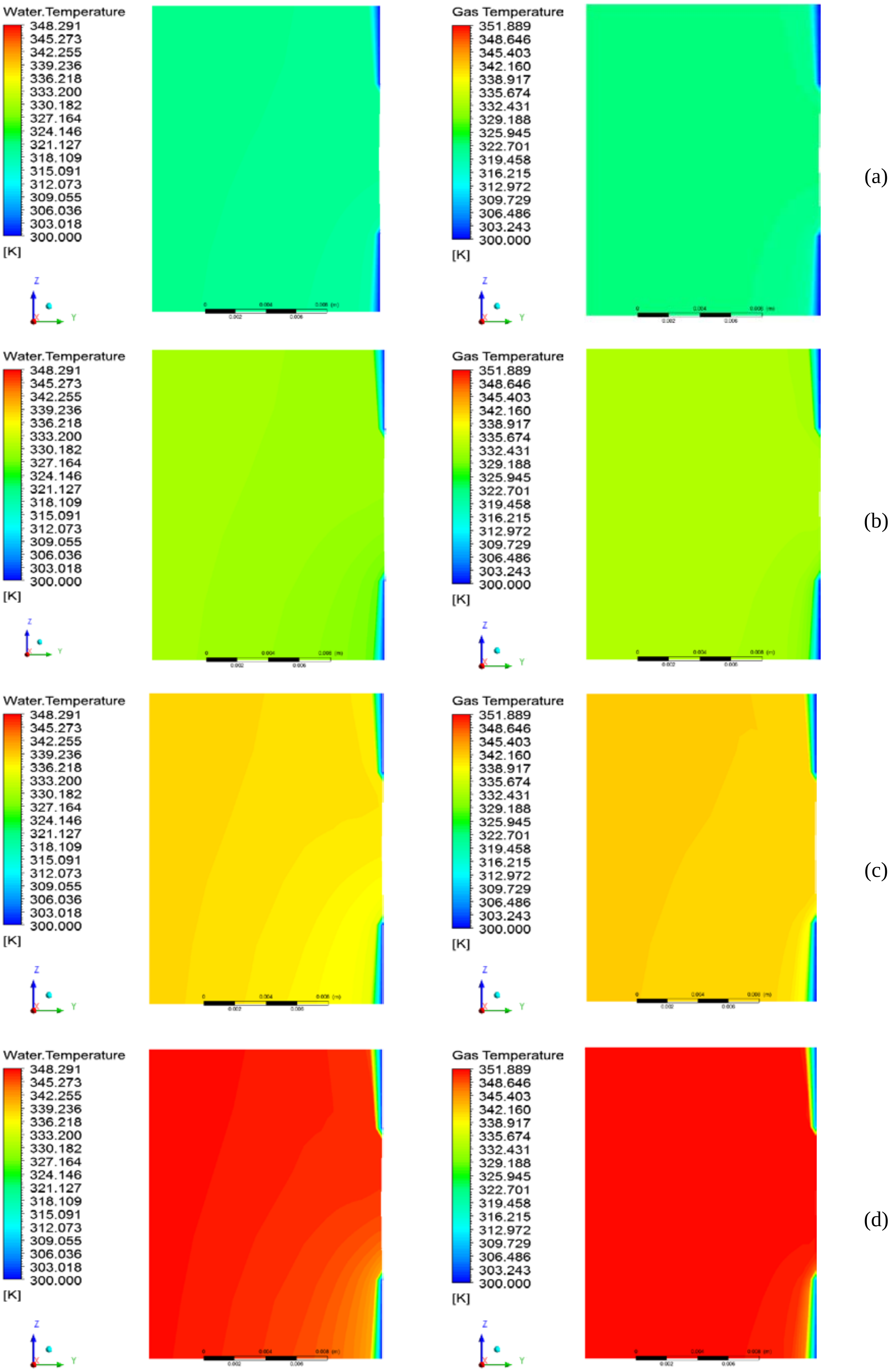


Figure 4. Distribution of the temperature of dispersed phase (water and gas) near the hole region for a) case 1, b) case 2, c) case 3 d) 4 case (longitudinal section).

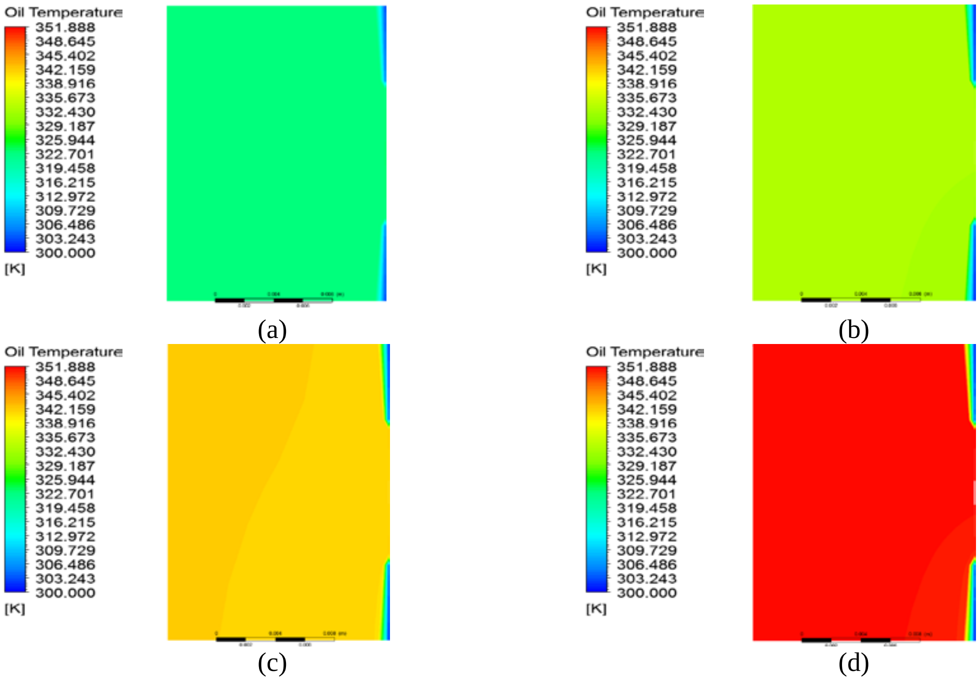


Figure 5. Temperature distribution of continuous phase (oil) near the hole region for a) case 1, b) case 2, c) case 3 and d) case 4 (longitudinal section).

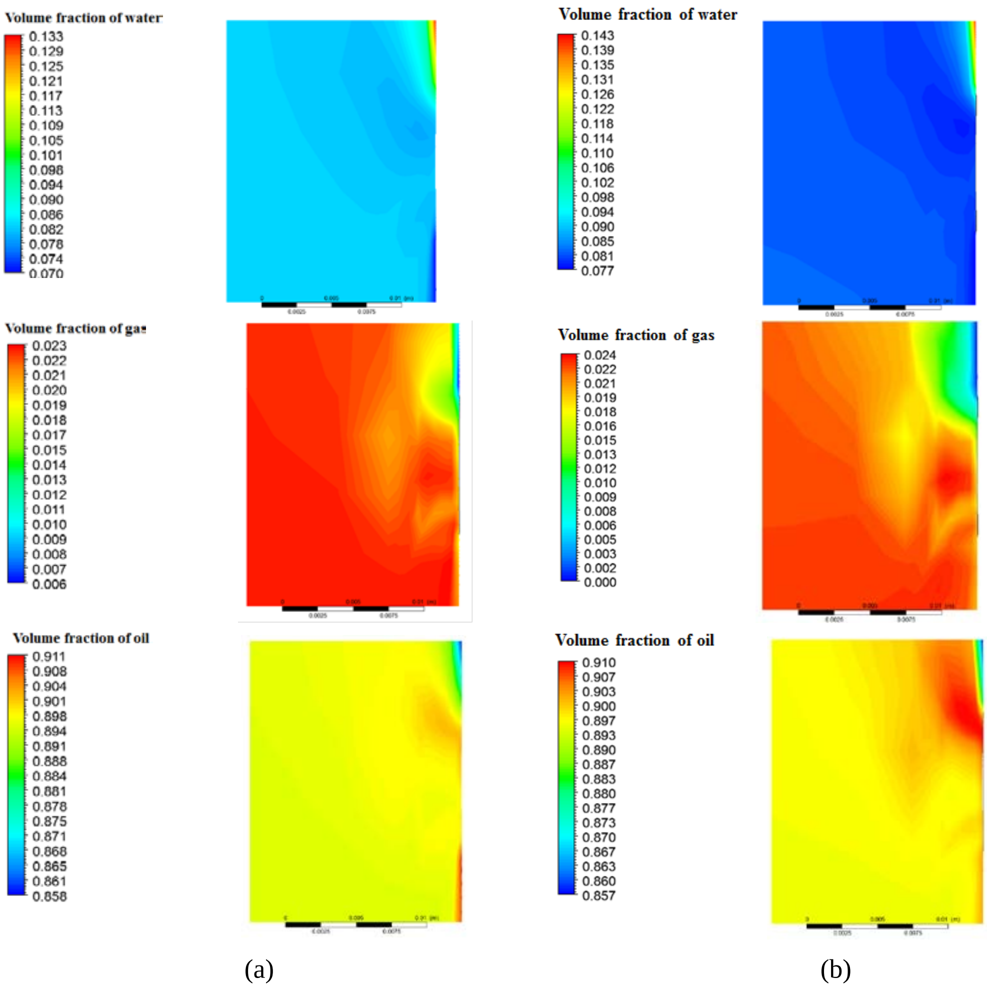


Figure 6. Distribution of the volume fraction of the phases (oil, water and gas) near the leak region (longitudinal section) for a) case 1 and b) case 4.

Figure 6 shows the distribution of volume fraction of the phases water, oil and gas (cases 1 and 4) in order to see the influence of temperature on the distribution of this parameter. It is seen that there is an influence of feed temperature on the volume fraction of the phases water, oil and gas. The region after the leak (cases 1 and 4) is the region of higher volume fraction of water and lower volume fraction of oil and gas which may be caused by oil output coupled to the gas in the hole.

4. CONCLUSIONS

From the analyzes and results obtained, it can be concluded that:

- ✓ The method used in the development of this work was effective in evaluating the influence of the feed temperature in the thermohydrodynamic of flow, and can detect the pressure variation in the leak area;
- ✓ According to the obtained results, it is verified that the presence of the leak causes disturbance in pressure, being thus a leak indication being used by the engineer to check the leakage. As usual sensors are equidistant, as from the sound propagation velocity and the time that the sensor detects the disturbance suffered by pressure, it can be check the location of the leak;
- ✓ The variation of inlet temperature influences directly in the average pressure drop of the flow: in general the higher the temperature, the lower the pressure drop;
- ✓ The temperature of the gas and water varies with the temperature of the continuous phase due to the small volume fraction and thermophysical properties of these phases.

5. ACKNOWLEDGEMENT

The authors would like to express their thanks to Brazilian researches agencies ANP/UFCG-PRH-25, CNPq, CAPES and FINEP for supporting this work, and are also grateful to the authors of the references in this paper, that helped in the improvement of quality.

6. REFERENCES

Andrade, T. H. F., 2013. *Transporte de Óleos Pesados e Ultraviscosos via Core-flow: Aspectos Geométricos e Termofluidodinâmicos.* Doctoral thesis, Post-Graduation in Process Engineering, Campina Grande, UFCG.

Ansys, 2012. *CFX – Theory Manual.*

Cunha, A. L., 2010. *Recuperação Avançada não Isotérmica de Óleos Pesadas em Reservatórios de Petróleo via Simulação Numérica.* Master's thesis, Post-Graduation in Chemical Engineering, Campina Grande, UFCG.

Santos, W. R. G., Barbosa, E. S., Farias Neto, S. R., Lima, A. G. B., 2013. "Hidrodinâmica do Escoamento Multifásico em Duto Vertical com Vazamento". In: 7º Congresso Brasileiro de P & D em Petróleo e Gás, 2013, Aracaju- SE. *Annals: do 7o Congresso Brasileiro de P & D em Petróleo e Gás*. v. 1. p. 1-18.

Santos, W. R. G., Barbosa, E. S., Farias Neto, S. R., Lima, A. G. B., Lima, W. M. P. B., 2014. "Three-phase flow (water, oil and gas) in a vertical circular cylindrical duct with leaks: A theoretical study". *The International Journal of Multiphysics*, v. 8, p. 253-270.

Sarmento, L. R. B., Leite, B. E., Farias Neto, S. R., Lima, A. G. B., 2014. "Hydrodynamics of oil-water with leakage by CFD", *Defect and Diffusion Forum*, v. 348, p. 58-63.

Sousa, J. V. N., Sodré, C. H., Lima, A. G. B., Farias, S. R., 2013. "Numerical Analysis of Heavy Oil-Water Flow and Leak Detection in Vertical Pipeline". *Scientific Research*, v. 3, n.1, p. 9-15.

Szalinski, L., Abdulkareem, L. A., Silva, M. J., Thiele, S., Beyer, M., Lucas, D., Hernandez, V., Hampel, U., Azzopardi, B. J., 2010. "Comparative study of gas–oil and gas–water two-phase flow in a vertical pipe". *Chemical Engineering Science*, v.65, n. 12, p.3836-3848.

Tavares, D. P. S. A., Vasconcelos, M. A., Neto, S. R. F., Lima, A. G. B., 2014. "Evaluation of multiphase flow in the presence of leak in oil pipelines: modeling and simulation". *Defect and Diffusion Forum*, v. 348, p. 64-70.