MODELING AND SIMULATION OF A HORIZONTAL THREE-PHASE SEPARATOR: INFLUENCE OF PHYSICOCHEMICAL PROPERTIES OF OIL

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ABSTRACT

Fluids produced from oil reservoirs typically contain oil, natural gas, water, sediments, in varying amounts, and contaminating gases. Considering that economic interest usually targets mostly oil and gas, primary processing is used to separate water/oil/gas, in addition to treating these phases. Therefore, the well stream should be processed as soon as possible after reaching the surface. Separator vessels are among the main equipment used at surface production facilities, being responsible for the separation of the produced phases. This work focuses on studying the fluid dynamic behavior in a horizontal three-phase separator. To accomplish this goal, we used the computer fluid dynamics software ANSYS CFX. First, we performed a detailed analysis of a “Standard Case” to understand in detail the entire separation process within the vessel. The results show the three phases through the simulation time, analyses of the separation efficiency, different fluids flow lines, pressure gradient inside the vessel, and effect of the diverter baffle. It also considers a variation of fluid flow at the inlet of the separator. These analyses include pictures of all cases studied. Afterwards, some parameters of the standard case were altered to evaluate its influence on fluid dynamics behavior and the functioning of the separator vessel. At last, we analyzed the influences of oil density and viscosity on the separation. The oil quality affects the primary separation directly, as the oil density and viscosity increase, for example, increases the drag between the fluids and decreases the rate of sedimentation, which stickles the separation process difficult. Two out of the three cases generated satisfactory results. The simulation with the heaviest oil presented the worse results.

KEYWORDS

separator vessel; computer fluid dynamics; ANSYS CFD

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1. INTRODUCTION

The use of fossil fuels as an energy source has driven many changes in the oil industry over the years, significantly boosting technological advances in the area. As an example, oil and its products correspond to about 32% of the world's energy matrix (EPE, 2018). This mineraloid is formed by the decomposition of organic matter which, under the action of pressure and heat, generates mixtures of compounds consisting mainly of hydrocarbons with structures that range from simpler to more complex chains. In an oil reservoir, there is also interstitial water, coming from the rock formation processes, and natural gas (Silva et al., 2007).

The reservoir configuration will depend on local pressure and temperature, the differences in density and immiscibility between the phases, and it is common to find natural gas occupying the upper part of the interior of the reservoir, while oil and salty water occupy the lower part. When the production of reservoir fluids occurs, in addition to oil and natural gas production, sediment, the so-called "production facilities", interstitial water and corrosive gases like CO₂ and H₂S are produced (Silva et al., 2007). The produced fluids need to go through separation and refining processes to have a market value of the product: oil and gas.

The first stage of separation is carried out in the primary petroleum processing plant and consists of using equipment such as the separating vessel, being responsible for separating the phases of the fluid produced. It can be classified in terms of position, as horizontal or vertical, or in terms of the number of phases, as two-phase or three-phase (Andrade, 2014; Diniz, 2017).

The use of computational fluid dynamics software can be helpful in the study of fluid behavior within a separating vessel. Among these computational programs, ANSYS CFX is capable of simulating the separation of phases in a separating vessel. This allows the visualization of phenomena that occur during the separation process, obtaining pressure, velocity, and residence time profiles, and pointing out best configuration choices for a given project.

The study of various aspects of primary petroleum processing, including the separating vessels, has been conducted by several authors

such as Silva (2004), Andrade (2014), and Anjos (2015). When it comes to numerical modeling, the literature is more restricted. However, recent studies made by Ghaffarkhah et al. (2017), Triwibowo et al. (2017), Scapin et al. (2017), and Ahmed et al. (2019) show the relevance of computer modeling and its potential uses in industry. All studies mentioned above address Horizontal Three-Phase Separator (HTPS), using Computational Fluid Dynamics (CFD) software.

Ghaffarkhah et al. (2017) studied two semi-empiric models, one by Arnold and Stewart and another by Monnery and Svrcek, for dimensioning HTPS, developing a comparative study between them. For the analysis of fluid behavior, the authors used a combination of Volume of Fluid (VOF) and Discrete Particle Method (DPM) models. The work of Triwibowo et al. (2017) focused on the modeling and simulation of a steady-state HTPS. To develop this study, Triwibowo et al. (2017) used the multiphase flow model VOF. Scapin et al. (2017) presented the analysis of a three-phase separator, based on a multifluid eulerian- eulerian model of Navier-Stokes equations. The aim of these authors was to construct a consistent numerical scheme for multiphase flow involving more than two phases.

Ahmed et al. (2019) compared two commonly used multiphase flow models, Eulerian and VOF, to predict separation performance and fluid flow patterns in an HTPS. To obtain experimental data, the authors developed two distinct three-phase separator vessels on a pilot scale: one operating at a low flow rate and the other at a high gas volume flow rate. By comparing the results of experimental and numerical data, the authors concluded that numerical simulation is highly recommended to size an industrial scale separator using the appropriate CFD model. Ghaffarkhah et al. (2017), Triwibowo et al. (2017), Scapin et al. (2017), and Ahmed et al. (2019) used their respective multiphase flow models associated with the turbulence model $k - \varepsilon$.

Thus, this work studies fluid dynamic behavior of a three-phase water-oil-gas mixture in a horizontal separating vessel, varying influence of oil properties. Such analysis was performed through simulations in the ANSYS CFX computational fluid dynamics software.

2. METHODOLOGY

The present work used only one geometry for the three-phase horizontal separating vessel. The dimensions used were based on the work **Anjos (2015)**, with an increase in the total length of the vessel, which is recommended for three-phase separators, because they have sections of the accumulation both for oil and water. Figure 1 shows the lateral view of the separating vessel used, as well as its dimensions. This separating vessel has two internal structures: a diverter baffle near the inlet of fluids and a plate that separates the accumulation sections from the water and gas, as shown in Figure 2a. The dimensions of the separating vessel are shown in Figure 2b.

2.1 Mesh generation

The mesh pattern for this work is unstructured. It is formed by 315936 elements and 56129 nodes (Figure 3a). This mesh is not completely regular. In the smaller parts, such as the plates, entrance and exits (Figure 3b), have a higher density of elements, providing more precise the results.

2.2 Mathematical modeling

The simulations for each case took an average of one hour to be processed. This work was performed using the ANSYS Student 18.2 package, which includes the ANSYS CFX 18.2 software, the computational fluid dynamics software used to perform simulations and analyze results. The

Figure 1. Three-phase horizontal separating vessel (side view).

Figure 2. a) Internal structures of the separator and b) dimensions.

Figure 3. a) Unstructured numerical mesh developed; b) Detailed view of the deflector plate and gas outlet.

simulations were performed in a computer with Intel Core i5 quad-core 3.5 GHz processor and 16 GB of DDR3 1600 RAM.

For the construction of the numerical mesh, ICEM CFD 13.0 was used. This software, which is part of the ANSYS package, is a powerful tool capable of working with both structured and unstructured meshes, from the simplest to the most complex ones. The mathematical modeling of the problem used a Eulerian-Eulerian model. It consists of adopting a time interval, choosing a section or a volume of control in space and considering all the particles that pass through this location (Triwibowo et al., 2017).

To simplify the problem, some hypotheses were considered: 1) Slight temperature variation in the region analyzed (isothermal process); 2) Transient

regime; 3) Effect of gravity; 4) Three-dimensional domain in Cartesian coordinates; 5) Constant physicochemical properties and no chemical reactions. Through these simplifications it is possible to reduce the number of required equations to three. These equations are applied to each of the control volumes with the use of ANSYS CFX, obtaining a numerical resolution.

2.3 Fluid domain equations

In fluid mechanics, the continuity equation, described by Equation 1, determines that the flow with which mass enters a system is equal to the flow with which mass leaves the system plus the accumulated mass. Its form differs is given by:

$$\nabla \cdot (\rho \vec{U}) = -\frac{\partial \rho}{\partial t} \quad (1)$$

Where:

r_α is volumetric fraction of phase α (non-dimensional);

ρ_α is specific mass of phase α in kg/m³;

$\vec{U}_\alpha$ is speed of phase α in m/s;

t is time in seconds.

The conservation of momentum is described by Equation 2, which encompasses the forces acting on the flow.

$$\begin{aligned} \nabla \cdot [r_\alpha (\rho_\alpha \vec{U}_\alpha \otimes \vec{U}_\alpha)] + \frac{\partial(\rho V)}{\partial t} = \\ = r_\alpha \nabla p + \nabla [r_\alpha (\tau_\alpha + \tau_\alpha^{turb})] + \vec{M}_\alpha \end{aligned} \quad (2)$$

Where:

p is pressure in Pa;

Δp is pressure gradient;

τ_α is tension in phase α in kg/ms²;

τ_α^{turb} is turbulent tension of Reynolds in phase α in kg/ms²;

$\vec{M}_\alpha$ describes the interfacial forces acting in phase α due to the presence of other phases in N/m³;

The value of $\vec{M}_\alpha$ can be calculated from Equation (3):

$$\vec{M}_\alpha = C_D \rho_{\alpha\beta} A_{\alpha\beta} |\vec{U}_\beta - \vec{U}_\alpha| (\vec{U}_\beta - \vec{U}_\alpha) \quad (3)$$

Where:

$\rho_{\alpha\beta}$ is specific mass of mixture in kg/m³;

$A_{\alpha\beta}$ is specific mass of interfacial area in m⁻¹;

$\vec{U}_\alpha$ is speed of phase α in m/s;

$\vec{U}_\beta$ is speed of phase β in m/s.

The value of $A_{\alpha\beta}$ is defined as a function of the dispersed fraction and the diameter of the particles according to Equation (4):

$$A_{\alpha\beta} = \frac{6r_\beta}{d_\beta} \quad (4)$$

Where:

r_β is the fraction of dispersed phase (non-dimensional);

d_β is the diameter of phase particles β (non-dimensional).

2.4 Turbulence model

The k- ε turbulence model was used for this work. It involves the modeling of two differential transport equations, one for turbulent kinetic energy k and the other for ε , which represents the rate of dissipation of turbulent kinetic energy per unit of mass. It is a very popular turbulence model, providing a good relationship between computational effort and accuracy. It is represented by equations (5) and (6).

$$\nabla(\rho \vec{U} k) = \nabla \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + (P_k - \rho \varepsilon) \quad (5)$$

$$\nabla(\rho \vec{U} \varepsilon) = \nabla \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + \frac{\varepsilon}{k} (C_{\varepsilon 1} P_k - C_{\varepsilon 2} \rho \varepsilon) \quad (6)$$

Where:

ε is rate of turbulent dissipation in m²/s³;

k is turbulent kinetic energy in kg.m²/s²;

μ is the dynamic viscosity in N.s/m²;

μ_t is turbulent viscosity in N.s/m²;

σ_k , σ_ε , and C_ε are dimensional constants of turbulence model k- ε

2.5 Boundary conditions and fluids properties

In this paper, the efficiency of fluid separation is evaluated in several situations through the modification of some variables. The standard operating conditions were 25 °C of temperature and 17.2 bar of pressure. The fluid properties for such conditions are shown in Table 1.

In order to make the operating conditions of the separating vessel in the standard case consistent with reality, both maximum gas and liquid capacity have been calculated. The gas and liquid capacities are represented, respectively, by Equations 7 and 8. Equation 7, proposed by Souders-Brown, is empirical and does not consider the length of the vessel and the level of liquid inside of it.

Table 1. Properties of fluids in standard conditions.

	Oil	Gas	Water
Specific Mass	813,464 kg/m ³	0.7236 kg/m ³	997 kg/m ³
Dynamic Viscosity	0.021 kg/ms	1.08E-05 kg/ms	8.899E-04 kg/ms
Surface Tension	0.072 N/m	-	0.072 N/m
Constant Pressure Heat Capacity	2140 J/kg.K	-	4181 J/kg.K
Average Droplet Diameter	100 µm	-	100 µm

Sources: Silva & Marinho (2016), Kharoua (2012), ANSYS (2013), and Copergás.

Table 2. Physicochemical properties of oil.

Simulation	Specific mass (kg/m ³)	°API	Viscosity (Pa.s)
1	813.464	42.28	0.021
2	845	35.80	0.03
3	870	30.99	0.05

$$q_{st} = \frac{2,4D^2Kp_{op}}{z(T + 460)} \sqrt{\frac{\rho_L - \rho_g}{\rho_g}} \quad (7)$$

Where:

q_{st} is gas capacity at standard conditions in MMscfd;

D is the inner diameter of the vessel in ft;

p_{op} is the operating pressure in psia;

T is the operating temperature in °F;

z is gas compressibility factor (non-dimensional);

ρ_L is specific mass of the liquid under operating conditions in lbm/ft³;

ρ_g is specific mass of the gas under operating conditions in lbm/ft³;

K is an empirical factor (non-dimensional).

$$q_L = \frac{1440V_L}{t} \quad (8)$$

Where:

q_L is liquid capacity in bbl/d;

V_L is sedimentation volume of liquid in bbl;

t_r is retention time in minutes.

In the boundary conditions, a mixture with 92% gas and 8% liquids, divided into oil (6%) and water

(2%) was considered for the inlet (Nakayama, 1999). In the vessel walls (0.0456 mm of medium roughness) and deflector and separator plates, the slip wall condition was admitted, in which the relative velocity of the fluid in relation to the wall is null.

The gas outlet is of opening type, with standard relative pressure. For the liquid outlet, a constant and negative velocity of 0.25 m/s was applied. The initial condition of the vessel considered it being full, with an oil-water mixture composed 50% of each phase up to 2/3 of the height, and the rest being filled with gas.

All simulations were performed in a transient regime with a maximum number of 20 loops for each iteration. Each case was simulated for a total time of 20 minutes with time steps of 10 seconds having a convergence criterion of 10⁻⁴ kg.s⁻¹.

3. CASE STUDY ANALYSIS

3.1 Standard case

The standard case, used as a basis for further studies, considered an input velocity of 13 m/s (flow rate of 0.105395 m³/s) with fractions of 92% gas, 6% oil, and 2% water. Physicochemical properties are demonstrated in Table 2. This results in a flow rate of 3436.71 bbl/day oil, 1145.57 bbl/day water, and 0.3 MMscfd gas.

3.2 Physicochemical properties of oil variation

This case analyzed the influence of the variation in the physicochemical properties of the oil. For the properties not present in Table 2 below, the properties shown in Table 1 were considered. In all cases, gas and water properties remained constant.

Besides the standard case and the analysis of the fluid flow variation, other studies can be done. Among them, the variations of the gas/liquid ratio, oil/water ratio, and the variation of fluid flow at the separator inlet.

4. RESULTS AND DISCUSSION

First, a detailed analysis of the standard case was performed. Afterwards, the results of the other cases were discussed, analyzing the influence of fluid flow variations.

4.1 Standard case

The Figures 4, 5, and 6 show, respectively, the volumetric fractions of oil, water, and natural gas inside the separator over 20 minutes.

After the analysis of Figures 4, 5, and 6, it is possible to see that the separator worked out as expected. At the end of the simulation, the separation of the three phases inside the equipment was obtained, as well as the flow of the required fluids in the three outlets of the separator vessel. This behavior is very similar to those obtained by [Ghaffarkhah et al. \(2017\)](#) and [Triwibowo et al. \(2017\)](#).

Through the results obtained, visually and numerically, some preliminary observations can be made:

- i. In the first minute it is possible to observe a considerable drop in the level of liquid inside the vessel. During this time there is still no stabilization of the flow in the water and oil outlets. Subsequently, the velocities at the

Figure 4. Oil volumetric fraction in a) 0 s, b) 150 s, c) 300 s, d) 450 s, e) 600 s, f) 750 s, g) 900 s, h) 1050 s and i) 1200 s.

Figure 5. Water volumetric fraction a) 0 s, b) 150 s, c) 300 s, d) 450 s, e) 600 s, f) 750 s, g) 900 s, h) 1050 s and i) 1200 s.

Figure 6. Natural gas volumetric fraction in a) 0 s, b) 150 s, c) 300 s, d) 450 s, e) 600 s, f) 750 s, g) 900 s, h) 1050 s and i) 1200 s.

outlets stabilize at 0.25 m/s- the value established by the modeling's boundary conditions. During the rest of the process, the liquid level remained, for the most part, constant, a little above the height of the overflow inlet diverter between the liquid separation sections. This allowed the oil to

continuously overflow into the oil collection section, which allowed the equipment to operate properly.

- ii. Although the separation of the components was relatively quick, the equipment took considerable time to reach a steady state

condition. Only after approximately 470 seconds it was possible to obtain more oil than water at the oil outlet, and with 520 seconds the oil fraction came closer to the intended goal, reaching about 90%.

- iii. Even after the separation process had stabilized and the vessel had begun operating continuously, it was possible to notice a small accumulation of water at the bottom of the oil storage section, as shown in Figure 7.
- iv. Following equipment stabilization, the

separation of the phases does not happen completely. It is possible to observe both traces of oil in the water accumulation section (Figure 8) and the presence of gas dispersed in liquid phase (Figure 9). In the first case, because of the low flow velocity at the water outlet and the long period for which the mixture is retained, it is not possible to notice traces of oil in the outlet most of the time. In the second case, it was not possible to avoid completely the gas drag through the liquid phases. Fortunately, this dragging does not happen in an amount capable of

Figure 7. Detail of water accumulation in the oil accumulation section (1200 s).

Figure 8. Traces of oil in the water accumulation section (1090 s).

Figure 9. Gas traces in liquid accumulation sections (660 s).

compromising the process, with an average gas fraction of only 0.0322% at the water outlet and 0.2046% at the oil outlet.

4.2 Variation of the physicochemical properties of oil

Simulations were performed to evaluate the influence of the physicochemical properties of oil, obtaining the values shown on Table 2. The results were, then, compared to the standard case. Figures 10, 11, 12, and 13 show the oil fraction inside the separator to all the three cases for 300 s (5 minutes), 600 s (10 minutes), 900 s (15 minutes), and 1200 s (20 minutes), respectively.

Observing Figures 10 to 13, it is possible to see that the heavier and more viscous is the oil, the faster it fills the oil accumulation section the higher the liquid level is. For 30.99 °API oil viscosity, one can observe that the water overflows to the oil section. We can also notice the presence of traces of oil at the bottom of the water accumulation section.

Figure 14 shows a graph of oil volumetric fraction at the oil outlet.

Looking at the graph closely, it is possible to notice that the lightest oil case took more time to stabilize than the others. This occurred because it separates faster from the water, floating on it. So,

Figure 10. Oil volumetric fraction inside the separator (300 s).

Figure 11. Oil volumetric fraction inside the separator (600 s).

Figure 12. Oil volumetric fraction inside the separator (900 s).

Figure 13. Oil volumetric fraction inside the separator (1200 s).

all the water in the oil accumulation section must flow to stabilize the process. However, this case could maintain a good separation for the rest of the simulation time, while in the case of the heaviest oil, there was a sharp loss of efficiency from 600s onwards, when the water from the water accumulation section overflows, flooding to the oil accumulation section.

The graph shows a strong oscillation between 130 and 170 seconds. This happened because during the stabilization process, the oil went down very quickly leaving a large accumulation of water, as can be seen on Figure 15. When the water is drained, the stabilization process continues.

Figure 16 shows the graph of the oil volumetric

Figure 14. Graph of oil volumetric fraction in the oil outlet.

Figure 15. Oscillation observed on Figure 14 for a) 130 s; b) 150 s and 170 s.

fraction at the oil outlet for the last 10 minutes of simulation.

Except for the heaviest oil case, there was no significant difference in separation process efficiency. The 35.8 °API oil viscosity, although heavier and more viscous, still separates from the oil with relative ease, and the overflow problem seen in the 30.99 °API oil does not occur. At the end of the simulation, the oil volumetric fraction at the oil outlet was 99.6074% for the 40.28 °API oil, 99.6602% for the 35.8 °API oil, and 89.5031% for the 30.99 °API oil. The water and gas outlet presented similar results.

Figures 17, 18, and 19 show the streamlines for oil, water, and gas, respectively.

The heaviest oil case presented more turbulence through water and oil. The increase in oil viscosity increases the drag between fluids, causing a deceleration at the oil/water interface, resulting in circular movements. However, given the low overall velocity of the system after the shock of the inlet stream with the baffle, it is unlikely that these movements were responsible for the differences seen in the numerical results.

The most likely cause for the lower separation efficiency is the higher density and viscosity of the oil used. The increase in value of both properties considerably reduces sedimentation rate, making it harder to separate oil from water. A better configuration of the level controllers could help to avoid the problem seen with the heaviest oil, increasing the time the oil/water mixture is

Figure 16. Oil volumetric fraction at the oil outlet for the last 10 minutes of simulation.

Figure 17. Oil streamlines (1200 s).

retained, which would prevent water overflow. In more extreme cases, such as the ones involving heavier and more viscous oils, a new dimensioning may be necessary.

5. CONCLUSIONS

Analyzing the results achieved through the

simulations performed, it was observed that the mathematical modeling proposed to describe the fluid dynamics behavior inside a horizontal three-phase separating vessel was able to reproduce satisfactorily the physical phenomena present in this type of equipment.

The study showed that the increase in oil viscosity and density may cause loss in efficiency of the vessel. After 20 minutes of simulation, for the

Figure 18. Water streamlines (1200 s).

Figure 19. Gas streamlines (1200 s).

40.28 °API oil viscosity, the volumetric fraction of oil at the oil outlet was 99.6074% against 99.6602% for the 35.8 °API oil and 89.5031% for the 30.99 °API oil. The increase in oil viscosity increases the drag between fluids, causing a deceleration at the oil/water interface, and reducing the sedimentation rate, hindering the separation. Adjustments in the separator vessel may be necessary to solve this type of problem. These adjustments may include a new configuration of the level controllers or even a new dimensioning of

the entire equipment.

None of the cases studied presented problems related to liquid drag at the gas outlet, with values of approximately 100% of gas in practically all simulation time. There were also no problems in the water outlet, always presenting a minimum presence of unwanted fluids.

The computational fluid dynamics (CFD) proved to be a powerful tool in studying fluid behavior in several situations. Besides allowing a better

understanding of the phase separation process, this type of software can be used to perform prior tests of various operating and sizing conditions, allowing a better prevention of operational problems in real situations, reducing risks of serious errors.

Future work in the field should investigate the influence of quality of the mesh on the results, perform simulations with even smaller time steps to obtain more precise results, test new sizing, and work on a more dynamic level controller system that better adapts to present conditions.

NOMENCLATURE

Latin Letters

r_a	volumetric fraction of phase a	—
$\vec{U}_\alpha$	speed of phase a	m/s
T	time	s
p	pressure	Pa
$A_{\alpha\beta}$	specific mass of the interfacial area	m^{-1}
$\vec{U}_\alpha$	speed of phase a	m/s
$\vec{U}_\beta$	speed of phase b	m/s
r_b	fraction of the dispersed phase	—
d_b	particle diameter of phase b	—
k	turbulent kinetic energy	$kg.m^2/s^2$
q_{st}	gas capacity at standard conditions	MMscfd
D	vessel inside diameter	ft
p_{op}	operating pressure	psia
T	temperature	°F
z	gas compressibility factor	—
K	empirical factor	—
q_L	liquid capacity	bbl/day
V_L	sedimentation volume of the liquid	bbl
t_r	retention time	min

Greek Letters

ρ_α	specific mass of phase α	kg/m^3
τ_α	tension of phase α	kg/ms^2

τ_α^{turb}	turbulent tension of Reynolds in phase α	kg/ms^2
$\rho_{\alpha\beta}$	mixing specific mass	kg/m^3
ε	rate of turbulent dissipation	m^2/s^3
μ	dynamic viscosity	$N.s/m^2$
μ_t	turbulent viscosity	$N.s/m^2$
$\sigma_k, \sigma_\varepsilon$ and C_ε	dimensional constants of the turbulence model k- ε .	—
ρ_L	specific mass of liquid under operating conditions	lbm/ft^3
ρ_g	specific mass of gas under operating conditions	lbm/ft^3

Symbols

$\nabla \cdot$	divergence operator	—
∇	gradient operator	—
$\otimes$	tensor product	—

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