Applying CFD in the Analysis of Heavy Oil/Water Separation Process via Hydrocyclone

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ABSTRACT

In recent years most of the oil reserves discovered has been related to heavy oil reservoirs whose reserves are abundant but still show operational difficulties. This fact provoked great interest of the petroleum companies in developing new technologies for increasing the heavy oil production. Produced water generation, effluent recovered from the production wells together with oil and natural gas, is among the greatest potential factors for environmental degradation. Thus, a new scenario of the oil industry appears requiring improvement in treatment units for produced water. Among the technological improvements in the facilities, the use of hydrocyclones has been applied in the treatment of the oily water. In this sense, this study aims to investigate numerically the separation process of heavy oil from a water stream via hydrocyclone, using the computational fluid dynamics technique. In the mathematical modeling was considered a two-phase, three-dimensional, stationary, isothermal and turbulent flow. Results of streamlines, pressure and volume fraction fields of the involved phases (oil and water) into the hydrocyclone, and mechanical efficiency and pumping power of the fluids are shown and analyzed. In conclusion, it seems that with increasing fluid input velocity in the device there is an increase in pressure drop, indicating a greater pumping energy consumption of the mixture, and greatly influences the separation process efficiency.

1. INTRODUCTION

The oil industry has significant importance in the energy, economic and strategic context of the world; however, it is also one of the sectors with the greatest potential for environmental degradation.

The management of oil-produced water is a huge challenge for petroleum companies. The alternatives usually adopted are discard, injection and reuse. In all cases, appropriate treatment is necessary to avoid damage to the environment and production facilities or in order, to allow its reuse without damaging the processes in which the water produced will be used [1].

In Brazil, regarding the disposal of oily water, the CONAMA standard established that the produced water must obey the monthly average concentration of oil 29 mg/L, not exceeding the daily limit 42 mg/L [2].

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Hydrocyclones are equipment that performs well in the oily water treatment [3-5].Because it is of simple construction, low cost of manufacture, maintenance and operation, besides use not moving parts and require little space for installation, these devices become ideal technologies in offshore primary processing plants.

Table 1 shows some results related with produced water treatment units in Brazil, with emphasis on the maximum production flow rate and the equipment used.

Recent developments in hydrocyclone technology have allowed the use of such equipment to cope with increasing oil content. A great difficulty is found when the stream of oily water is formed by heavy and ultra-viscous oils, because the high viscosity induces a pressure drop of load, which requires high pumping power in the separation process [5].However, the evolutionary scenario of oil indicates, in general, an increasing share of the so-called unconventional oils in world production.

The expectation of a strong growth in heavy oil production in Brazil in the coming years, especially with the advent of the “Pre-Sal” region, justify an increase in investments in exploration and production activities, besides has also led to the expansion of research activities and development in the area.

Farias et al. [7] studied numerically the effect of geometric parameters (vortex finder diameter) of the hydrocyclone and sand concentration on the inlet fluid separation process. They observed that the particles concentration and geometry affect the separation efficiency of the equipment.

Souza et al. [8] analyzed the effects of inlet fluid mixture temperature and oil droplet size on hydrocyclone performance in separating dispersed heavy oil from continuous streams of water. Numerical results indicate that superficial velocity and oil mass flow rate in the overflow have a positive relationship with oil droplet size and temperature.

Luna et al. [9] studied a new device of water/oil separation with operation principle similar to traditional hydrocyclone, called cyclonic separator. Results showed that pressure and tangential velocity present symmetrical behavior inside the equipment and that water/oil separation efficiency increases with increasing feed volumetric flow rate at the inlet section of the cyclone separator.

In this context, the present study aims to evaluate the process of separating the oil from a stream of oily waters by hydrocyclone, using a computational fluid technique, in order to obtain better performance of this equipment with a greater use of the energy required.

2. METHODOLOGY

2.1 Geometry and Numerical Mesh

In order to study numerically the behavior of the fluids inside the hydrocyclone, it is necessary to create a representation of the equipment as faithful as possible to reality. This representation is obtained through the construction of a geometry and numerical mesh of the hydrocyclone, in which it will schematize the configuration of the device to be analyzed.

The hydrocyclone used in the present study corresponds to the device proposed by Souza [10], whose dimensions are according to Figure 1. The unstructured mesh was generated in the CFX-Build 5.5 module and consists of 228,219 tetrahedral elements and 42,393 nodal points after refinement, as shown in Figure 2. Further details of the geometry and numerical meshing are reported in Souza [10].

Table 1: Produced water treatment units in Brazil [6]

Field / Unit	Maximum flow rate of produced WATER	Treatment capacity	Treatment process for TOG (Oil and grease content in water)	Input and output TOG
East Albacora FPSO P-50 PETROBRAS	22.315,1 m³/day in 2021	Current: 16,000 m³/day Enlargement in 2012	Battery for hydrocyclones, flotation and produced water tank	Input: 1000 mg /L. Discard: ≤ 20 mg /L and 40°C
Caratinga FPSO P-48 PETROBRAS	12.996 m³/day in 2014	Current: 20,000 m³/day	Hydrocyclone battery with maximum output at 100 mg/L, cooled and conducted to the float	Input: 100 mg /L, but prepared for 300 mg/L. Discard: ≤ 20 mg/L and 40°C
Espadarte FPSO PETROBRAS	9000 m³/day in 2016	Current: 8,040.63 m³/day	Separation by decanting in slop tanks and hydrocyclone battery	Input: 1000 mg/L. Discard: ≤ 20 mg/L and 40°C
South Marlim SS P-40 PETROBRAS	13.850 m³/day in 2022	Current: 17,400 m³/day	Hydrocyclone battery and float vessel	Input: 1000 mg/L. Discard: ≤ 20 mg/L and 40°C
South Area of the Bacia de Campos SS-06 PETROBRAS	11.151 m³/day in 2005	Volume not available	Hydrocyclone battery and float vessel	Discard: ≤ 20 mg/L and 40°C
Bijupirá Salema FPSO – Fluminense SHELL	7000 m³/day in 2016	Current: 7,950 m³/day	Hydrocyclone battery and flotation	Discard: ≤ 20 mg / L and 38°C

2.2 Mathematical Modeling

The mathematical conditions adopted are related to an Eulerian-Eulerian study, in which it allows an analysis considering that each phase has its field of flow, thus, a set of solutions for each phase separately. The phases present in the flow are represented by the letters α and β.

2.2.1 Governing Equations

The mathematical model used in the present study considers the two-phase (heavy oil-water), three-dimensional, stationary, isothermal and turbulent flow. To describe the flow inside the hydrocyclone the following equations were used:

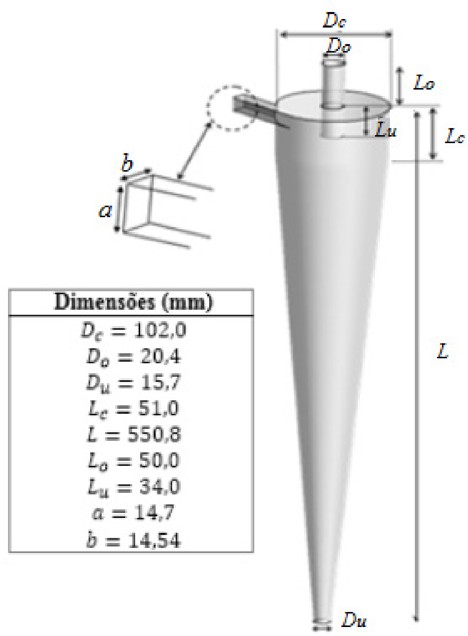


Figure 1: Geometric representation of the hydrocyclone.

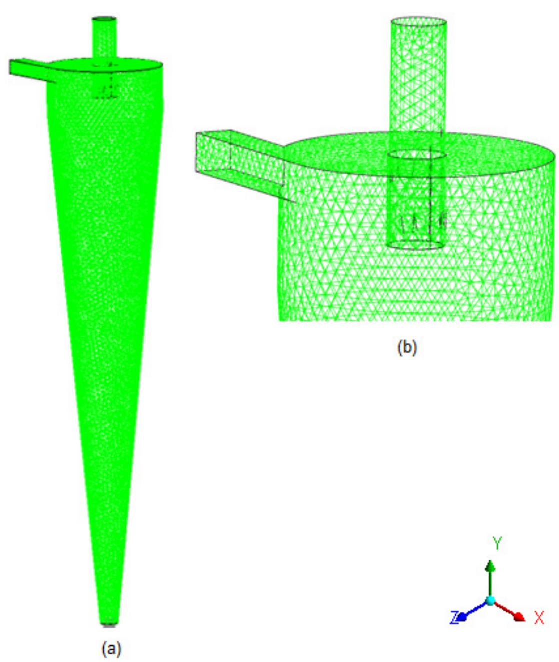


Figure 2: Representation of the unstructured mesh of the hydrocyclone (a) and detail of the upper part of the mesh (b).

- Mass Conservation Equation:

$$\frac{\partial}{\partial t}(f_\alpha \rho_\alpha) + \nabla \cdot \left(r_\alpha \rho_\alpha \vec{U}_\alpha\right) = 0 \tag{1}$$

- Momentum Conservation Equation:

$$\frac{\partial}{\partial t}\left(f_\alpha \rho_\alpha \vec{U}_\alpha\right) + \nabla \cdot \left[f_\alpha(\rho_\alpha \otimes \vec{U}_\alpha)\right] - f_\alpha \nabla p_\alpha + \nabla \cdot \left\{f_\alpha \mu_\alpha\left[\nabla \vec{U}_\alpha + (\nabla \vec{U}_\alpha)^{\ T}\right]\right\} = \vec{S}_{M\alpha} + \vec{M}_\alpha \tag{2}$$

where it is assumed that for the α phase, f is the volume fraction, ρ is the density, $\vec{U}_.$ is the velocity vector, μ is the dynamic viscosity, p is the pressure, the term $\overrightarrow{S_{M\alpha}}$ describes the linear moment of the strength due to external body strength (gravitational force), while $\vec{M}_\alpha$ describes the interfacial forces (drag force, lift force, virtual mass force, wall lubrication force and turbulent dispersion force at the interface). These forces act on α phase due to the presence of other phases.

2.2.2 Constitutive Equations

For the flow inside the hydrocyclone, the turbulence model k-ε was used. The equations of turbulent kinetic energy and turbulent viscous dissipation, respectively, are:

$$\frac{\partial}{\partial t}(\rho_\alpha f_\alpha K_\alpha) + \nabla \cdot \left\{f_\alpha\left[\rho_\alpha \vec{U}_\alpha K_\alpha - \left(\mu + \frac{\mu_\alpha}{\sigma_k}\right)\nabla K_\alpha\right]\right\} = f_\alpha(G_a - \rho_\alpha \varepsilon_\alpha) \tag{3}$$

$$\frac{\partial}{\partial t}(\rho_\alpha f_\alpha K_\alpha) + \nabla \cdot \left\{f_\alpha \rho_\alpha \vec{U}_\alpha \varepsilon_\alpha - \left(\mu + \frac{\mu_\alpha}{\sigma_\varepsilon}\right)\nabla \varepsilon_\alpha\right\} = f_\alpha \frac{\varepsilon_\alpha}{K_\alpha}(C_1 G_a - C_2 \rho_\alpha \varepsilon_\alpha) \tag{4}$$

where G_aa is the turbulent energy generation within the α phase, $C_1$and $C_2$are empirical constants. Also in this equation, ε_α corresponds to the turbulent energy dissipation rate of the phase α and K_α the turbulent kinetic energy for the phase, respectively, defined by:

$$\varepsilon_\alpha = \frac{C_\mu {q^3}_\alpha}{l_\alpha} \tag{5}$$

$$K_\alpha = \frac{{q^2}_\alpha}{2} \tag{6}$$

where l_α is the spatial scale length, q_α is the velocity scale and C_μ is an empirical constant calculated by:

$$C_\mu = 4{C_\alpha}^2 \tag{7}$$

In the equation (7) C_α is also an empirical constant. The term μ_α corresponds to the turbulent viscosity, defined by:

$$\mu_\alpha = C_\mu \rho_\alpha \frac{{K^2}_\alpha}{\varepsilon_\alpha} \tag{8}$$

where the constants used in the previous equations are: $C_1 = 1.44$, $C_2 = 1.99$, $C_\mu = 0.09$, $\sigma_\varepsilon = 1.3$ and $\sigma_k = 1.0$.

2.2.3 Boundary Conditions and Fluids Physical Properties

In order to carry out the analysis of fluid flow in the hydrocyclone, the following initial and boundary conditions were used:

- Input: Velocity, volumetric fraction of the phases (oil and water), particle diameter and fluid inlet temperature values were established previously;
- Output: It was adopted the pressure condition established in the two hydrocyclone outputs (overflow and underflow) equal to the atmospheric pressure (P = 101325 Pa);
- Wall: All velocity components were defined zero on the inner walls of the hydrocyclone (non-slip condition) and wall roughness 0.045 mm.

The physical properties of the fluids (water and heavy oil) used in the present paper are shown in Table 2. Table 3 assumes all the numerical conditions used in the simulations.

2.2.4 Separation Efficiency and Pumping Power

The separation efficiency of the fluids inside the hydrocyclone was calculated considering the mass flow rate of the oil in the overflow, Mo, divided by the mass flow rate of the oil in the feed, Mf, given by Equation (9).

$$E(\%) = \frac{M_o}{M_f} x100 \tag{9}$$

The pressure drop in the hydrocyclone was determined from the difference in pressure in the inlet section and in the upper and lower outlet sections. From the values of the pressure drop in the hydrocyclone it was possible to determine the pumping power of the mixture using Equation (10).

$$P_{mec} = \Delta P x Q \tag{10}$$

where ΔP is the pressure drop in the hydrocyclone and Q is the volumetric flow of the mixture at the hydrocyclone inlet.

Table 2: Physical properties of fluids [10]

Physical property	Oil	Water
Density (ρ) [kg/m3]	963.6	997.0
Viscosity (μ) [Pa.s]	1.2	0.000904
Molar mass [kg/kmol]	100	18.015

Table 3: General considerations of the problem and the numerical solution

Flow Type	Two-phase (oil-water), three-dimensional, incompressible and isothermal
Flow Regime	Permanent and turbulent
Turbulence Model	K-ε
Interfacial Transfer Model	Particle model
Interfacial Force	Drag (drag coefficient = 0.44 - valid for the turbulent regime)
Pressure Interpolation Scheme	Trilinear
Velocity Interpolation Scheme	Trilinear
Influence of the Wall to Fluids	No slip
Influence on Fluid Interface	Free slip
Advection Scheme	High resolution
Convergence criterion	10^{-8}

2.3 Cases Studied

The CFX 15.0 Release®, computational software of the ANSYS commercial package, was used in the present research.

Table 4 presents different simulated cases, where the temperature (T_i), the volumetric fraction of the phases (f_o and f_w for oil and water, respectively), the feed velocity (V_i) and the oil diameter (d_p) are presented.

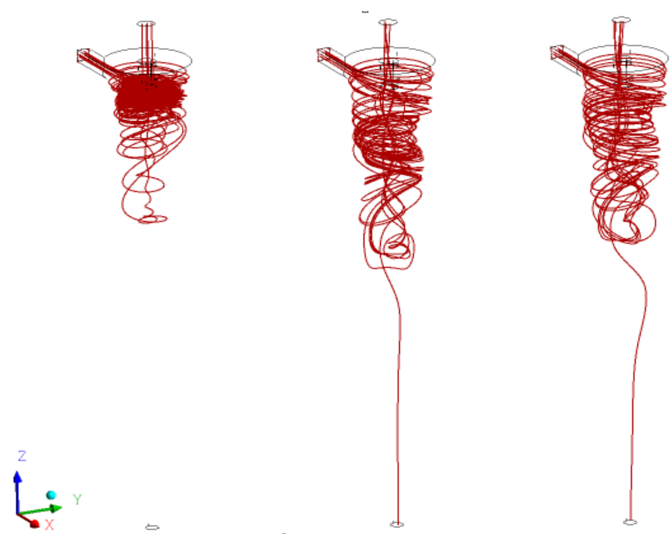
Table 4: Geometric and physical parameters used in the numerical simulations

Case	dp (m)	Ti (K)	Vi (m/s)	fo (-)	fw (-)
1	0.001	298	1	0.30	0.70
2	0.001	298	2	0.30	0.70
3	0.001	298	4	0.30	0.70
4	0.001	298	5	0.30	0.70
5	0.001	298	10	0.30	0.70
6	0.001	298	15	0.30	0.70
7	0.001	298	20	0.30	0.70
8	0.001	298	25	0.30	0.70
9	0.001	298	30	0.30	0.70
10	0.001	298	32	0.30	0.70

3. RESULTS AND DISCUSSIONS

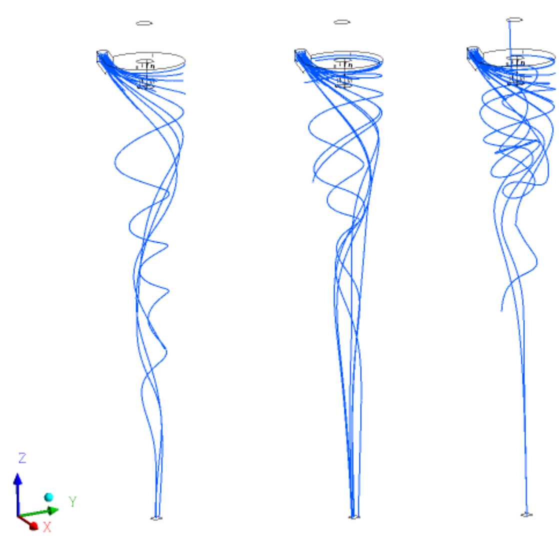
3.1 Streamlines Analysis

The streamlines of the heavy oil and water inside the hydrocyclone are shown in Figures 3 and 4, considering the input velocities of 4 m/s, 15 m/s and 32 m/s, and oil volumetric fraction of 0.30in the mixture (Cases 3, 6 and 10, respectively, as reported in Table 4).



(a) (b) (c)

Figure 3: Streamlines of the heavy oil at different inlet velocities. (a) 4 m/s and (b) 15 m/s and (c) 32 m/s.



(a) (b) (c)

Figure 4: Streamlines of the water at different inlet velocities. (a) 4 m/s and (b) 15 m/s and (c) 32 m/s.

From the analysis of these figures, the presence of two distinct streams of fluids is observed, both of which have a spiral shape. This behavior is similar to what is observed in traditional hydrocyclones, presented in several articles in the literature, for example, Farias et al. [7], Souza [10], and Luna [11]. It is verified that the inlet velocity affect the behavior of the fluid flow, favoring an increase of the centrifugal and drag forces, thus providing an increase in the number of turns of the flow lines inside the hydrocyclone.

Further, it can also be observed that the flow of the water stream tends to flow in the wall of the equipment, whereas the oily stream flows more internally. This is due to the density difference between the phases and the forces to which the fluids are subjected (drag, centrifugal and gravitational forces).

3.2 Pressure Field Analysis

The pressure fields on the YZ plane passing through the central axis of the hydrocyclone are shown in Figure 5. A pressure difference of 7466 Pa for the inlet velocity of 4 m / s (Case 3), 66519 Pa for 15 m / s (Case 6) and 311983 Pa for 32 m / s (Case 10) is observed. Thus, it is noted that, with increasing feed flow rate of the mixture, there is an increase in the pressure drop, indicating higher energy consumption for the pumping of the mixture into the hydrocyclone.

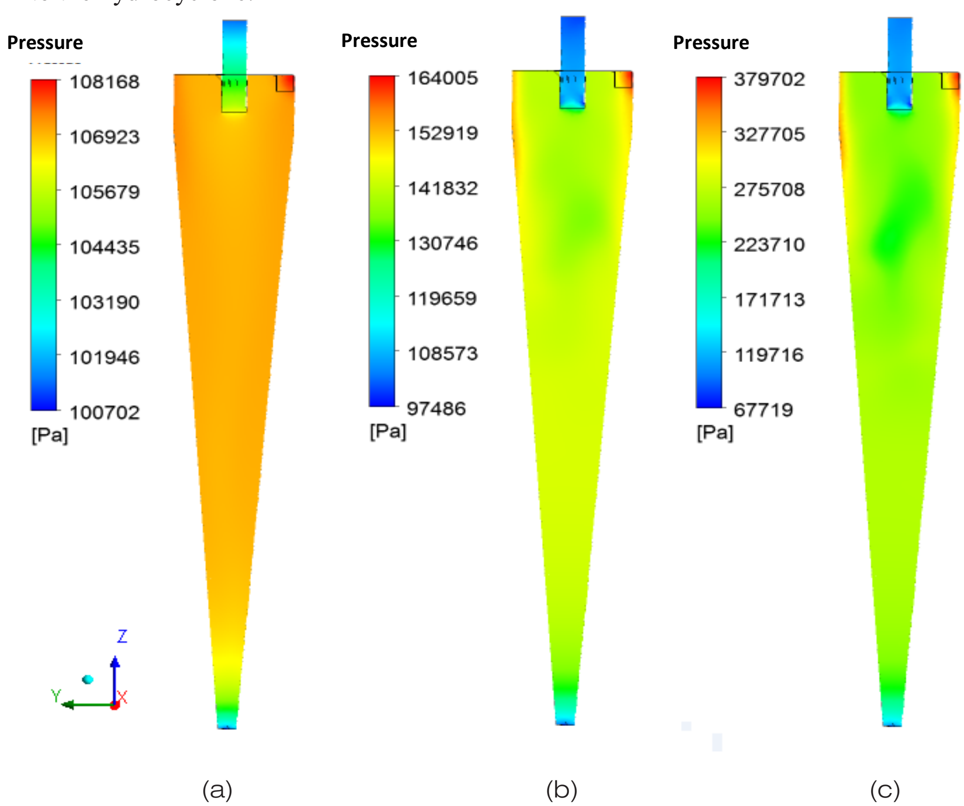


Figure 5: Pressure fields on the YZ plane for different inlet velocities.(a) 4 m/s (b) 15 m/s and (c) 32 m/s.

Figure 6 shows the pressure fields on the XY planes at the Z position 0.595 m. It is possible to see regions of low pressure near the central axis of the hydrocyclone and higher pressures in the regions near the walls and in the tangential entrance in the top of the hydrocyclone. This behavior is attributed to the forces that are acting in these regions.

These figures show that the pressure decreases in the radial direction towards the separator from the center to wall. This behavior was also observed by other authors such as Farias et al. [7], Souza [10], Luna [11], Barbosa [12], Souza et al. [13] and Farias et al. [14], when studying traditional hydrocyclones.

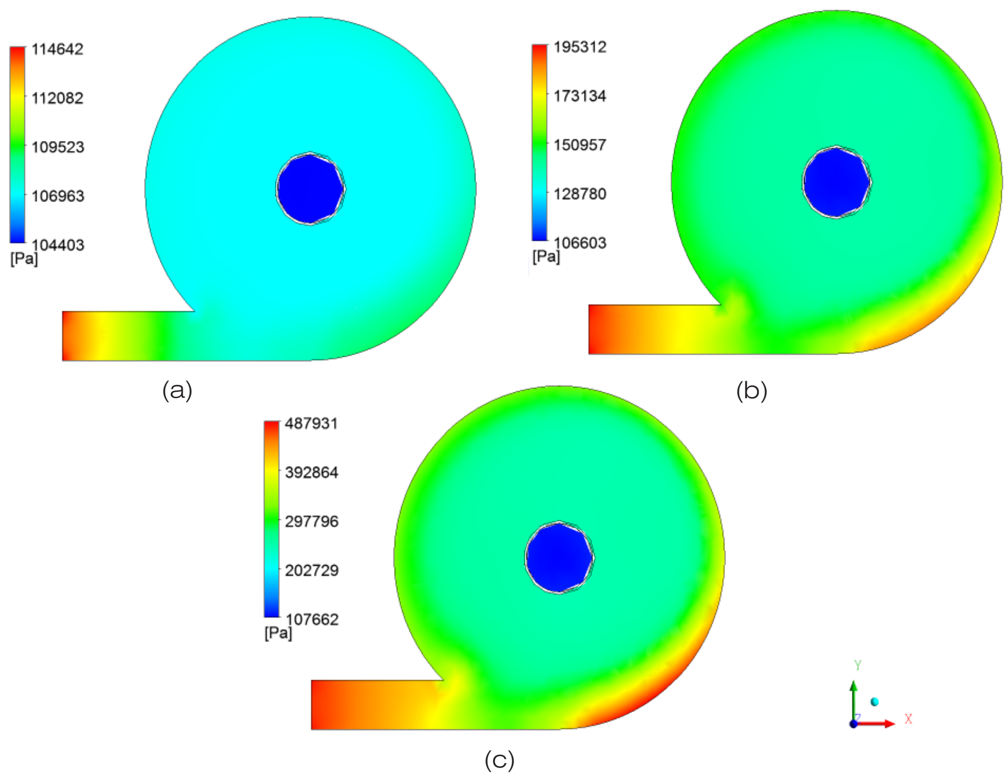
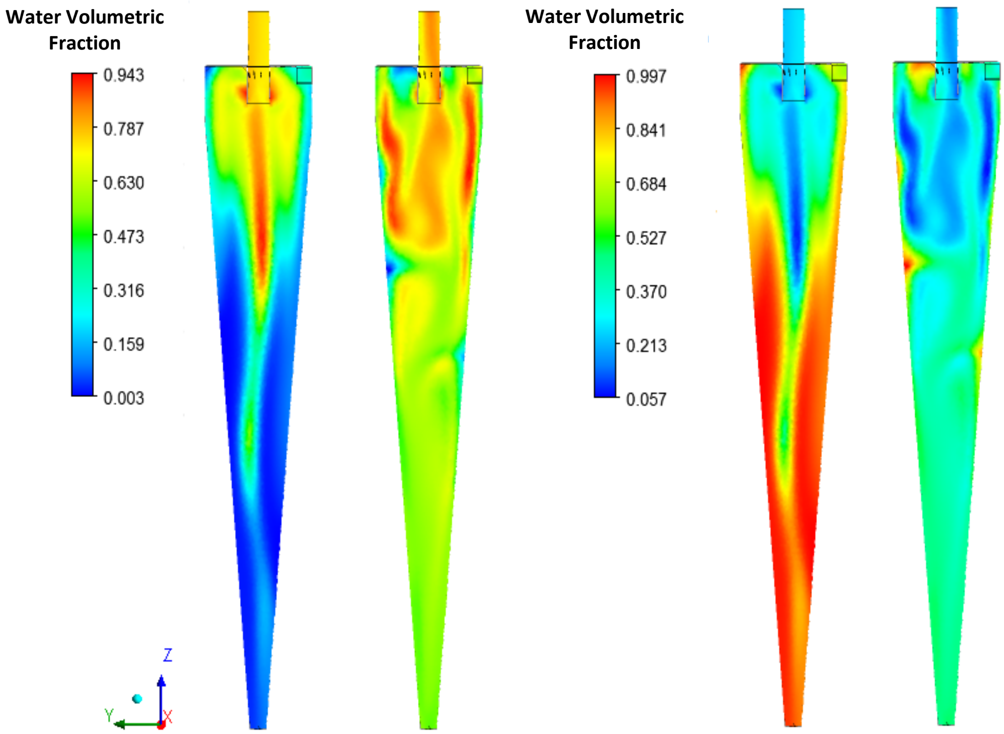


Figure 6: Pressure fields on the XY plane at the Z position equal to 0.595 m for different inlet velocities. (a) 4 m/s and (b) 15 m/s and (c) 32 m/s.

It can be seen in Figure 6(c) that a high pressure region appears near the hydrocyclone wall. In this case, a continuous use of the equipment under these severe conditions may result in operational problems, such as an intense corrosive process in that area. Thus, it is necessary to protect that section of the device by reinforcing the material to be used in its manufacture, in order to avoid damage to the equipment and to guarantee efficiency in separating the process of the phases.

3.3 Volumetric Fraction Field Analysis

Figure 7 presents the fields of the volumetric fraction of the phases (oil and water) on the YZ plane for the velocities 4 m/s (Case 3) and 32 m/s (Case 10). We can see that there is a higher concentration of water in the lower part of the equipment and oil near the central axis. This is due to the difference in density between the phases of the fluid mixture.



(a) 4 m/s (b) 32 m/s (c) 4 m/s (d) 32 m/s

Figure 7: Volumetric fraction fields on the YZ plane of the oil and water phases for the inlet mixture velocities 4 m/s and 32 m/s.

3.4 Velocity Field Analysis

Figure 8 shows the axial velocity profile on a longitudinal plane XZ of the hydrocyclone, for the input velocities 4 m/s (Case 3), 15 m/s (Case 6) and 32 m/s (Case 10). It is observed that the higher axial velocities are presented in the center and the smaller ones near the walls of the equipment. It is also verified that there are axial velocities of negative value, evidencing the presence of fluid recirculation zone. This behavior can be confirmed from the analysis of the Figure 9, where the oil dispersed phase velocity vectors along the XZ plane are presented for different inlet velocities inside the hydrocyclone. Note that the recirculation region is more accentuated for higher feed flow rate of the mixture.

3.5 Separation and Energy Efficiencies

Figure 10 shows the efficiency of the mechanical separation of the phases as a function of the inlet velocity of the fluids inside the hydrocyclone for all the cases cited in Table 4. From the analysis of this Figure, we can see that the phase separation efficiency increases with increasing feed flow, reaching its maximum value at the velocity 4 m/s (Case 3), with separation efficiency 90%.Then, even increasing the inlet velocity, this separation efficiency decreases until reaching the value of 58%, to the value of 10 m/s (Case 5) and then remains practically constant, around 60% , for velocities changing from 10 m/s (Case 5) to 32 m/s (Case 10).

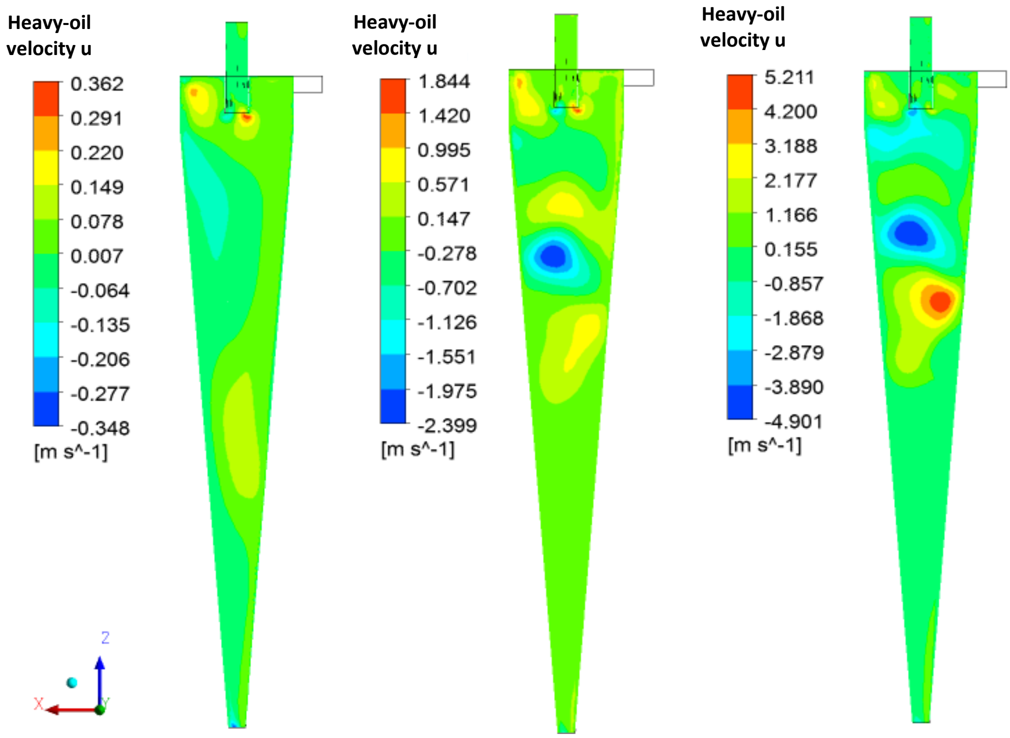


Figure 8: Axial velocity field over a longitudinal plane XZ inside the hydrocyclone, for the input mixture velocities (a) 4 m/s, (b) 15 m/s and (c) 30 m/s.

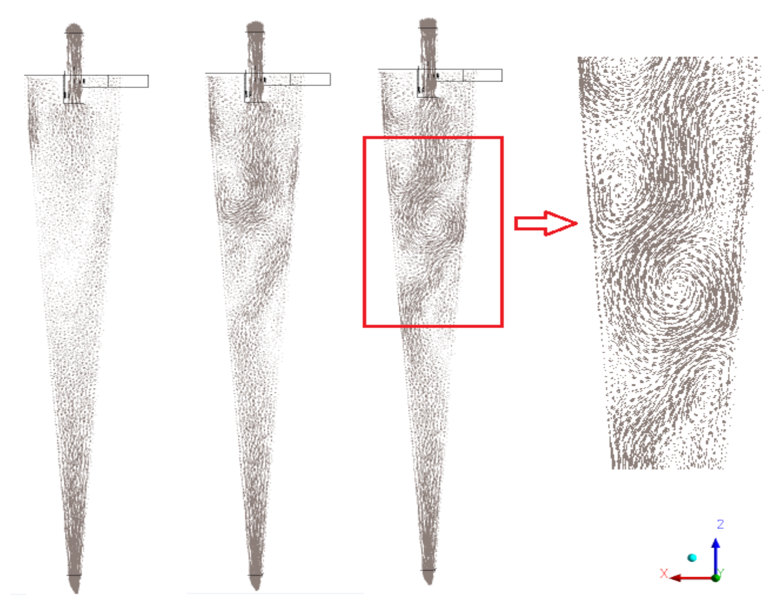


Figure 9: Axial velocity vectors of the oil along the plane XZ, for the input mixture velocities (a) 4 m/s, (b) 15 m/s and (c) 32 m/s, and (d) detail for the region of the recirculation zone

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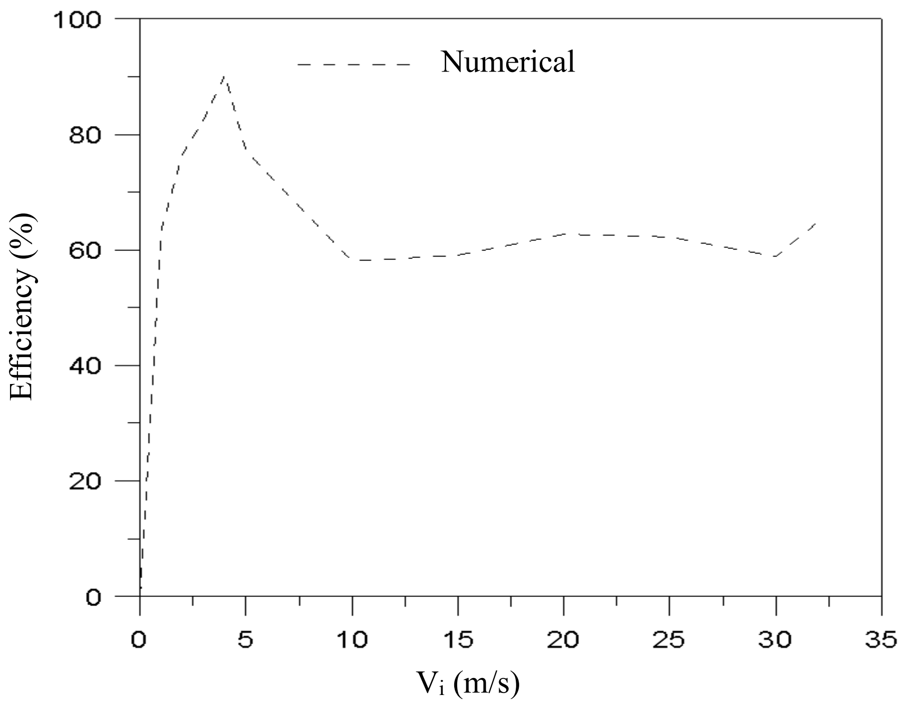

Figure 10: Mechanical separation efficiency as a function of the fluid inlet velocity.

From the values of the mass flow rate (from the oil in the overflow) and the volumetric (from the mixture at the inlet), it was possible to verify the oil content at the output of the equipment. When considering an inlet mixture velocity 10 m/s (Case 5), a value 25.12 mg/L of oil content was obtained at the upper outlet of the hydrocyclone, complying with the CONAMA Brazilian Standard, whose daily limit is 42 mg /L.

Figure 11 shows the behavior of the pumping power as a function of the inlet velocity of the mixture. Note that there is an increase in energy power for higher velocity values and this fact can be attributed to an increase in pressure drop in the equipment, which indicates higher energy consumption for the pumping of the mixture inside the hydrocyclone.

Table 5 shows the time spent by the equipment in days to process the mixture when considering different fluid inlet velocities. Considering, for example, the FPSO PETROBRAS unit of the Espadarte field, mentioned in Table 1, with a production of 9,000

m^3 of total volume of water produced per day, it can be noted that, the higher the inlet fluid flow rate in the hydrocyclone, the processing time spent by the equipment to separate the fluids will be lower, however, the greater the power required for such operation. For optimize the process a battery of hydrocyclones can be used to ensure maximum separation efficiency and shorter processing time.

Figure 12 shows an optimum range of operation considering the study of the mechanical and energy separation efficiencies and the processing time of a hydrocyclone. For Case 3 (4m/s), whose phase separation efficiency was 90% and the pumping power was low, its application is not feasible due to the long processing time of a hydrocyclone under these conditions (see Table 5). On the other hand for the Case 10 (32 m/s), which presented a shorter processing time and a considerable mechanical separation efficiency, was not feasible due to its high energy consumption.

Therefore, a recommended operating range would be that with values between 15 m/s (Case 6) and 25 m/s (Case 8), since this configuration will favors a good separation of the phases involved, with a lower processing time of the equipment. Further, the water after processing, under these conditions, is already in accordance with the CONAMA Brazilian Standard.

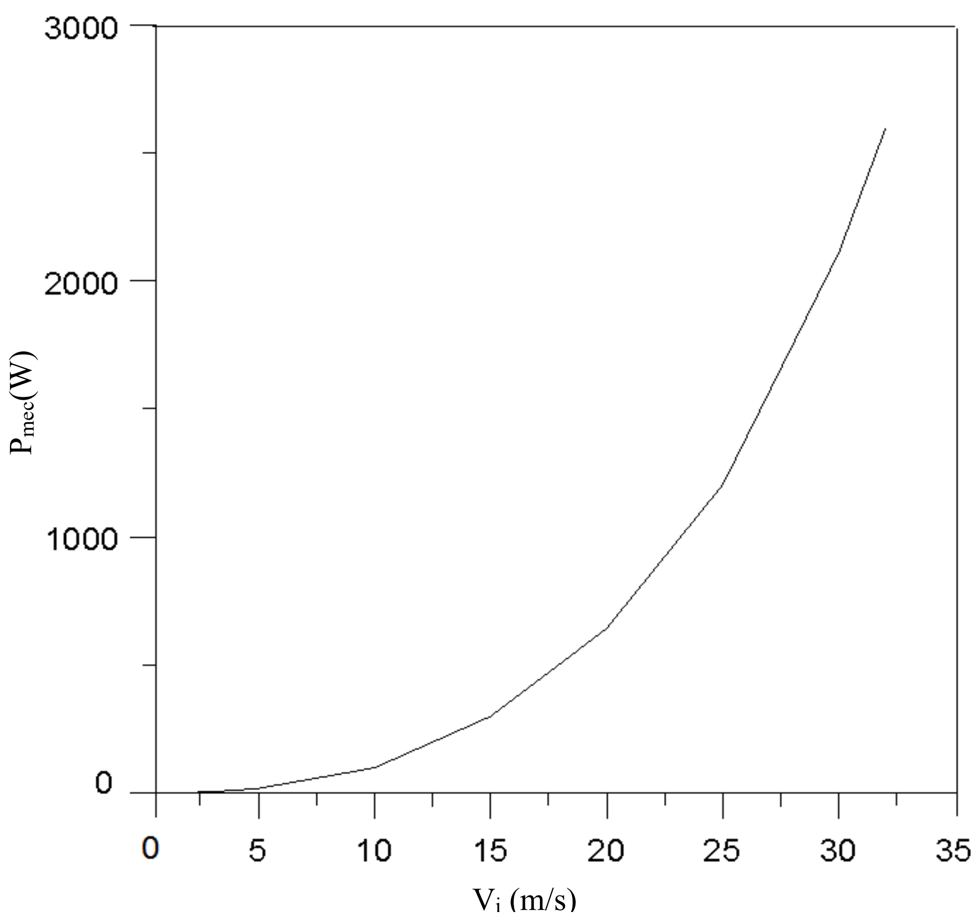

Figure 11: Pumping power as a function of the fluid inlet velocity

Table 5: Time spent by a hydrocyclone for fluid processing

Cases	Vi (m/s)	Volumetric flow rate (m³/h)	Time (days)
1	1	0.76968	195
2	2	1.53936	97
3	4	3.07872	65
4	5	3.84840	49
5	10	7.69680	39
6	15	11.54520	19
7	20	15.39360	13
8	25	19.24200	10
9	30	23.09040	8
10	32	24.62976	7

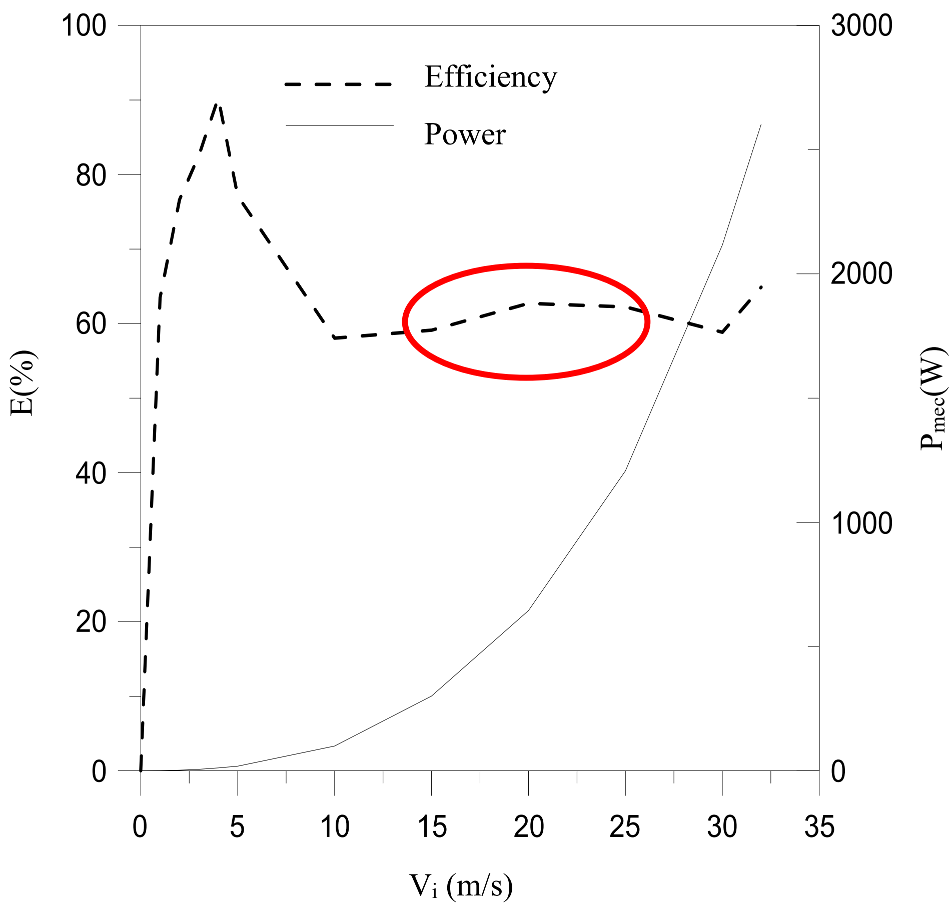

Figure12: Optimum range of operation when considering the mechanical and energy efficiencies and the processing time of the hydrocyclone.

4. CONCLUSIONS

From the results obtained with the numerical simulations of the fluid behavior inside the hydrocyclone, we can conclude that:

a) The mathematical model was adequate to describe the phenomenon in a realistic and detailed manner, being able to predict the process of heavy oil-water separation via hydrocyclone;
b) The inlet fluid mixture velocity influences the streamline behavior, favoring an increase of the centrifugal and drag forces, thus providing an increase in the number of turns inside the hydrocyclone;
c) The volumetric fraction fields showed that there is a higher concentration of water in the lower part of the equipment and oil near the central axis of device, because the difference in density between the phases of the mixture;
d) With increasing feed fluid flow rate there is an increase in the pressure drop, indicating a higher energy consumption for the pumping of the mixture into the hydrocyclone;
e) The separation efficiency of the phases increases with the increase of the feed fluid flow rate, reaching its maximum value for the velocity 4 m/ s (90%);
f) The higher the inlet fluid velocity, the shorter the processing time of the equipment, but the pumping power required for such an operation should be greater;
g) A recommended range of operation would be to operate with inlet fluid ranging values between 15 m/s and 25 m/s. This configuration has a good phase separation, a considerable equipment processing time and that the treated water already exits the device according to CONAMA Brazilian Standard.

5. ACKNOWLEDGMENT

The authors thanks to ANP/UFCG/PRH-42, CAPES, CNPq and FINEP (Brazilian Research Agencies) and PETROBRAS (Brazilian Oil Company), for all financial support and the researchers cited in the text which help in improvement.

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