SIMULATION AND DEVELOPMENT OF COMPACT HYDROCYCLONE IN CFD (COMPUTATIONAL FLUID DYNAMICS) FOR USE IN CENTRIFUGAL FLOTATION UNIT OF OILY WATER

SOUZA, A. D.; FILHO, A. S. F.; PINHEIRO, F. S. B.; BARBOSA, S. A.
Coordenadoria de Química
(Instituto Federal de Educação, Ciência e Tecnologia de Sergipe – IFS)
Av. Eng° Gentil Tavares da Mota, 1166, Bairro Getúlio Vargas, CEP: 49055-260, Aracaju, Sergipe – Brasil
E-mail: (souza.andersond@gmail.com)

Abstract. The increasing of industrial pollution has led environmental agencies to review the legislation and provide for increasingly stringent limits for the disposal of industrial wastewater. In Brazil, defined by the National Environmental Council (CONAMA), the limits for rejecting oily waters, as the oil and grease content (TOG) are 29 mg/L (average for one month) and 42 mg/L (maximum for one day). The complexity of the problem and the growing demands of environmental regulations have forced companies to improve their wastewater treatment systems requiring that treatment systems whose main feature high removal efficiencies even though under unfavorable conditions, i.e. when the oil droplets is finely dispersed in the aqueous phase in a size range of oil 10 to 30 micron and concentrations between 100 mg/L and 200 mg/L. In this work it was used Computational Fluid Dynamics (CFD) to study the performance and optimize the geometry of a hydrocyclone. The main objective was to drive performance prediction and especially to get optimal dimensions of the defined geometry to the established conditions. Therefore it was developed a numerical experimental design with three factors. With this it was possible to check the profiles of concentration and flow over the equipment, with different sizes realize the effect analysis of each factor separately on the separation efficiency and the analysis of the interaction effects. The results showed that there is a great relationship between the factors studied, as it is possible to develop a compact hydrocyclone that suits space-restricted conditions in offshore primary processing units.

Palabras clave: Computational Fluid, Hydrocyclone, Offshore Primary Processing.

1. Introduction

During the productive life of an oil field there is generally the simultaneous production of gas, oil and water, together with impurities. A significant amount of co-produced water is typically representing the largest waste stream, unwanted, in oil production (Thomas, 2001).

The function of a platform production processing plant is to separate the produced fluid to the wells in three phases: oil, gas and water, and also to process these phases in order to fit them according to the required (Arnold and Stewart, 2008).

The oil, after being conditioned, it is transferred to shore by pipeline or tanker, whereas the gas is dehydrated after being compressed. The produced water, after being treated, can be discharged in the ocean or reinjected into the reservoir to maintain the same pressure.

As previously mentioned, one of the most abundant and undesired contaminants in the oil production process is water, and its amount produced varies according to various factors such as the characteristics of the reservoir, the age of the producing wells and the recovery method used (water or steam injection).

The water associated with the produced fluid may be present in three different forms (Souza Filho, 2006):

- Free Water: Water flowing in the oil, but constitute a separate phase;
- Emulsified Water: very small water droplets dispersed in the oil phase, generating a water-oil emulsion;
- Dissolved Water: small amount of water dissolved in the oil.

The oil should generally present a BSW (Basic Water and Sediments) less than 1% by mass and a maximum concentration of dissolved salts 570 mg/L to be sent to the refinery.

During the course of the reservoir to the surface, the oil and water emulsions which form stability is varied depending mainly on the flow rate and the presence of emulsifying agents (asphaltenes, clay, metallic salts, among others) that prevent the coalescence of water droplets.

Much of the water that comes associated with the oil is easily separated by decanting the tabs. To remove the remaining water, which remains emulsified, it is necessary to use physical and chemical processes (Thomas, 2001).

Many platforms have floaters downstream of electrostatic separators to retain excess water still exists mainly in the form of emulsion, and frame the oil in pre-established quality standards for refining (Teixeira, 2013). This process consists in the separation of emulsified water from oil by applying a high voltage electrical field to the emulsion, causing the water droplets dispersed in oil acquire an elliptical shape and are aligned in the direction of the electric field with the induced poles opposite signs which create an attraction force that causes coalescence of the droplets. The continuous electric field causes the coalescence by electrophoresis and the alternating electric field causes the coalescence induced dipole mechanism. However, this machine can not totally separate the hydrocarbons from the produced water being common to have a volume 0.1 to 10% after the separation (Thomas, 2001).

The amount of produced water associated with the oil varies greatly, reaching 1% of the volume values in order beginning of the productive life of the well and reach values close to 100% to the end of its economical life. The water treatment is aimed at recovering part of the oil present therein in the form of emulsion and condition it for reinjection into the reservoir or disposal at sea (Teixeira, 2013).

Environmental regulations for disposal of produced water in the sea vary according to the country being developed and supervised by government environmental regulators. In the case of disposal, the limit is up to 20 mg/L of oil and grease in the produced water, under Resolution 430/2011 of the National Council of Environment of Brazil. Specifically for disposal on offshore oil platforms, applies Resolution 393/2007 of the National Environmental Council establishing the simple arithmetic average of the monthly oil content and greases up to 29 mg/L, with a maximum daily value of 42 mg/L (CONAMA, 2014).

Currently, hydrocyclones and electrostatic treaters are the separation equipment oil/water most used by the oil industry. The hydrocyclones seek to recover the water oil residues through the action of centrifugal force causes the heavier fluid to enter tangentially into the larger diameter section of the equipment, get in contact with the walls of the liner and follow spiral flow toward the smaller diameter portions, while the less dense flowing to the center of the liner forming a reverse axial flow, thereby separating the two liquid phases. The hydrocyclones can reduce one TOG up to 1000 ppm to between 100 and 200 ppm, depending on the equipment design (Teixeira, 2013).

The performance of a hydrocyclone is mainly influenced by the geometry of the equipment, density difference of the phases, the operating conditions such as input flow, concentration and diameter distribution of the dispersed phase in addition to the output pressure.

According to Svarovsky (2000), the principle and the basic design of conventional hydrocyclone have almost 120 years, since the first patent is dated 1891. In the mid-40s, around the time of World War II, the hydrocyclones came to be used in the industrial environment.

In the 70s, the British government encouraged studies to develop a device that collects contaminated water, withdraw the oil and give back to the sea almost clean. And Prof. Thew pioneer and patentee of an outfit that would become known as hydrocyclone Calman - Thew (Moraes, 2006). But it was in the late 90s that the hydrocyclone became popular, being adhered to certain industrial functions, beginning in minerals processing and then in petrochemical, chemical, power generation, among others.

The scope of the hydrocyclones is vast. These devices are used for solid-liquid separations as concentrator classifier or cleaner, solid-solid separations, liquid-liquid separation and gas-liquid systems to remove dissolved gases (Castilho & Medronho, 2000 and Heiskanen, 1993).

On several occasions can not be experimentally produce what you want, so for this, the computer serves as a basic tool. In addition, with the advancement of the same processing power and advances in numerical algorithms and techniques, tools of computational fluid dynamics (CFD) are increasingly being used to solve problems involving fluid flow in complex conditions. Even though the numerical simulation does not replace experiments entirely, it reduces costs for the experimental design variables investigations and its optimization, and allows studies to improve operational conditions.

2. Methodology

The study was conducted following the methodological steps of geometry development, domain definition and mesh simulation, definition of representative mathematical models of the problem in question and their solutions. For this was used CFX® 12.0.1 ANSYS software.

Table 1 shows the defined set parameters, test parameters (factors) and the simulation parameters.

Table 1 - development parameters and simulation.

Fixed parameters	**Value (cm)**
Nominal diameter of the hydrocyclone	20,00
Feed diameter	5,00
Base trunk cone diameter	18,00
Vortex finder length	5,00
Cylinder length	5,00
Trunk cone diameter	10,0
Test Parameters	**Value (cm)**
Diâmetro do *overflow*	[3,00 – 5,00]
Diâmetro do *underflow*	[2,00 – 4,00]
Comprimento de cone	[50,00 – 70,00]
Simulation Parameters	**Value**
Volumetric flow rate of feed	$6{,}0 m^3.h^{-1}$
Water phase	continuous fluid
Initial molar fraction of water	0,95
Specific mass of water	$997 kg.m^{-3}$
Water molar mass	$18{,}02 kg.kmol^{-1}$
Oil phase	dispersed fluid
Diameter of oil droplet	300µm
Initial molar fraction of oil	0,05
Oil specific gravity	$850 kg.m^{-3}$
Oil molar mass	$1 kg.kmol^{-1}$
Oil viscosity	13,4cp
Initial turbulence model	k-ε
Secondary turbulence model	SSG

With the test parameters was developed the design of experiments making use of the Minitab 17 software, defined by three variable factors, two levels and a variable response (separation efficiency), resulting in eight computer-numerical experiments, as shown in Table 2. The separation efficiency was determined by the ratio of the fluid (f), defined as the oil flow in the overflow relative to the oil flow in the feed, for each numerical experiment.

Table 2 – Design of the experiments.

Experiment	D_o (cm)	D_u (cm)	L (cm)
1	5,00	2,00	50,00
2	3,00	2,00	50,00
3	5,00	4,00	50,00
4	3,00	4,00	50,00
5	3,00	4,00	70,00
6	5,00	2,00	70,00
7	3,00	2,00	70,00
8	5,00	4,00	70,00

Top of execution of the first experiment was performed mesh test, in order to ensure that the mesh set did not influence the results. The Table 3 shows the mesh statistics for a set of experiments, and Figure 1 shows the geometry and mesh, especially the mesh set for the overflow. In the feed and underflow regions, the mesh was set identical to overflow.

It is observed in Figure 1 that close to the walls of the inputs and outputs there is a further refinement of the mesh. These forms are called inflated boundaries. This further refinement close to the walls allows better results in these regions of higher gradients.

Table 3 - Statistical mesh elements.

Number of Nodes	Tetrahedrons	Pyramids and Prisms	Total of Elements
115511	377250	91790	469040

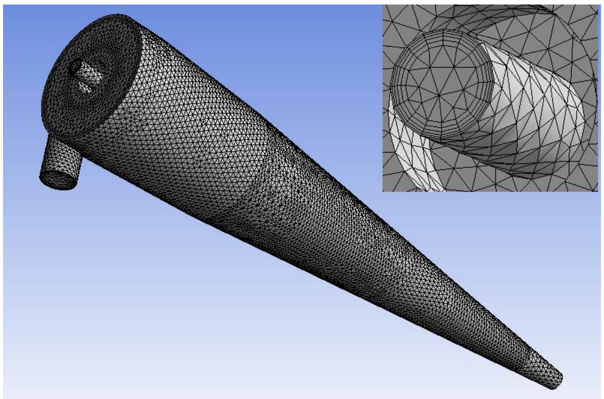


Figure 1 - Geometry and mesh of one of the experiments.

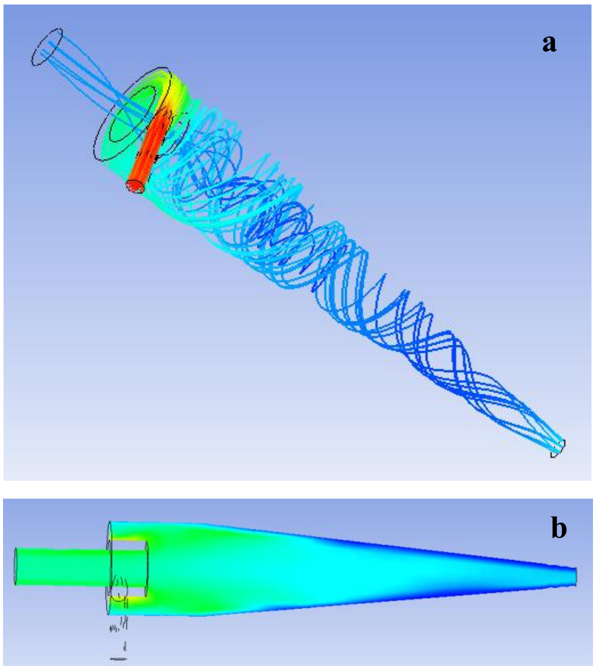
With the results of each experiment, the rate of fluid was calculated and the degree of influence of each variable and its interactions was determined.

3. Results and Discussion

The numerical experiments provided the mass flow rates of oil and water in the overflow and underflow, allowing the calculation of the variable desired response: reason fluid, shown in Table 1.

Figure 2 shows the qualitative results of the numerical experiments. It is observed in Figure 2a a flow rate of variation of power fluid to the hydrocyclone discharges. The feed is observed that the flow rates are larger, while the overflow and underflow are smaller. In the center of the hydrocyclone is observed a reverse flow, indicating that the oil phase (less dense) is displaced to overflow the water phase (dense), which covers the regions close to the walls of the equipment.

In Figure 2b it is observed the mass fraction distribution of oil phase, indicating higher concentrations at the center of the hydrocyclone overflow. The opposite occurs with the mass fraction of water, as shown in Figure 2c.



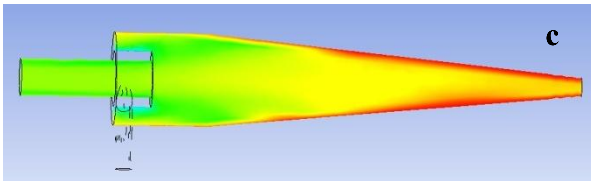


Figure 2 - Qualitative results of the simulations.

The best result, rightly fluid 77.78% was obtained with the experiment 6, by reducing the mass fraction of oil 1.16%. It is noted that this experiment was adopted the largest diameter of overflow, underflow smaller diameter and longer cone length from the simulated factors.

The results obtained from the experiment 1 can also be considered satisfactory. Also in this experiment it was observed that the largest diameter of overflow combined with the underflow smaller diameter produces good results. However, in this case, the lower cone length reduced the ratio of fluid relative to the result of the experiment 6. Nevertheless, it shows that the main reason dependence of fluid is connected with the underflow and overflow diameters and cone length is not influent. This result is encouraging the development of compact hydrocyclone, objective of this work.

It can also be seen in Table 3, with experiments 4 and 5, that larger diameters underflow overflow diameters suggest efficiency hydrocyclone zero, regardless of the cone length.

Table 4 - Ratio of fluid for each numerical experiment.

Experimento	**D_o (cm)**	**D_u (cm)**	**L (cm)**	**R_f (%)**	**X_o *undeflow* (%)**
1	5,00	2,00	50,00	70,97	1,50
2	3,00	2,00	50,00	20,43	4,02
3	5,00	4,00	50,00	27,41	3,68
4	3,00	4,00	50,00	0,00	5,00
5	3,00	4,00	70,00	0,00	5,00
6	5,00	2,00	70,00	77,78	1,16
7	3,00	2,00	70,00	21,12	3,99
8	5,00	4,00	70,00	36,32	3,24

Figure 3 shows, through Pareto chart of the effects of each factor and their interactions, because the fluid is primarily influenced by the underflow and overflow diameters and their interactions. Cone length influences and other interactions are considered insignificant.

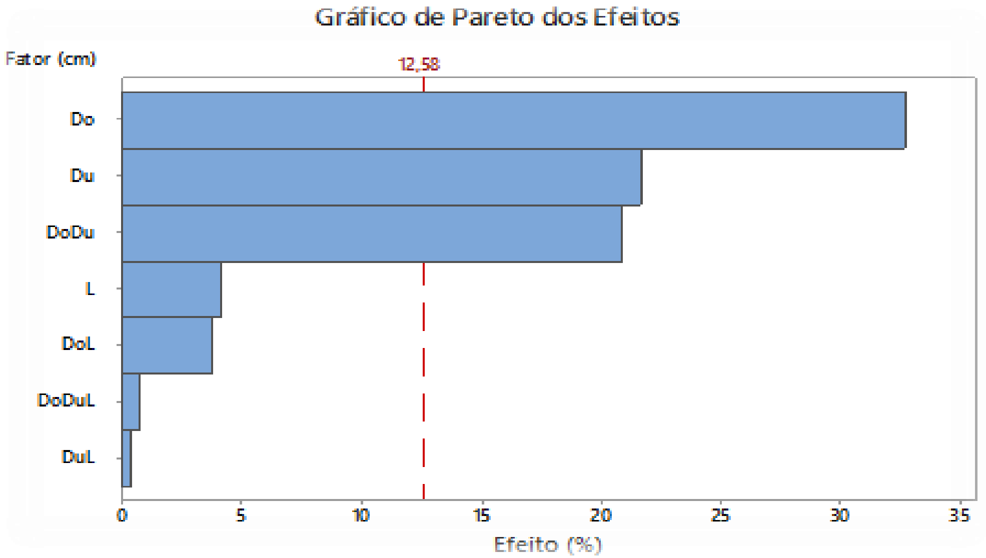


Figure 3 - Pareto chart for the significance of factors.

In Figure 4 we observe the main effects, indicating overflow diameter greater relevance factor, followed by an underflow diameter and finally, less effect attributed to the cone length.

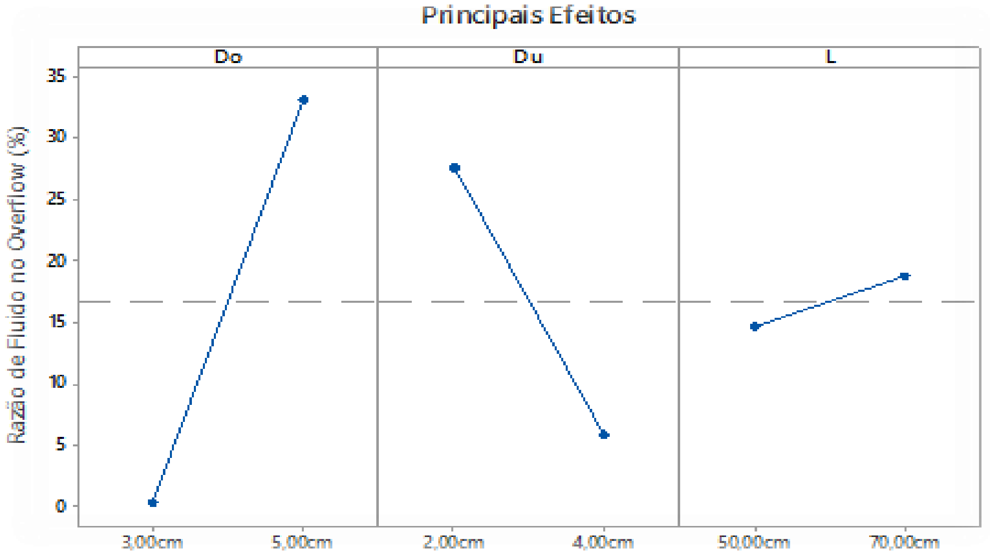


Figure 4 - Effect of the factors in the fluid ratio.

In the Figure 5 observe the effects of interaction of defined factors. Noteworthy is again the effect of the interaction between the diameter of the overflow and underflow diameter, indicating that there is a large influence due to this interaction in the fluid.

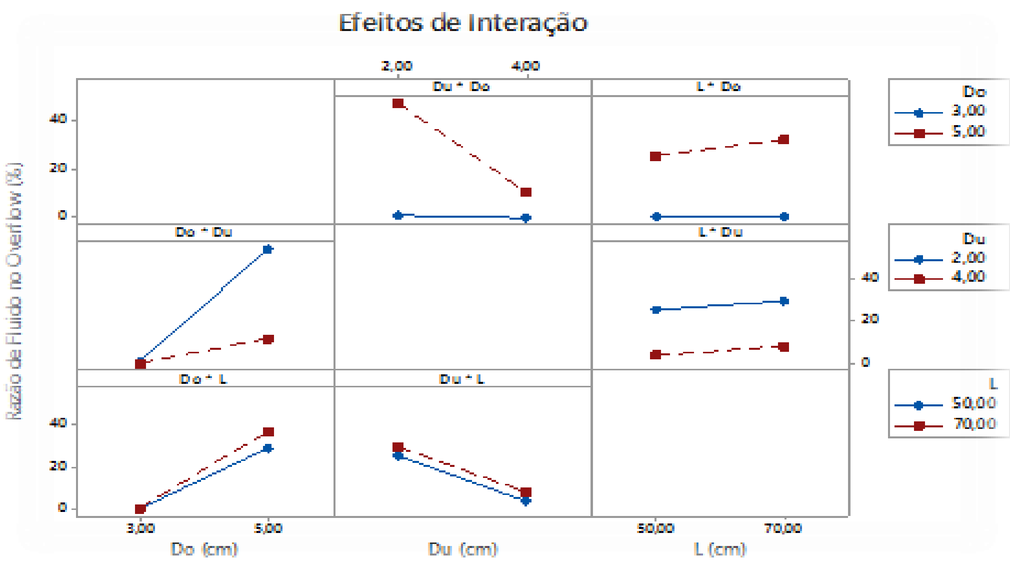


Figure 5 - Effects of interaction between factors.

4. Conclusions

The theme worked showed relevant results to the applicability of equipment sized to separate water/oil. It has been shown that computational fluid dynamics is a class of powerful and efficient tools for the analysis and design of industrial equipment in an economically viable manner. And the principal factor that influences the good separation is the overflow and underflow diameters.

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