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FEASIBILITY OF USING A HYDROCYCLONE AS A CORE ANNULAR FLOW PROMOTER IN VERTICAL PIPES. AN EXPERIMENTAL INVESTIGATION

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Abstract. *The shortage of new light oil deposits has led to the exploration of heavy oil reserves, which exceed 400 billion barrels not yet produced in the world. However, the transportation and refining of heavy oil are very expensive. Due to this, chemical and petrochemical industries are looking for technologies to reduce operating costs. The concept of flowing oil through a core annular flow pattern is one of the most promising techniques to reduce power consumption during the transport of viscous fluids in pipelines. In this work, a hydrocyclone device was employed to promote a core annular pattern in a vertical section of an experimental bench using different compositions of an oil-water mixture. To evaluate the efficiency of the hydrocyclone, a flow fractionator device was installed at the end of the pipeline loop and had the objective of separating the entire flow into two sections: annular and core. The obtained data showed that the hydrocyclone attended the proposal of organizing the biphasic flow towards a core annular pattern, reducing in about 70 % the amount of oil in the annular section for low oil concentration mixtures as low as 20 %.*

Keywords: Liquid-liquid flow; Core-annular pattern; Hydrocyclone; Heavy oil; Transportation of oil-water mixtures

1. INTRODUCTION

The lack of new light oil reserves is leading to an exploitation increase of heavy oil reservoirs, which represents about 70 % of the not-yet-tapped oil resources in the world (BP Global). Techniques to energy saving improvements on heavy oil transportation are in general costly and aim to reduce the pressure drop in the flow line with, for example, the addition of light diluents/dispersants or gas in the media, or heating the pipeline. The first method depends on the availability of light oil in the same production area, while the second is excessively expensive and restricted to short distances (Rodriguez and Bannwart, 2006). For this reason, it is necessary to develop alternative methods that enable the production and displacement of this good with less energy consumption, in lower operating times and regardful to environmental issues.

The technique of transporting oil in a core annular pattern with water seems to be one of the promising tools to decrease the pumping power consumption observed in monophasic oil flow. In this technique, water is carefully injected to the oil, so that it performs an annular film along the pipe wall, encapsulating the core region where the oil flows. In this configuration, since the oil barely touches the pipe wall, the wall shear is comparable to the shear encountered on pure water flow, saving energy greatly in comparison to the other transportation processes (Ghosh et al., 2008).

The first work related to the use of a core annular pattern for oil transportation dates from the early twentieth century with the patent of Isaacs and Speed (1904). They were the pioneers to discuss this innovative method, which consisted of a helically riffled pipe wall capable to generated sufficient centrifugal force to direct the denser fluid, water, to the duct wall, and concentrate the less dense, heavy oil, in the central region. Since then, several studies have been carried out.

Russel and Charles, in 1959, developed a mathematical model for two immiscible liquids flowing horizontally between parallel plates and inside a circular duct. Through the proposed equations, the group could quantify the pressure drop reduction and the energy savings of the core annular flow technique. Later, the same group described several oil-water flow patterns for different oil viscosities and horizontal arrangement (Charles et al., 1961). They concluded that the core annular profile could not be established below a critical oil superficial velocity, specific for each water fraction. Subsequently, Bai et al. (1992) complemented the flow pattern chart with the inclusion of ascending and descending vertical flow profiles.

Prada and Bannwart (2001) developed a theoretical model to calculate the pressure drop in ascending vertical flow. They showed that even using a small fraction of water in the oil stream, it was possible to reduce the pressure drop by 45 times when compared to the single-phase oil flow. Next, Rodriguez and Bannwart (2006) conducted an experimental study on water-oil interfacial phenomena of an annular flow. They evaluated the amplitude, the wavelength, the speed and the profile of the waves. According to the authors, the amplitude of the wave increases abruptly up to a certain volume of fluid injection. As soon as the oil fraction tends to be larger than the water fraction, the amplitude decreases more slowly. More recently,Vuong et al. (2016) measured the pressure drop and the water holdup of a biphasic oil-water flow in a horizontal installation. The group observed the flow patterns and the influence of the temperature in the biphasic system and concluded that viscosity of the oil, as well as the fluid flow and the flow profile, play an important role in determining the pressure drop.

The drawback of the core flow technique for oil transportation is to keep the organized profile along the whole pipeline, which in real installations can reach several kilometers from the point of departure to its point of arrival. Therefore, it is mandatory the use of devices or the existence of reinjection stations to ensure the development of the core annular flow pattern during its entire course.

Hydrocyclones are used for solid/liquid, solid/solid/liquid, liquid/liquid and gas/liquid separations. The studies about their operation began in the end of the nineteenth century, and, nowadays, its application is rapidly increasing widespread in several areas of industry, especially in petroleum and mineral processing fields. These devices are in general more compact than the traditional gravitational separators used for the same function on offshore platforms for example, and are considered a feasible alternative, economically attractive and versatile because it does not have moving parts (Odilon et al., 2007).

The hydrocyclone geometry consists of a cylindrical part, which defines their diameter, coupled to a conical part (Castilho et al., 2005). The mixture is injected tangentially into the upper part of the cylindrical section and, because of the tangential entry, a strong swirling motion is developed within the cyclone (Svarovsky, 1977). According to Moraes et al. (2013), the velocity around the vertical axis is greater than the feed velocity, thus, the centrifugal field becomes the mechanism of the radial segregation, concentrating the light phase next to the axis and the heavy one next to the walls. Another important characteristic of the flow in cyclonic devices is the existence of two opposite flows in axial direction, which is caused by the pressure gradient in the hydrocyclone wall and the pressure gradient in the hydrocyclone vertical axis that point opposite directions. Thus, the portion next to the axis goes to the upper of the device (overflow) and the portion next to the wall goes to the lower outlet (underflow).

The studies available in the literature about the employment of hydrocyclones in the oil industry considers this device as a simple phase separator, emphasizing mostly environmental issues through the treatment of effluents. Hence, the proposal of this work through the usage of a hydrocyclone as a core annular flow pattern promoter seems to be innovative and an interesting alternative to the traditional methods for guarantee of flow.

The present study aimed to verify the performance of a hydrocyclone as a flow organizer instrument towards a core annular flow pattern accomplishment in a vertical pipe.

2. EXPERIMENTAL SETUP AND PROCEDURE

2.1 The Biphasic Flow Facility

The core annular flow experimental setup was installed at the Unit Operations Laboratory of the Santa Cecilia University (UNISANTA), Brazil, and comprises two storage tanks, one separation tank and a closed loop of vertical pipes with 27 mm internal diameter and, approximately, 4 m length for biphasic flow. The complete operating line includes a 500-mm-long pipe segment with static mixers and a coupling site that can be used for both the standard straight pipe and the hydrocyclone as shown in Fig. 1. The experiments were carried out with water being pumped from the storage tank by a regenerative turbine pump to the operating line. Meanwhile, Lubricant Oil with viscosity 2500 mPa.s and density 940 kg/m³ (at the temperature of the experiments) was also pumped by another regenerative turbine pump to the biphasic system, so that water and oil meet in the mixing section, where the oil-water mixture was developed. Each pump motor was individually controlled by frequency inverters, for the mass flow variations and the mixture composition. The whole bench was constructed using transparent acrylic sheets and transparent PVC pipes to allow visual monitoring.

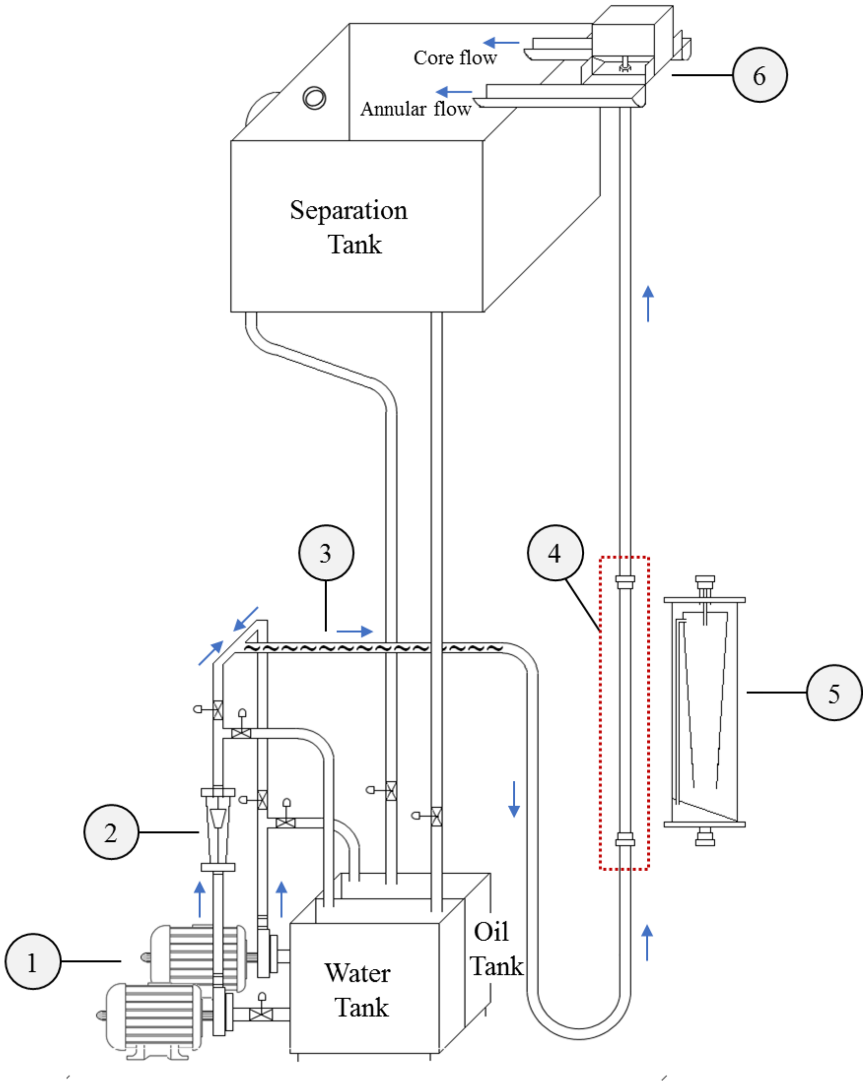

Figure 1. Schematic of Biphasic Flow Experimental Bench. Composed by: 1) Regenerative turbine pumps with 670 W motors, 2) Rotameter for water line, 3) Mixing Section – static mixers, 4) Coupling Site with a standard straight pipe, 5) Hydrocyclone for the Coupling Site, 6) Flow Fractionator Device with annular and core return gutters.

The procedure to determine the mass flow rate consisted in collecting, in a given time, a certain amount of the mixture mass on the return gutters. The overall mass flow rate was the sum of those obtained from both sides, while the individual contributions either on the core or on the annulus side were measured 24 h after the experiment, when the phases collected were completely separated. The option to control the system by the outlet mass flow rate was due the need to quantify the water and the oil portions in each section of the flow, although the rotameter allowed the inlet water flow measurement in redundancy. All the runs were performed with the water pump frequency inverter set at 20 rps, but it did not provide a fixed water flow rate because of the difficulty of flow imposed by the increase of oil in the biphasic system. Therefore, the range of water mass flow was 0.03 to 0.20 kg/s. The oil pump frequency inverter varied 15 to 45 rps, which was determined as the bench operation limit. The oil flow rate was 0.02 to 0.19 kg/s.

In addition, the tests were performed in triplicate to regard the experimental uncertainties in the obtained responses. Thus, the whole experimental data were completely inserted in the presented graphs and were responsible for the generation of the regressions used to analyze the results.

2.2 Coupling site

The coupling site corresponds to an, approximately, 1-m-lenght pipe section where two replacement units, one at a time, can be attached to the pipe loop. One replacement unit is a standard straight pipe, which simulates the traditional flow. It was used as a standard of comparison. The second replacement unit is the hydrocyclone, whose efficiency on operating the mixture flow in core annular pattern was the aim of this study.

The hydrocyclone was designed and built in the Unit Operations Laboratory of the Santa Cecilia University and has its dimensions based on the US Patent number 4764287 (Colman and Thew, 1988). The project was adapted to incorporate a jacket around the structure and, thus, to manage the water underflow to return to the top of the apparatus in the void between the jacket and the conical part. An inclined plate was installed on the bottom of the device to conduct, through a side channel, the feed up to the proper inlet site. On the top outlet, a concentric tube along the vertical axis was placed to collect mainly oil from the upper conical part and to conduct it to the sequential pipeline. Figure 2 shows a picture of the Hydrocyclone with its operating scheme and its detailed drawing.

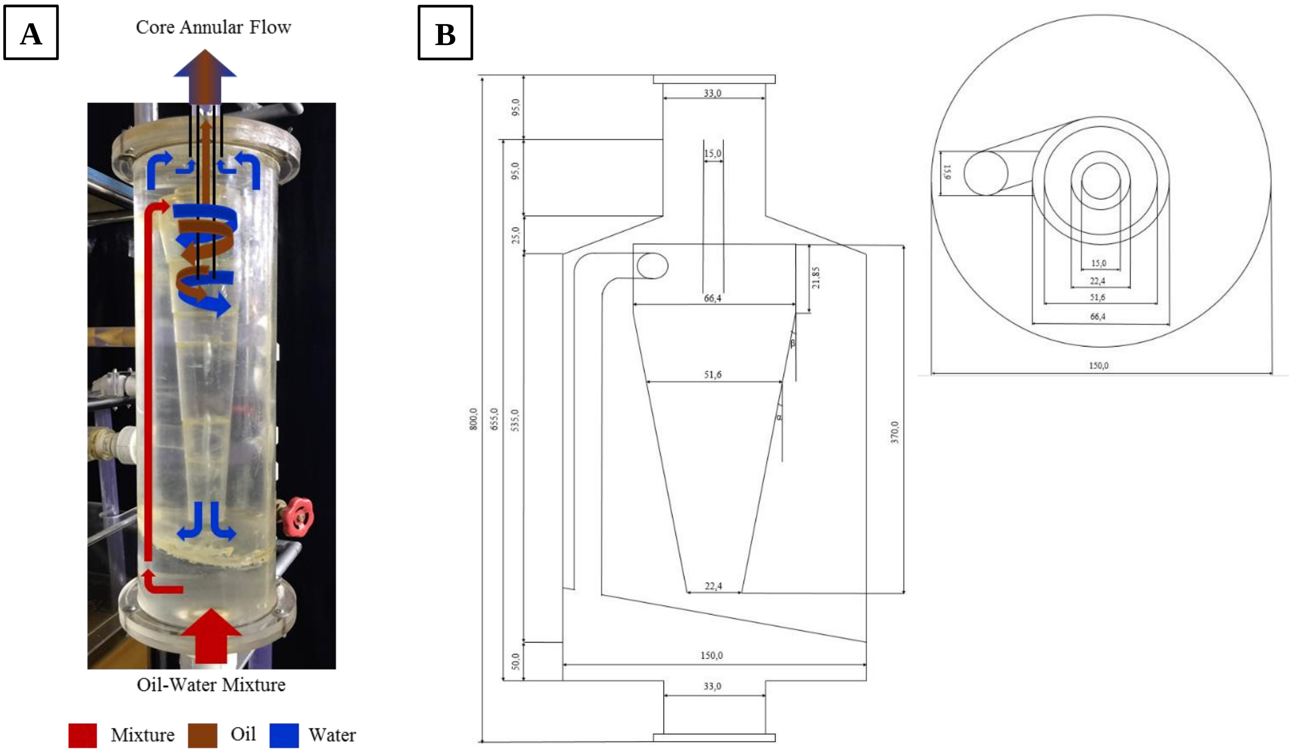

Figure 2. A) Hydrocyclone picture with the fluid paths during operation. B) Hydrocyclone detailed drawing, front and top views with the dimensions in mm.

2.3 Flow Fractionator Device

The Flow Fractionator Device (Fig. 3) was also designed and built in the Unit Operations Laboratory of the Santa Cecilia University, Brazil, and had the objective of separating the entire flow into two sections: annular and core. It was constructed using transparent acrylic sheets to allow observations during its operation. As one can see, in the bottom of the instrument there is a smaller tube installed concentrically with the pipe, which is responsible for separating the flow either to the annular section, or to the core section. Thus, the fluids flow through the corresponding section until they collide with an inclined wall that conduct them to two side exits.

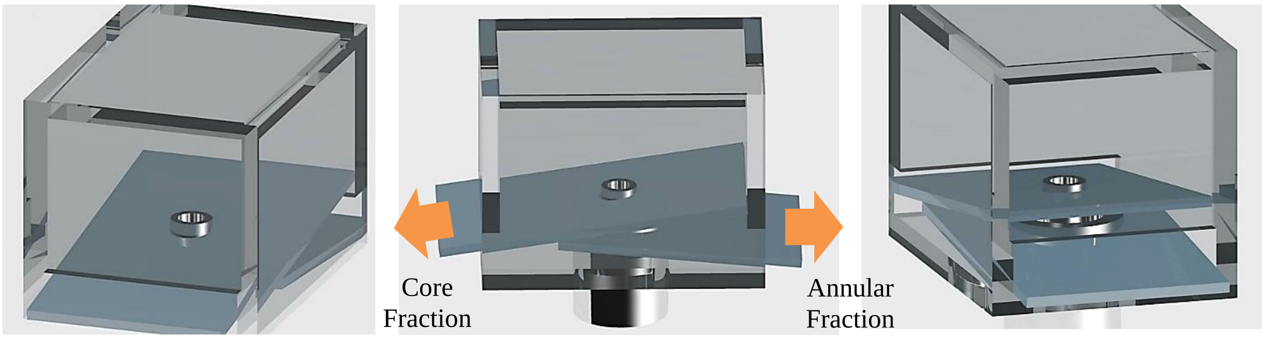

Figure 3. 3D Drawings of the Flow Fractionator Device built in the Unit Operations Laboratory of Santa Cecilia University.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 4 presents the experimental data for the mass flow distribution over the annular and the core sections using the standard straight pipe at the coupling site. These results represent the behavior that the biphasic flow would demonstrate when being transported through the traditional method. As one can observe, the pump rotation described a linear relationship with the mass flow rate, moreover, it exhibited similar angular coefficients for both overall and partial flows. It was also noticed that the increase in fluid flow propagated proportionally in the sections, with approximately 60% of the mass flow being driven to the core, which corresponds to about 60% of the total area. Hence, these evidences suggest absence of preferential channel in the fractionator device inlet and impartiality of the apparatus on the obtained data.

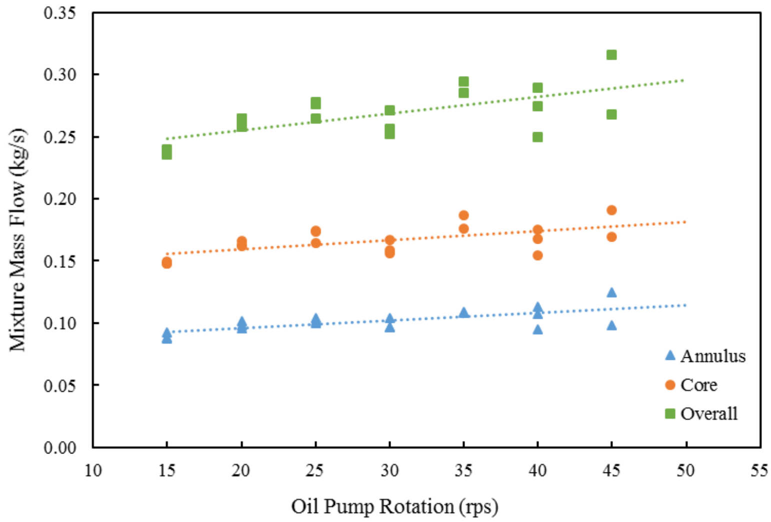

Figure 4. Effect of the addition of oil on the overall and sections mass flow for the traditional method of oil-water mixture transportation.

In Fig. 5, the square data represent the overall composition changes on the biphasic mixture due to oil insertion in the system, while the round and triangle data show the behavior in the core and annular sections, respectively. It was possible to observe that, for all the tests, the oil fraction in the core was higher than that showed by the overall flow, which corresponds to the average oil portion in the mixture. On the other hand, the oil fraction in the ring was always lower. In such manner, it suggests that the oil of an oil-water mixture naturally tends to flow preferentially through the central part of the pipe in vertical installations. This observation agrees with other studies of the literature, for example the one published by Renardy (1997), which reports that, in a vertical flow, the fluid of lower viscosity tends to encapsulate the one of greater viscosity directing it, therefore, towards the center of the tube.

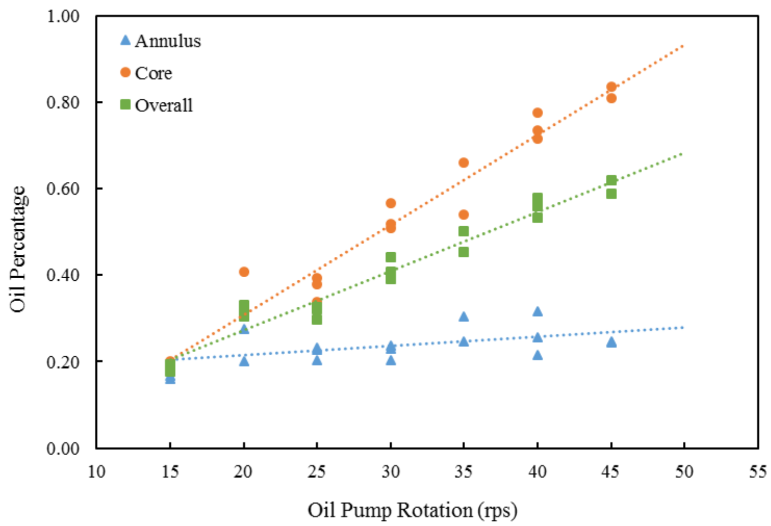

Figure 5. Oil distribution in the sections of the pipe for the traditional method of oil-water mixture transportation.

Figure 6 shows the mixture mass flow rate behavior as a function of the oil increase for the hydrocyclone as the replacement unit at the coupling site. From the experimental data, one can notice that, as soon as the overall mass flow rate reached, approximately, 0.23 kg/s (that corresponds to about 40% of the oil in the overall mixture), there was an abrupt decrease in the flow that could be associated to the hydrocyclone operating limit and to the great pressure drop that it generated. Accordingly, the hydrocyclone device proved to be efficient in the separation of oil-water mixtures with maximum 40% of oil.

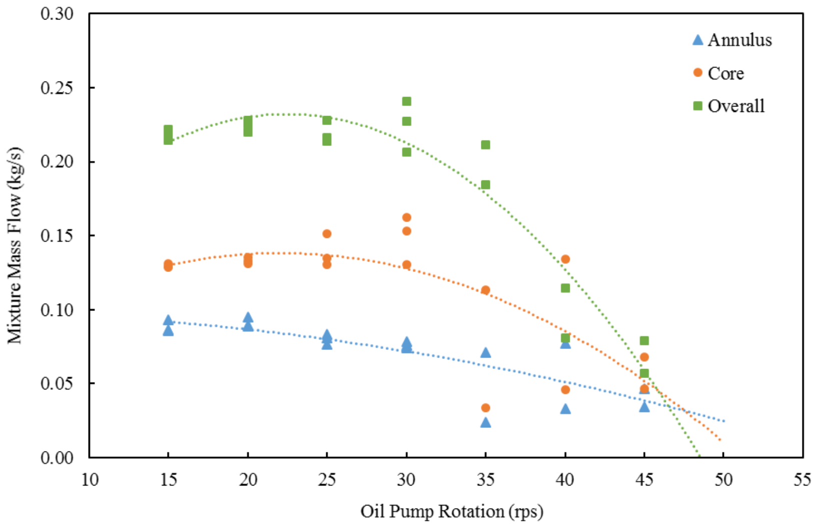

Figure 6. Mass flow rate variations as a function of the oil pump rotation for the overall and the partial sections of the flow using the hydrocyclone attached to the coupling site.

Figure 7 presents a comparison between the percentage of oil found in the fractions of the flow for both transport techniques: the traditional one with a standard straight pipe attached to the coupling site and the one proposed in this work, with the hydrocyclone being connected at the site. Through these experimental data, it was evident that at concentrations of up to 40%, both techniques did not show significant composition differences in the overall flow, which does not occur from that point due to hydrocyclone operation limit. In the individual sections, the fragmentation of the oil between the annulus and the core suffered a positive influence of the hydrocyclone use, since it was efficient in bringing oil that would flow through the annulus to the core region. This change in the fluid composition of the flow regions generates the expectation that there will be a friction reduction in the pipe wall, leading to pumping energy savings.

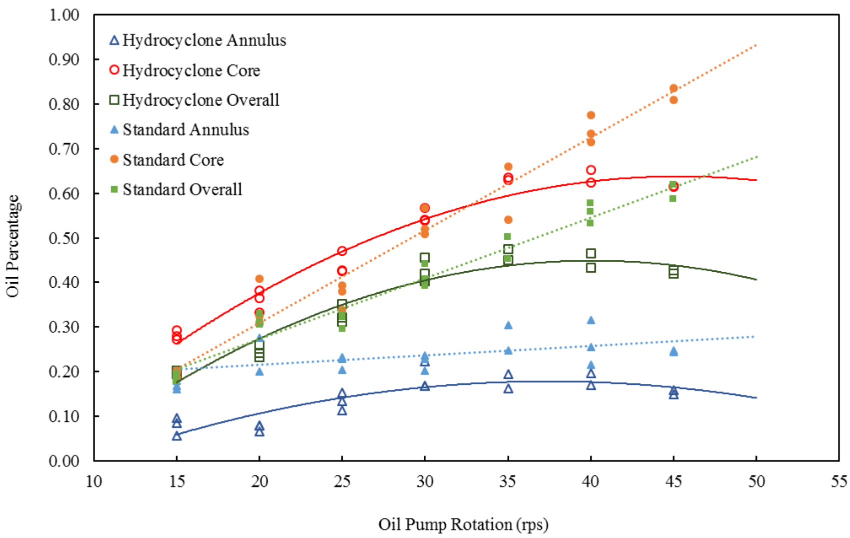

Figure 7. Comparison between the traditional and the hydrocyclone-based flow in the average composition of the flow sections.

Figure 8 presents the numerically efficiency of the hydrocyclone in adjusting the oil-water mixture towards a flow with a rich oil core and a poor oil annulus configuration, so, in core annular flow pattern. The lower was the oil fraction in the mixture, the better was the fluid separation, achieving a 70 % reduction of oil in the annular region when the feed oil fraction was 20 %. The effect of the hydrocyclone in promoting core annular flow pattern decreased with the gradual addition of oil in the system, showing the best results for low oil mixture compositions. However, the device still showed satisfactory results of 20 % reduction for mixtures with 40 % of oil.

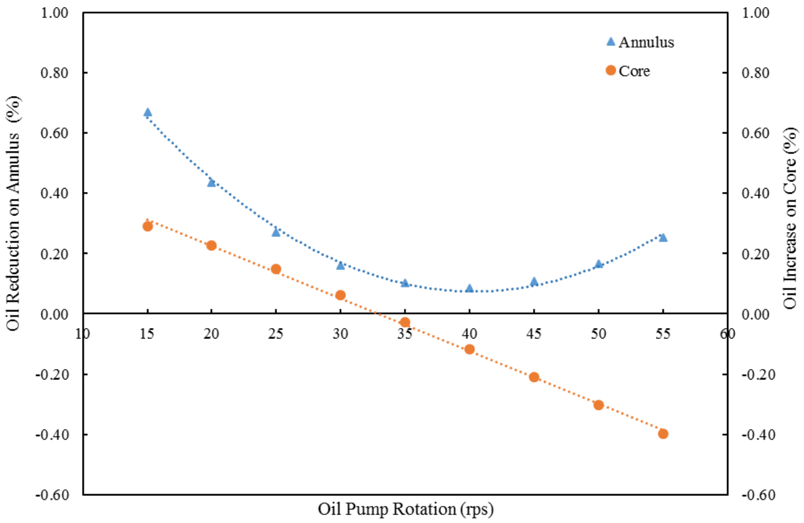

Figure 8. Efficiency of the Hydrocyclone in separating the biphasic mixture and directing oil to the central region of the flow.

4. CONCLUSIONS

Many applications of hydrocyclones in the oil industry are based on its ability to separate different components of a mixture. However, the usage of this device as a core annular flow pattern promoter seemed to be an interesting alternative to core annular nozzles and to conventional heavy oil transportation. The innovative approach proposed in the present work for the hydrocyclone, seemed to be feasible for oil-water mixtures with oil contents of maximum 40 %. For low oil mixture compositions, the device showed its best remark, providing, approximately, 70 % reduction of oil in the annular region when the feed oil fraction was as low as 20 %.

5. REFERENCES

Bai, R., Chen, K., Joseph, D.D., 1992. “Lubricated pipelining: stability of core-annular flow: Part 5, Experiments and comparison with theory”. *Journal of Fluid Mechanics*. Vol. 240, p. 97-132.

BP Global. “Researching new heavy oil recovery techniques”. 08 Jan. 2017 <http://www.bp.com/en/global/corporate/sustainability/the-energy-challenge-and-climate-change/case-studies/researching-new-heavy-oil-recovery-techniques.html>.

Castilho, L.R., Medronho, R.A, 2005. “A simple procedure for design and performance prediction of Bradley and rietema hydrocyclones”**.** *Journal of Mineral Engineering*. Vol. 13, n. 2, p. 183-191.

Charles, M.E., Govier, G.W., Hodgson, G.W, 1961. The horizontal pipeline flow of equal density of oil–water mixtures. *Canadian Journal of Chemical Engineering.* Vol. 39, n. 1, p. 27-36.

Colman, D. A. and Thew, M. T., 1988. “Cyclone Separator”. US. Pat. 4764287.

Ghosh, S., Mandal, T.K., Das, G. and Das, P.K., 2009. “Review of Oil Water Core Annular Flow”, *Renewable and Sustainable Energy Reviews*, Vol. 13, n. 8, p. 1957- 1965.

Isaacs, J. D.; Speed, J. B. “Method of Piping Fluids”. US Pat. 759.374, 1904.

Moraes, C.A.C., Martins, L.P.M., Melo, D.C., Silva, F.S., Oliveira Junior, J.A.A., Souza, M.A., Barca, L.F., Souza, A.M.R.F., Almeida, C.S, 2013. “Development of high, médium and low oil content hydrocyclones”, In *Boletim Técnico da Produção de Petróleo*, Rio de Janeiro – RJ, Brazil. Vol 3, p. 259-287.

Odilon, A.S., Sampaio, J.A., Oliveira, G.P, 2007. *Classification of hydrocyclone*. Mineral Engineering. CETEM/MCT.

Prada, V.J.W., Bannwart, A.C, 2001. “Modeling of vertical core-annular flows and application to heavy oil production”. *Journal Energy Resour Technologycal, ASME, 2001.*Vol. 123, p. 194.

Renardy, Y. Y., 1997. “Snakes and corkscrews in core–annular down-flow of two fluids”. *Journal of Fluid Mechanics*, Vol. 340, p. 297–317.

Rodriguez, O.M.H., Bannwart, A.C, 2006. “Analytical model for interfacial waves in vertical core flow”. *Journal Petroleum Science Engineering.* Vol. 32, p. 323-343.

Russell, T.W.F., Charles, M.E., 1959. “The effect of less viscous liquid in the laminar flow of two immiscible liquids”. *Canadian Journal Chemical Engineering*. p. 18-24.

Svarovsky L., 1977. Hydrocyclones. *FPS Institute*, England and University of Pardubice, Czech Republic. Vol. 12, p. 193-244.

Vuong, D.H., Zhang, H.Q., Sarica, C., Li, M., 2009. “Experimental study on high viscosity oil/wáter flow in a horizontal and vertical pipes”. *Journal SPE Annual Technical Conference and Exhibition,* University of Tulsa. p. 1-10.

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