

STUDY OF TWO-PHASE FLOW IN ANNULAR SPACES THROUGH MECHANISTIC APPROACH

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Abstract. *Even with the advancement of technology, the oil industry still has many challenges in many different areas, such as production. One of these problems that can occur is the multiphase flow, making it difficult to explicitness of basic parameters for the flow characterization. In annular geometry, the multiphase flow can occur in wells using submerged centrifugal pumping units, in underbalanced operations, subsea separators and other cases. Therefore, the detailed study of this flow geometry has great importance for the pressure drop prediction. This work aims to study the behaviour of annular flow pattern in two-phase flow of gas/liquid in annular geometries. The methodology follow the mechanistic approaches found in literature (Yu et al., 2010), (Lage and Time, 2000) and (Caetano, 1986) using computational tools, in this case, VBA (Visual Basic for Applications) routines, along with available experimental data in work of Caetano (1986). The proposed strategy aims to obtain a qualitative and quantitative analysis, and identify the model that best represents the phenomena of petroleum production in annular space. The quantitative analysis, emphasized in the applicability of mechanistic approaches to annular systems, outstand the models accuracy. In the qualitative analysis, has been found that these approaches are more sensitive to the liquid film thickness, than the other parameters, such as the hydraulic diameter, demonstrating the importance of a reliable prediction of this variable, since the in situ measurement is complex, especially considering the scenario of offshore production.*

Keywords: *multiphase flow, annular geometry, annular flow pattern, mechanistic approach, simulation*

1. INTRODUCTION

The oil industry still has many challenges in several areas, from exploration to transportation and refining. The presence of multiphase flow in pipe production, complicates the prediction of the basic parameters for the flow characterizing. This type of flow may occur in many types of geometry being the most commons circular and annular geometries. According to Metin and Azbayoglu (2007), the two-phase flow phenomenon in tubes has been being widely investigated, but to the applicability of the two-phase flow in annular geometries there are many features to be studied.

According to Yu et al., (2010) and Metin and Azbayoglu (2007), the gas/liquid flow in annular geometries can be found in many practical situations, such as: oil production with high rate of gas; "gas kick" (uncontrolled gas influx into the well) in underbalanced drilling and at some methods of artificial lift.

The modeling methodology of this flow can be divided into two categories: empirical correlations and mechanistic models. The correlations strategy model the phenomenon through empirical equations without considering the phenomena physics. The mechanistic approaches postulate the existence of different flow patterns and formulate models for each pattern separately considering the physical phenomena. According to Brill and Mukherjee (1999), empirical correlations were frequently used to predict two-phase flows, but the correlations were used mainly for flow in pipes, extrapolating to annular geometries with the concept of hydraulic diameter. Figure 1 present the main flow patterns for upward gas/liquid flowing in vertical annular space at concentric pipe.

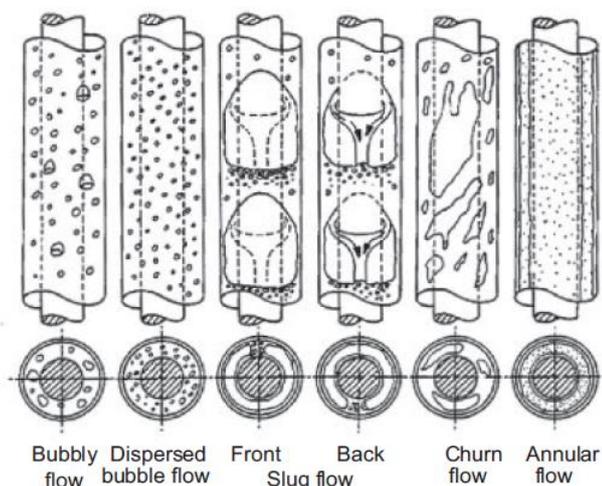


Figure 1 – Flow patterns for two phase flow in vertical annular space at concentric pipe (Caetano, 1986).

Among these main flow patterns, the focus of the present is about the annular flow pattern, which the pressure reduction below the bubble pressure, results at a high release of gas that was dissolved in oil. In this pattern, the dominant flow is the gas, because of its large amount and high speed. The main physical characteristic of this pattern is the presence of a liquid film on the pipe walls, and the formation of some liquid droplets dispersed among the gas core.

In this study, the main objective is the investigation of the sensitivity of the parameters of mechanistic models found in literature to analyze the annular flow pattern in the annular space, considering concentric pipes with upward vertical two-phase flow. The analysis was performed estimating the values of the pressure gradients and liquid holdup, aiming to determine the models accuracy and a better characterization about the liquid/gas flow.

2. METHODOLOGY

Considering the studies of Yu et al. (2010), Lage and Time (2000) and Caetano (1986), the respective models were selected, based on mechanistic approaches to annular two-phase flow. Based in these models, the calculating the pressure gradient and the liquid holdup, as well as the evaluation of the influence of the physical properties were performed.

The experimental data assumed to the models comparison were extracted form Caetano's work (1986), investigating the two-phase flow of water/air and kerosene/air, considering the annular geometry with the concentric pipe. The main parameters used in this study are shown in Table 1.

Table 1 - Parameters and their values.

Parameters	Values
Outside diameter	0,0762 mm
Inner diameter	0,0422 mm
Water density	996 kg/m ³
Kerosene density	820,5 kg/m ³
Air density	2 kg/m ³
Water viscosity	0,00082 Pa.s
Kerosene viscosity	0,0022 Pa.s
Air viscosity	0,000019 Pa.s
Water/Air tension	0,0714 N/m
Kerosene/Air tension	0,0263 N/m

The models implementation in this work, were performed using Visual Basic for Applications (VBA) routines, with the aim of systematization and standardization the calculation procedure for pressure gradient and the liquid holdup prediction. In order to present the models analysis, the results were presented at tables and graphs for a better understanding about the two-phase flow in annular geometries and evaluating some sensitivity parameter, such as the liquid film thickness and hydraulic diameter.

3. RESULTS

During the methodology implementation, was observed some features that increase the calculation complexity. These study took into account the physical characteristics of each flow pattern for the development of their equations. Therefore, their equations are complex and the models solution depends of several parameters that must be previously calculated, such as: friction factors, interfacial tension, in situ velocities and liquid droplets entrainment factor. However, modeling and simulating the mechanist strategy to annular flow at annular geometry was necessary to take some input parameters such as: geometrical characteristics, fluid properties, speed of fluids, and especially the thicknesses of the inner and outer liquid film. Although, it was possible to observe that these thicknesses are not measured neither easily found in the previous available works. Thus it can be seen that these approaches have a limitation regarding this parameter, because they are essential for the use of mechanistic approaches.

Considering Yu et al. (2010) model, it was necessary to create a code in MATLAB software perform the calculation procedure (iterative). But the pressure gradient prediction was not predicted due to the model limitation. Even though the liquid holdup values were obtained in a considerable range of acceptance.

Aiming a better understanding of the selected models, two types of studies were implemented: a qualitative and a quantitative analysis.

3.1 Quantitative analysis

In this analysis, the available data into Caetano's (1986) work has been used in order to obtain a comparison between of the pressure gradient and liquid holdup values, calculated and experimental values for each selected model

in this work. This analysis is interesting in this work because Lage and Time (2000) and Yu et al. (2010) models were based on Caetano's (1986) model and also use the data from this work. Then, the quantitative comparison between these models is a way to demonstrate how these models are more efficient than Caetano's (1986) model. Therefore, to make a quantitative analysis of the models in a better way, errors and deviations of each model will be calculated, using the equations presented in Yu et al. (2010).

Through modeling and simulation of mechanistic approaches to the water / air flow, it was possible to obtain a graph and its respective error table with the relationship between the experimental and calculated liquid holdup through the three models, represented by Figure 2 and Table 2.

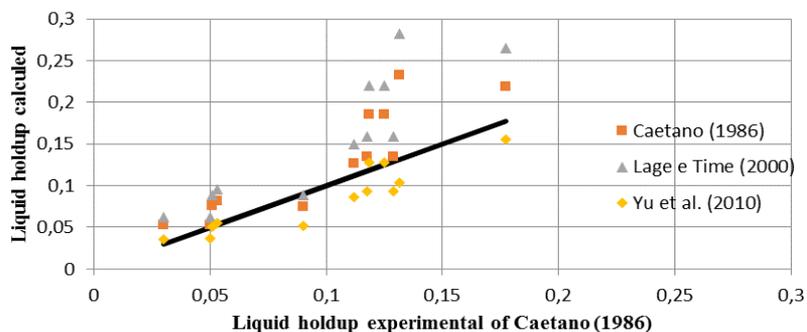


Figure 2 - Relationship between the liquid holdup calculated and experimental of water / air flow to the models of Caetano (1986), Lage and Time (2000) and Yu *et al.* (2010).

Table 2 - Errors and deviations of the liquid holdup for the water / air flow for each model.

Models	Average percentage error (%)	Percentage error average absolute (%)	Percentage of standard deviation (%)	Average error (-)	Average absolute error (-)	Standard deviation (-)
Caetano (1986)	7,56	13,10	8,20	0,01122	0,01621	0,01861
Lage and Time (2000)	27,18	27,83	29,48	0,03442	0,03501	0,03070
Yu <i>et al.</i> (2010)	-11,54	17,14	11,93	-0,0138	0,01707	0,017

First, in Caetano's (1986) model it is observed that at the beginning (until the holdup value of 0.1), the calculated values approach get closer to the experimental value, but above 0.1 the verification is the opposite. However, despite this dispersion in the end, it is also possible to see in Table 2 that this model is the one presenting lower error values and deviations, being for these experimental data used the model that has the best values of this parameter as a whole. Lage and Time's (2000) model, can be seen in Figure 2 a tendency to overestimate the results in relation to Caetano's (1986) model. This can be explained by differences between their equations for the liquid holdup, which in Lage and Time (2000) takes into account only the geometrical parameters of the system, while in Caetano (1986) takes into account the system's geometric speeds and the entrainment factor of the liquid droplet. So, can be said that the liquid holdup equation of Caetano (1986) is a more robust equation, when compared with Lage and Time (2000), what can be observed quantitatively in Table 2 when comparing the results with the experimental values. In relation to the model of Yu et al. (2010), it is observed in Figure 2 that this model has a good agreement with the experimental values, the iterative process for the calculation of this parameter can explain this behavior. Therefore, in Table 2 this model has low error and deviations values, it shows a worse result when compared with the results obtained by Caetano (1986).

The other parameter that was measured is the main purpose of the mechanistic approaches, the system pressure gradient. Therefore, by modeling and simulation of mechanistic approaches to water / air flow, it was possible to obtain a graph relating the pressure gradient of the experimental and calculated system for the Caetano's (1986) and Lage and Time's (2000) models, represented by Figure 3 and Table 3.

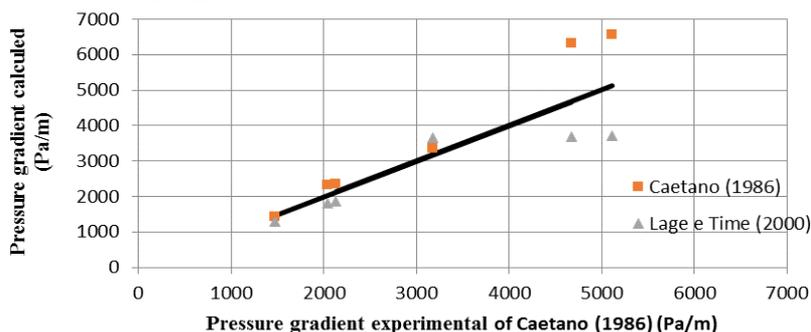


Figure 3 - Relationship between the pressure gradient calculated and the experimental of water / air flow to the models of Caetano (1986) and Lage and Time (2000).

Table 3 - Errors and deviations from the pressure gradient for the water / air flow for each model.

Models	Average percentage error (%)	Percentage error average absolute (%)	Percentage of standard deviation (%)	Average error (Pa/m)	Average absolute error (Pa/m)	Standard deviation (Pa/m)
Caetano (1986)	15,24	16,14	16,52	623,85	637,13	721,45
Lage and Time (2000)	-11,13	19,38	12,07	-421,68	581,38	668,05

In Figure 3, a comparison between the models can be made, it is observed that both models show values close to experimental ones, thus both models could be used in this situation. However, through the Table 3, it is possible to select the model, which shows the best values. In this case, Lage and Time's (2000) model is the one with the best measured values, thus proving that this model is a way of improving Caetano's (1986) model for the used situation, since this model was based on the data and used Caetano's (1986) model for its development.

With all of these measured and analyzed values, it points out that Lage and Time (2000) is not a better improvement of Caetano (1986) in a whole, as for the calculation of liquid holdup Caetano's (1986) model has better results in some situations, and has a better developed equation for this parameter. However, the model of Lage and Time (2000) has better calculated values for the pressure gradient to the selected data. As for the model of Yu et al. (2010), which was also based on Caetano's (1986) model and it was only possible to measure the liquid holdup in the system, it is reinforced that for the flow of water/air this gets good results for this variable, while to the flow of kerosene/air, shown in full work, the results were not satisfactory.

Therefore, it is observed that the mechanistic approaches can reach values close to the real, where errors and deviations are smaller when compared with the empirical correlations in most situations. Because of this, mechanistic approaches are considered the best measurement method of some units, because they take into account the physical characteristics of the system and the mechanisms that govern each flow pattern, and then errors and deviations are smaller compared with empirical correlations in most situations. Some observed considerations for using the mechanistic approaches are their input parameters of the models. As an example, the annular flow pattern one of the main input parameters in this case is the thickness of the liquid film. Being that, this parameter is difficult to determine, thus hindering the implementation of mechanistic approaches in this case. It is also highlighted, when the mechanistic approaches are used it is essential to apply more than one approach, in order to analyze the values obtained for each model to obtain more accurate considerable value to this situation.

3.2 Qualitative analysis

In the second part of the analysis of models, it has a qualitative analysis, in which are varying system parameters and physical properties of fluids in order to analyze the sensitivity of each model due these variations. However, in this work will only be shown the analysis of the physical parameters of the system, where the analysis of the fluid properties is available in the full work. Thus being able to point out which models are more disturbed according to the variation of these parameters. This analysis will be made only to the flow of water/air, because the purpose of this step is to analyze the influence of the parameters on each mechanistic approach, and in this work will only be shown the analysis to the system physical parameters, where the analysis of the properties fluid is available in full work.

Therefore, the main system physical parameters are changed, being them, the hydraulic diameter of the system (D_H , given by the difference between the external and the internal diameter system) and the thickness of the liquid film (δ).

3.2.1 Influence of hydraulic diameter of the system

In this situation, it is analyzed the influence of the hydraulic diameter of the system in the main parameters of the selected mechanistic approaches, being made a change of 32% in the value of the hydraulic diameter. First, it is checked the influence of variation of this parameter on the calculated liquid holdup values, represented by Figures 4, 5 and 6.

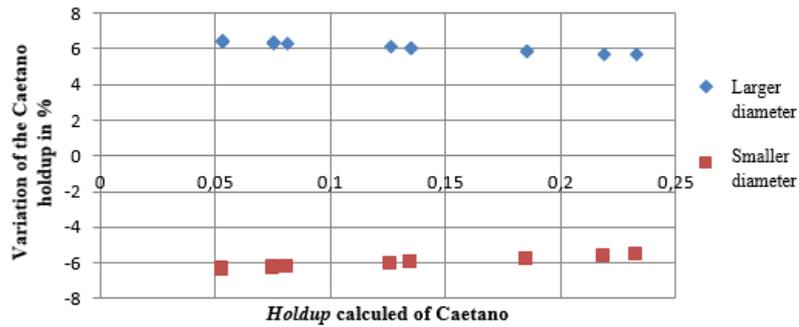


Figure 4 - Sensitivity of liquid holdup of Caetano's (1986) model with varying diameter hydraulic of the system.

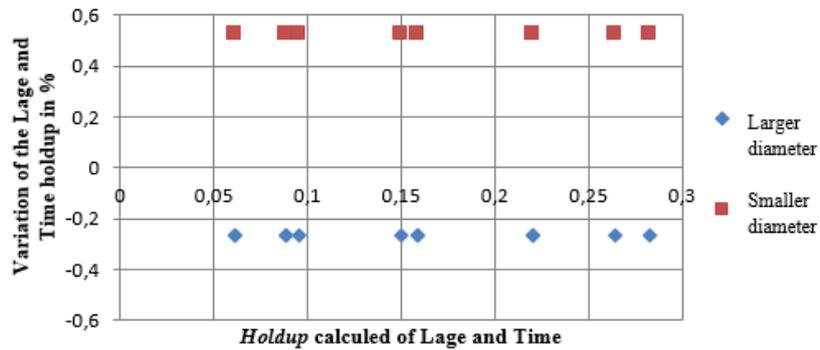


Figure 5 - Sensitivity of liquid holdup of Lage and Time's (2000) model with varying diameter hydraulic of the system.

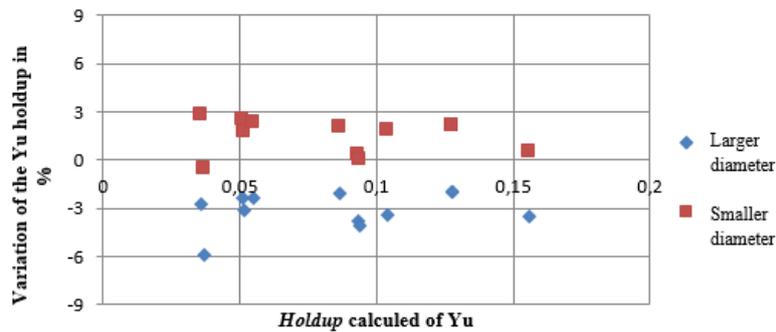


Figure 6 - Sensitivity of liquid holdup of Yu et al. (2010) model with varying diameter hydraulic of the system.

Analyzing the Figures 4, 5 and 6, it is possible to observe that the liquid holdup of Caetano's (1986) model has an average variation of 6% of the calculated value when the hydraulic diameter is varied by 32%. While the holdup of Lage and Time (2000) and Yu et al. (2010) presented a very low variation and observed an opposite tendency to Caetano's (1986) model, where an increase in the diameter causes a reduction in liquid holdup, this happens because these models holdup are inversely proportional to the system's hydraulic diameter.

Now it is verified the influence of variation in the system's hydraulic diameter on the pressure gradient values calculated by the models, represented by Figures 7 and 8.

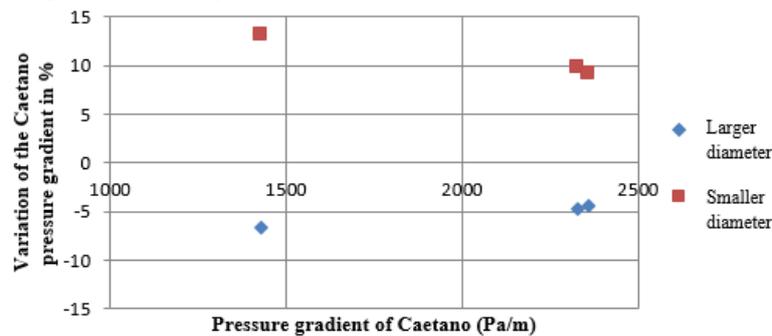


Figure 7 - Sensitivity of pressure gradient of Caetano's (1986) with varying diameter hydraulic of the system.

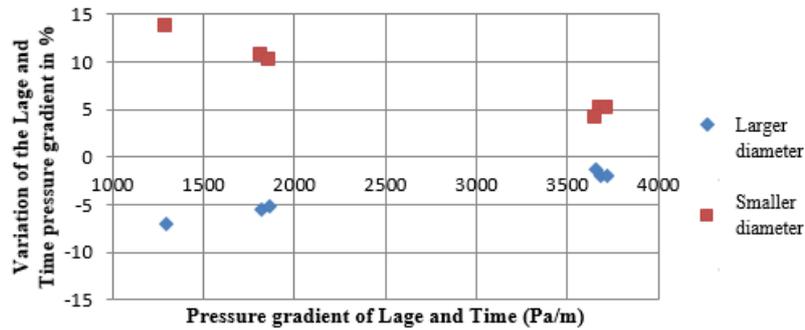


Figure 8 - Sensitivity of pressure gradient of Lage and Time's (2000) with varying diameter hydraulic of the system.

In Figure 7 was placed only half of the calculated pressure gradient values, in order to facilitate the visualization of the variation of this parameter, since the remaining values follow the pattern of removed values shown in figure. Then analyzing Figures 7 and 8, perceive a response already waiting for this parameter, because the pressure gradient calculated by the Caetano's (1986) and Lage and Time's (2000) models are in parts divided by areas or by the hydraulic diameter. It is, therefore, seen that an increase of hydraulic diameter of the system causes a reduction of the pressure gradient. However, it is observed that the pressure gradients from both models are more influenced due to a reduction in hydraulic diameter, and the model that suffers the biggest variation is Lage and Time's (2000) model.

In this step, it is observed that the liquid holdup which is more disturbed by the variation of the hydraulic diameter is the Caetano's (1986) model, while in the other models this variation is minimal. But, when considering the pressure gradient variation due to the diameter change, it was observed that the model of Lage and Time (2000) has a higher sensitivity of this parameter.

3.2.2 Influence of thickness of the liquid film

At this stage, the analysis of the liquid film thickness influence over the main parameters on the selected mechanistic models were performed implementing a variation of 10% at the film thickness values. Therefore, it is verified the influence of the variation of this parameter on the liquid holdup values calculated for each model, represented by Figures 9, 10 and 11.

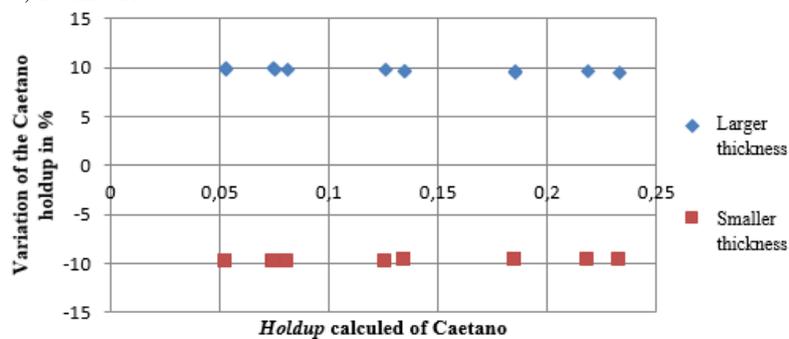


Figure 9 - Sensitivity of liquid holdup of Caetano's (1986) model with variation of liquid films thickness of the system.

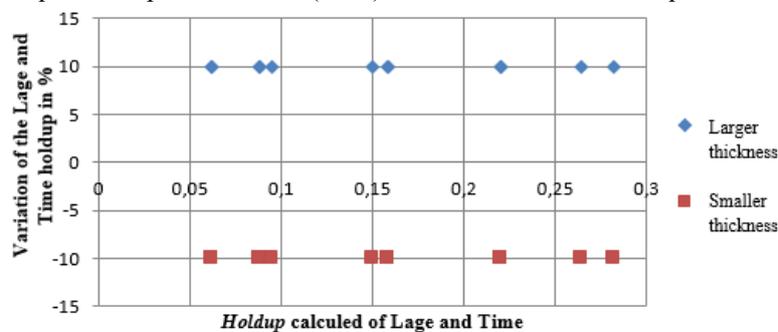


Figure 10 - Sensitivity of liquid holdup of Lage and Time's (2000) model with variation of liquid films thickness of the system.

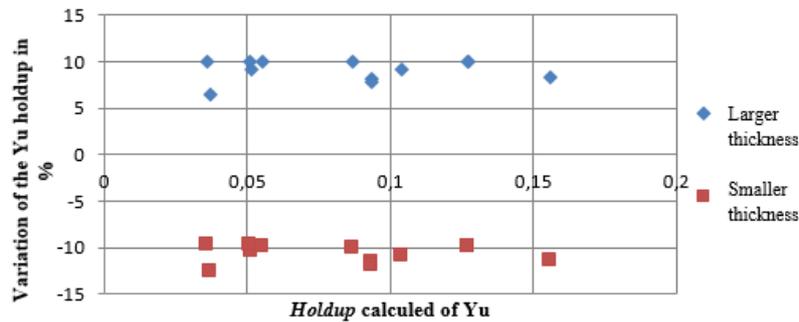


Figure 11 - Sensitivity of liquid holdup of Yu *et al.* (2010) model with variation of liquid films thickness of the system.

It is observed in Figures 9, 10 and 11, that the models' liquid holdup has increased due to an increase in the value of thickness of the liquid film. Where for the three selected models, a 10% variation of film thickness promotes an average variation of 10% also in liquid holdup, demonstrating that the thicknesses of the films are practically directly proportional to the liquid holdup in the three models.

Now, the influence of variation of the thickness of the liquid film on the pressure gradient values calculated by the models will be checked, represented in Figures 12 and 13.

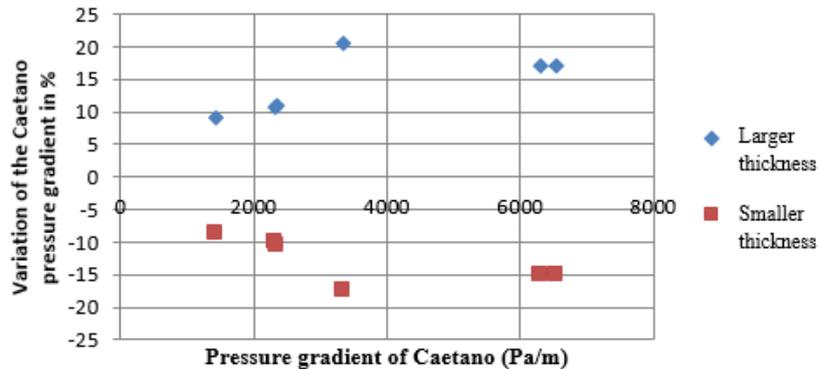


Figure 12 – Sensitivity of pressure gradient of Caetano's (1986) model with variation of liquid films thickness of the system.

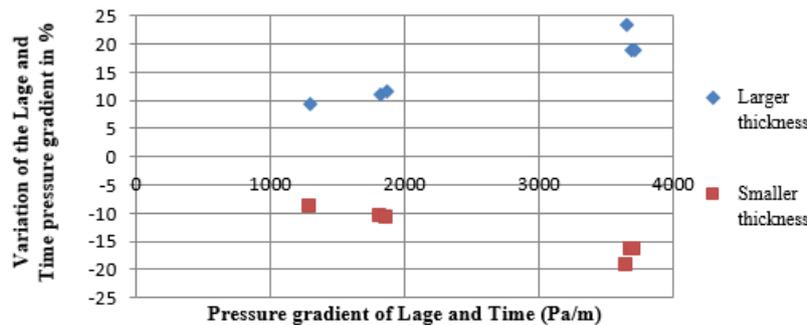


Figure 13 – Sensitivity of pressure gradient of Lage and Time's (2000) model with variation of liquid films thickness of the system.

In Figures 12 and 13, it is observed through the analysis that the bigger the thickness of the liquid film, the bigger will be the pressure gradient of the system. Therefore, Caetano's (1986) model suffers an average variation of the pressure gradient of 13% to 14%, however the Lage and Time (2000) suffers an average variation of 14% to 16%. Thus, for the experimental data used and analyzing the Figures 12 and 13, it can be said that the pressure gradient of both models suffers a greater influence due to the increased thickness of the liquid film, but the difference between these values is very low.

Thus, it was examined the influence of the main parameters of the physical system, hydraulic diameter and thickness of the liquid film, where in the hydraulic diameter was varied at 32% of its initial value and the thicknesses of the films at 10%. However, the variation of only 10% of the thickness of the film caused a higher influence on the liquid holdup and pressure gradient values than a variation of 32% in hydraulic diameter. Thus confirming the importance of prediction and measurement of the thickness of the liquid film of this system.

4. CONCLUSION

In view of the presented results, the applicability of the mechanistic approach to a system with vertical flow of gas and liquid in annular geometries in an annular flow pattern can be highlight. It is observed that the models of Lage and Time (2000) and Yu et al. (2010) that were based on the Caetano's (1986) model, have in some situations more satisfactory results, but this does not apply to a whole analysis. Due to this, it is essential to use more than one approach, in order to analyze the values obtained for each model to obtain a more accurate considerable value to this situation. It is observed that the mechanistic approaches selected are more sensitive to the liquid film thickness than the hydraulic diameter, thus underlining the importance of the correct prediction of this factor. It is shown in full working that these approaches are more sensitive to the properties of the dominant fluid system. It therefore can show that the mechanistic approaches investigated, in specific to annular flow pattern, the thickness of the liquid films are the main parameters; however, these are complex data to obtain in situ, especially considering the offshore production scenario. It is emphasized that the model's accuracy is directly related to the prediction of this parameter, many times arbitrated from the literature information.

5. REFERENCES

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