

COBEM-2017-1051

PREDICTION OF PRESSURE GRADIENT IN STRATIFIED LIQUID-LIQUID PIPE FLOW WITH ENTRAINMENT EFFECTS

Gustavo Bochio

Oscar M. H. Rodriguez

Industrial Multiphase Flow Laboratory (LEMI), Mechanical Engineering Department, São Carlos School of Engineering, University of São Paulo (USP), São Carlos, SP, Brazil

gustavo.bochio@usp.br

Abstract. *Unidimensional models are widely used in oil & gas industry to predict pressure drop and volumetric fraction, especially for horizontal stratified liquid-liquid flows. One limitation of these models is the good representation and accuracy for cases when drop entrainment is important. In this context, this work merges a unidimensional model (Rodriguez and Baldani, 2012) with entrainment parameters (Hadžiabdić and Oliemans, 2007) and a correction of wetted perimeters for each fluid phase in order to obtain a model capable of predicting pressure drop in stratified flow with mixture on the interface. This new approach is evaluated against experimental data and a well-established unidimensional model. The results show that the new model is capable of minimize errors and obtain better predictions for pressure drop.*

Keywords: *stratified flow, entrainment, oil-water flow, pressure gradient*

1. INTRODUCTION

The multiphase flow of oil and water in pipes is a subject of great interest for the petroleum industry, because these two phases are often transported together for long distances. Depending on the superficial velocity of each phase, different flow patterns are observed along the pipe (Trallero, 1995; Elseth, 2001) and some of the most important project parameters, such as pressure drop, heat transfer and structural vibration, depend on this pattern.

The stratified flow pattern is of particular interest for the petroleum industry, because it occurs in directional oil wells and is the most common in horizontal pipelines. It can be subdivided into stratified smooth, stratified wavy and stratified with mixture on the interface. Trallero (1995) proposed a unidimensional model to predict pressure drop and hold up in stratified flow and achieved good predictions for stratified smooth flow with high Eotvos numbers using this approach.

Rodriguez and Baldani (2012) expanded this approach introducing interfacial curvature and a new correlation for the interfacial shear stress that accounts for the effect of waves in the boundary between the fluids. This model was capable of predicting pressure gradient and hold up with good accuracy in stratified smooth and stratified wavy flow.

One factor that is not considered in Trallero (1995) or Rodriguez and Baldani (2012) is the effect of entrainment of droplets from one of the phases into the other. Hadžiabdić and Oliemans (2007) studied this phenomenon and divided its impact in two parcels: momentum transfer between the phases and changes in the distribution of oil and water. The momentum transfer was calculated by adding a parameter called entrainment rate, while the changes in distribution were evaluated using the entrainment factor.

In this context, this work combines the concepts of entrainment factor and entrainment rate to the unidimensional model proposed by Rodriguez and Baldani (2012) in order to create a model that is better suited to predict pressure loss in stratified flow with mixture on the interface.

2. METHODOLOGY

Figure 1a shows a representation of the oil-water stratified flow. Unidimensional models are based in the solution of the two-fluid equations (Ishii and Hibiki, 1975; Wallis, 1969). Equations 1 and 2 represent the momentum for each phase, where the subscripts w and o indicate water and oil respectively.

$$A_w \left(-\frac{dP}{dz} \right) - \tau_w S_w \pm \tau_i S_i - \rho_w A_w g \sin(\beta) = 0 \quad (1)$$

$$A_o \left(-\frac{dP}{dz} \right) - \tau_o S_o \mp \tau_i S_i - \rho_o A_o g \sin(\beta) = 0 \quad (2)$$

A_w and A_o are the areas occupied by water and oil in a cross section of the pipe, S_w and S_o are the wetted perimeters

of water and oil, S_i is the interfacial perimeter, τ_w and τ_o are the wall shear stresses of water and oil, τ_i is the interfacial shear stress, dP/dz is the pressure gradient and β is the inclination angle of the pipe.

Knowing that the pressure gradient is the same in both equations 1 and 2, they can be added, what leads to equation 3.

$$-\frac{\tau_w S_w}{A_w} + \frac{\tau_o S_o}{A_o} \pm \tau_i S_i \left(\frac{1}{A_w} + \frac{1}{A_o} \right) - (\rho_w - \rho_o) g \sin(\beta) = 0 \quad (3)$$

When we analyze stratified flows (fig. 1a), a mean interface height and shape can be assumed, like shown in figure 1b. If the proper correlations are used for the tensions (τ_w , τ_i and τ_o) all the parameters of equation 3 are solely dependent on geometric characteristics, so the unidimensional models previously cited simply try to guess the position of the interface that satisfies this equation. The main differences between Rodriguez and Baldani (2012) and Trallero (1995) is that the former introduces a new correlation for the interfacial tension and considers a curved interface that is a function of the Eotvos number and the contact angle.

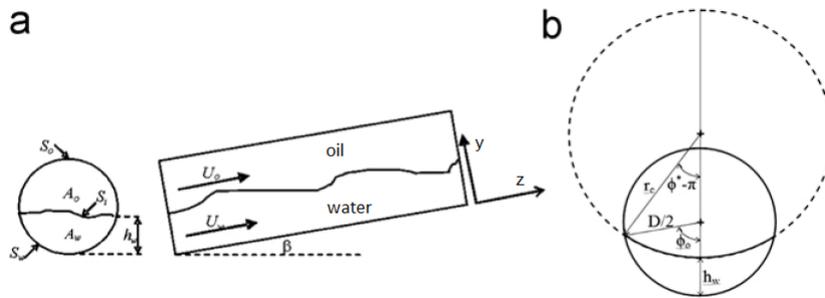


Figure 1: (a) Stratified wavy flow representation; (b) Mean interface position and shape. [Adapted from Rodriguez and Baldani (2012)]

This work expands the model of Rodriguez and Baldani (2012) introducing the concepts of entrainment factor and entrainment rate as proposed by Hadžiabdić and Oliemans (2007). One effect of entrainment is the change in the areas occupied by the upper mixture (oil with droplets of water) and lower mixture (water with droplets of oil) (fig. 2). The presence of droplets from one phase into the other can lead to a greater volume of fluid in the region above or below the interface. This will cause a change in all the geometric parameters, like interface position or wetted perimeters. Other effect is a change in physical parameters, once the upper and lower layers are no longer composed of only one fluid, but of a mixture. All of these changes are calculated using the parameter called entrainment factor that is defined by the ratio between the area occupied by droplets of one phase and the total area of that phase (eq. 4 and 5)

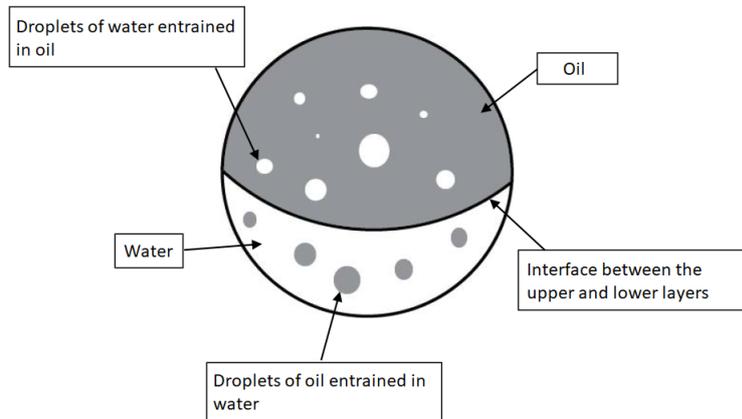


Figure 2: Representation of stratified flow with entrainment

$$E_w = \frac{A_{w_gotas}}{A_w} \quad (4)$$

$$E_o = \frac{A_{o_gotas}}{A_o} \quad (5)$$

Therefore, equations 6 and 7 represent the upper and lower areas.

$$A_u = A_o(1.0 - E_o) + A_w E_w \quad (6)$$

$$A_l = A_w(1.0 - E_w) + A_o E_o \quad (7)$$

The densities of upper and lower layers are given by equations 8 and 9, while the viscosities are calculated using the correlation presented in Guet *et al.* (2006).

$$\rho_u = \frac{\rho_w A_w E_w + \rho_o A_o (1 - E_o)}{A_u} \quad (8)$$

$$\rho_l = \frac{\rho_o A_o E_o + \rho_w A_w (1 - E_w)}{A_l} \quad (9)$$

A second effect of entrainment occurs in its onset and leads to a change in the momentum equation, so a new term, that accounts for the drag force in the droplets, appears. This is represented by the last term in the left hand side of equation 10, where \dot{e}_w and \dot{e}_o are known as the entrainment factor of water and oil respectively. Equation 10 is the new one that needs to be solved. The subscripts u and l refers to the upper and lower mixture respectively and all the effects of entrainment are represented explicitly or implicitly in this equation.

$$-\frac{\tau_l S_l}{A_l} + \frac{\tau_u S_u}{A_u} \pm \tau_i S_i \left(\frac{1}{A_l} + \frac{1}{A_u} \right) - (\rho_l - \rho_u) g \sin \beta - \left(\frac{1}{A_l} + \frac{1}{A_u} \right) (U_l - U_u) (\dot{e}_w + \dot{e}_o) = 0 \quad (10)$$

Figure 3 is a flowchart of the calculation routine that was implemented using MATLAB.

3. RESULTS

Data for entrainment rate and factor does not exist for the studied flow. Some previous works tried to model these parameters (Al-Wahaibi *et al.*, 2007), but there are many difficulties to measure them, so we chose to make a sensibility analysis of these two parameters, which means, the entrainment factor was considered null while the entrainment rate underwent a continuous change and vice versa. In his work, Castro (2013) observed that, for his flow conditions, the entrainment of water does not occur. The same assumption was made in this work, because the flow conditions are the same. In this section we present results for the flow of oil ($\rho = 828 \text{ kgm}^{-3}$; $\mu = 0,280 \text{ Pa} \cdot \text{s}$) and water ($\rho = 998 \text{ kgm}^{-3}$; $\mu = 0,001 \text{ Pa} \cdot \text{s}$) in a pipe of 26 mm of internal diameter.

Figure 4 shows how the entrainment rate impacts the pressure gradient given superficial velocities of water and oil of 0,2 m/s. The graphic shows that even great changes in the entrainment rate are unable to generate considerable variations in the pressure gradient for this flow condition. In fact, even for an extreme case, when the entrainment rate is equal to the mass flux of oil, the variation is lower than 0,5%. The same evaluation was done for different superficial velocities and the results were always the same, the impact of the entrainment rate in the overall pressure drop is very small.

Figure 5 shows the sensibility analysis for the entrainment factor and it is clear that this parameter has a big impact in the pressure loss. In fact, the results show a reduction of 23% in the pressure gradient for an entrainment factor of 0,2 (20% of the oil volume as droplets). The image shows a decrease in pressure loss as the factor increases. This is expected, because as the oil disperses into the water, its region of contact with the pipe walls gets smaller and, in consequence, the wall friction decreases.

It is important to see that this model may not be suitable for cases when dispersion is accentuated, once the two-fluid model and the closure correlations are not appropriated.

As a next step, we decided to use the proposed model and compare its results with experimental data from Castro (2013). As previously shown, the entrainment rate effect is negligible, so it was not considered in this case. The entrainment factor, in the other hand, varied from zero to 0,75 until we found the optimum value, which means, the one that best fits the numerical and experimental results. Figure 6 shows the comparison between the current model and the one proposed by Rodriguez and Baldani (2012). While the former tends to overestimate the pressure gradient, specially for higher oil flow rates, the new model can capture all the points with good accuracy. Besides that, table 1 show a trend of increase in entrainment factor with oil flow rate. This is expected: as the oil flow rises, the water fraction gets smaller, which causes an increase in its velocity, increasing the interfacial shear stress and the drop formation. Figure 7 shows a similar result for $U_{ws} = 0,23 \text{ m/s}$.

Tables 1 and 2 show that the stratified flow with entrainment is not very stable to changes in water flow. For example, for $U_{os} = 0,18 \text{ m/s}$, we observe an increase in the optimum factor from 0,15 to 0,6 from one table to the other. This means that a small increase in the superficial velocity of water (0,03 m/s) can greatly increase the entrainment process.

Lastly, figure 8 shows the shape and position of the interface calculated with Rodriguez and Baldani (2012) and the current model, assuming entrainment factor of 15%. The presence of oil droplets in the water drastically changes the area occupied by the upper and lower layers and, as stated before, decreases the wetted perimeter of oil.

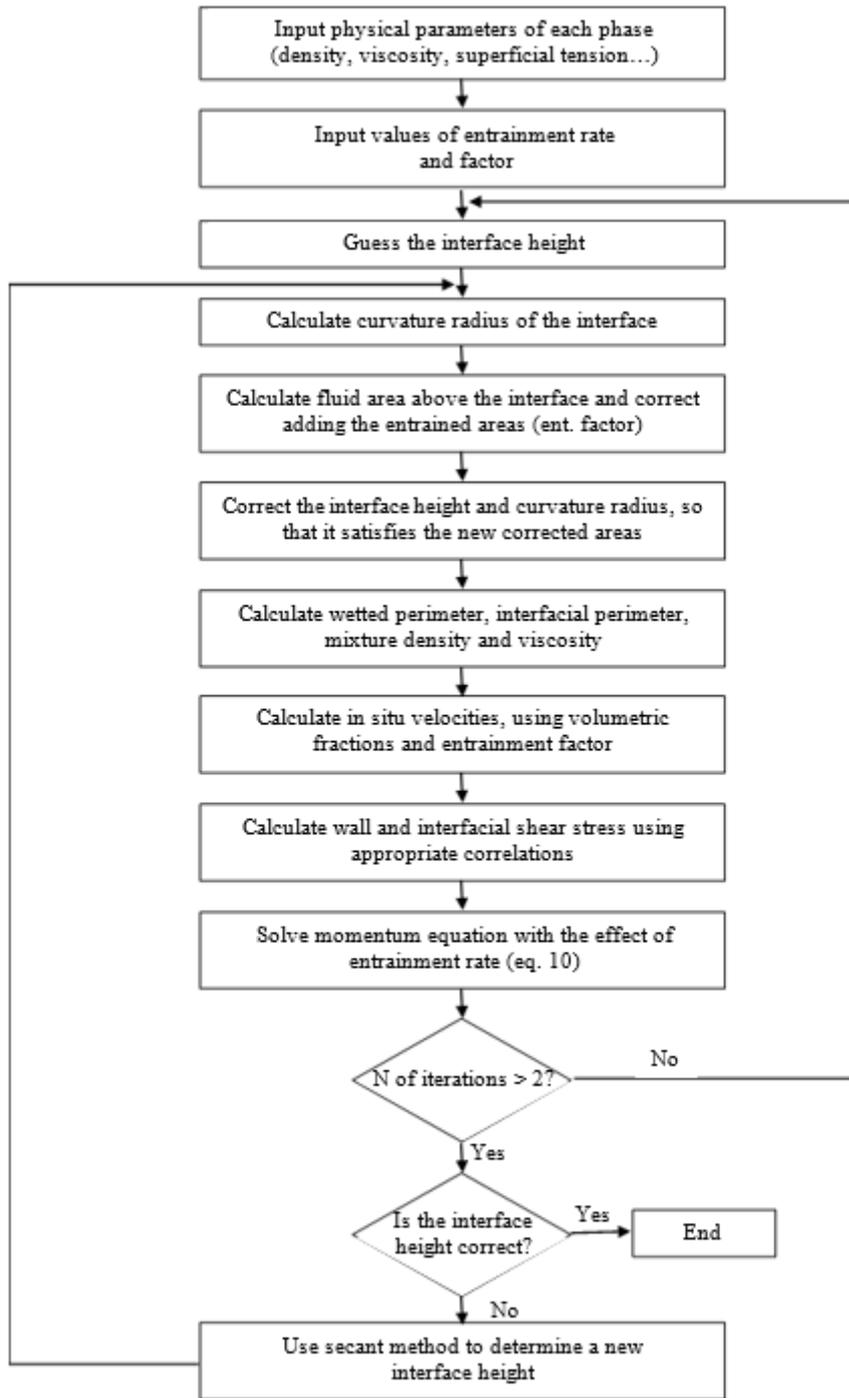


Figure 3: Algorithm for unidimensional model with entrainment effects

Table 1: Entrainment factor associated with figure 6

$U_{os} (m/s)$	0,06	0,08	0,12	0,14	0,16	0,18	0,2	0,22	0,31
E_o	0	0	0,2	0,1	0,15	0,15	0,35	0,4	0,65

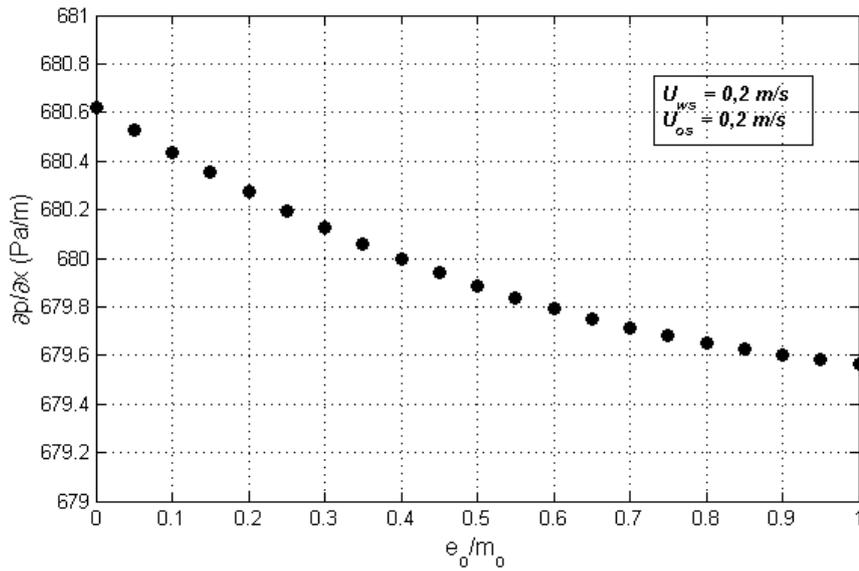


Figure 4: Pressure gradient variation against entrainment rate

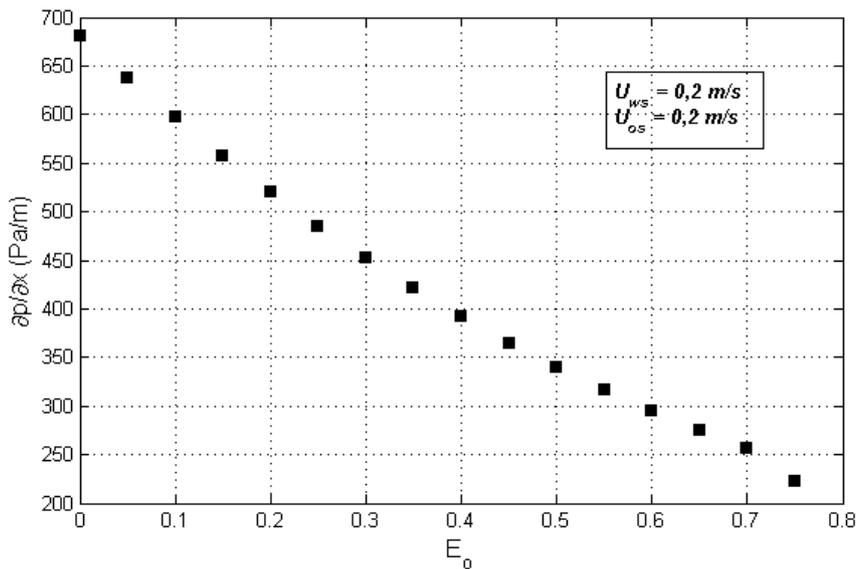


Figure 5: Pressure gradient variation against entrainment factor

4. CONCLUSIONS

The one dimensional model developed was based in the studies of Rodriguez and Baldani (2012) to calculate wall shear stress, interfacial stress and interface shape. At the same time, entrainment parameters, proposed by Hadžiabdić and Oliemans (2007), were introduced to account for the droplets effect.

A sensibility analysis showed that the entrainment factor has an important impact in the pressure loss, while the effect of the entrainment rate is negligible. This result was based in the pair oil-water tested by Castro (2013) and the results may be different for different flow conditions.

The model was tested using experimental data for stratified flow with mixture. In this case, we used the optimum value for the entrainment rate. The results showed that the model can capture the experimental points well, different from the model of Rodriguez and Baldani (2012). This indicates that this new methodology has the potential to improve predictions of stratified flows with entrainment. The main issue with the model is the necessity of data of entrainment rate and factor as inputs, once there are not correlations for these parameters in the literature.

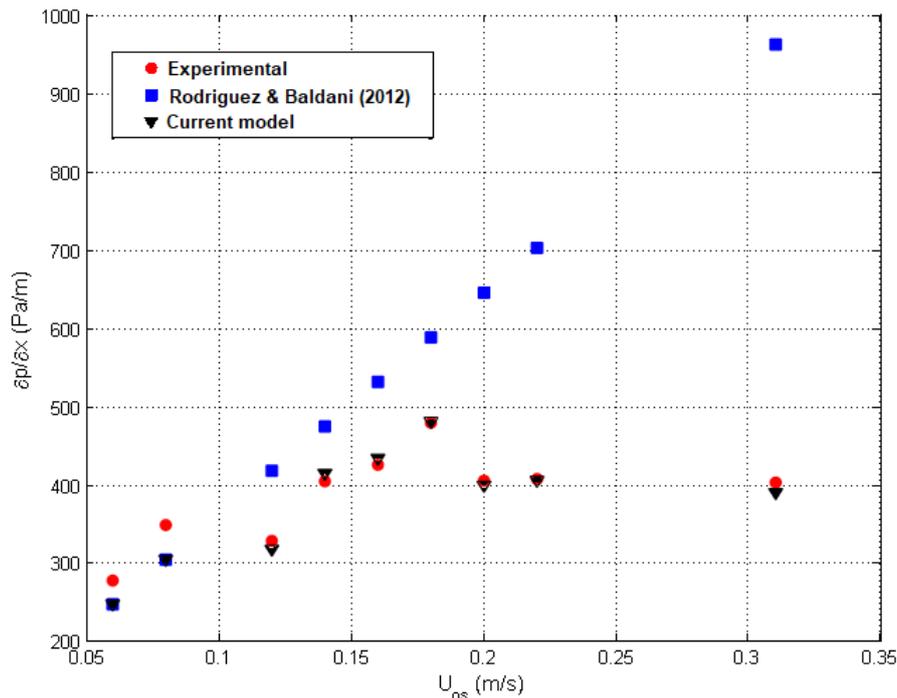


Figure 6: Pressure gradient comparison: experimental, Rodriguez and Baldani (2012) and current model. ($U_{ws} = 0,2 \text{ m/s}$)

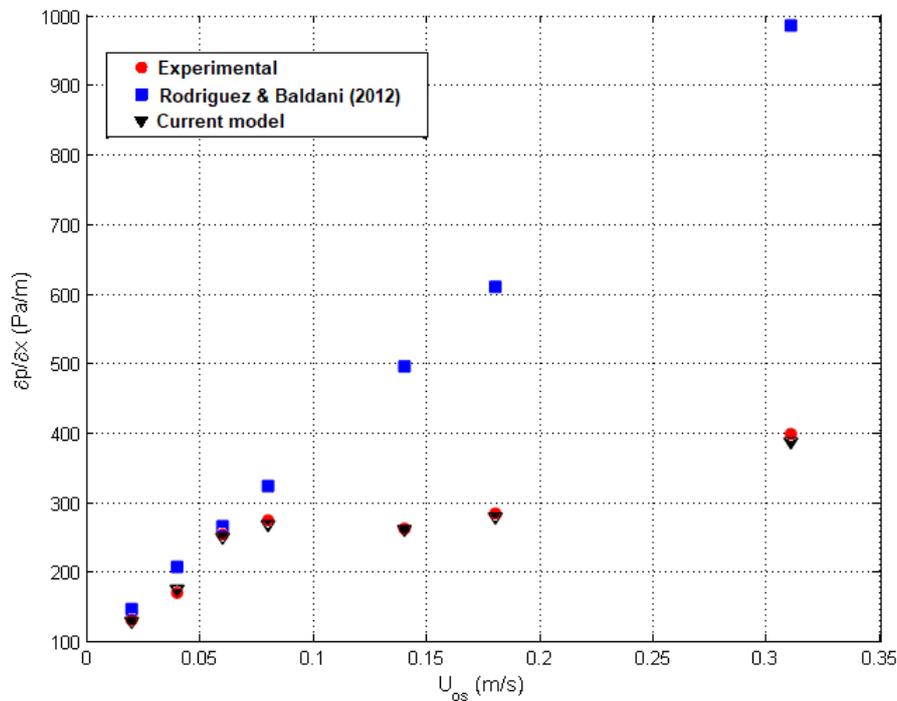


Figure 7: Pressure gradient comparison: experimental, Rodriguez and Baldani (2012) and current model. ($U_{ws} = 0,23 \text{ m/s}$)

5. ACKNOWLEDGEMENTS

This work is supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

Table 2: Entrainment factor associated with figure 7

U_{os} (m/s)	0,02	0,04	0,06	0,08	0,14	0,18	0,31
E_o	0,05	0,15	0,05	0,15	0,45	0,60	0,70

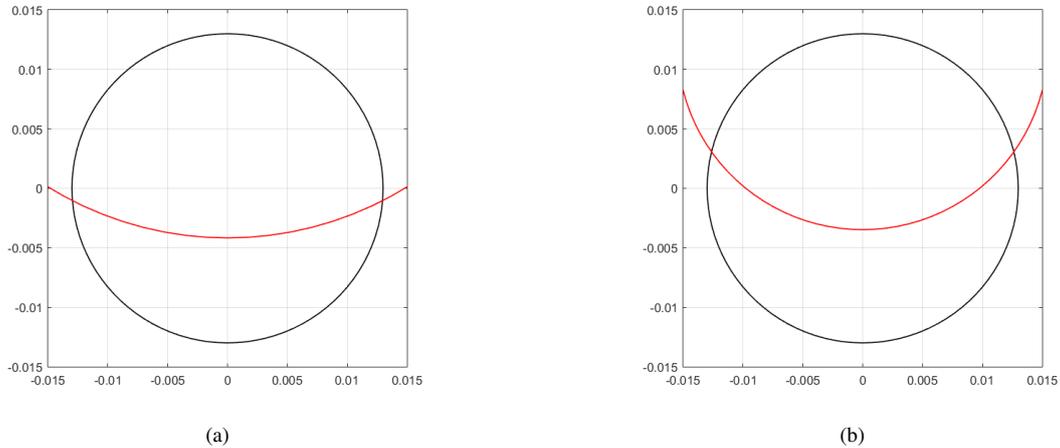


Figure 8: Interface position $U_{os} = 0,2$ m/s and $U_{ws} = 0,2$ m/s (a) Rodriguez and Baldani (2012) model; (b) current model with $E_o = 0,15$.

6. REFERENCES

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