IV Journeys in Multiphase Flows (JEM 2015)
March 23-27, 2015, Campinas, SP, Brazil

Paper ID: JEM-2015-0021

VELOCITY PROFILE MODELS FOR STRATIFIED OIL-WATER FLOWS

Vinícius Pessoa Mapelli
Engineering School of Sao Carlos, University of Sao Paulo
Av. Trabalhador São Carlense, 400
13566-590, Sao Carlos, SP, Brazil
vinicius.mapelli@usp.br

Oscar Mauricio Hernandez Rodriguez
Engineering School of Sao Carlos, University of Sao Paulo
Av. Trabalhador São Carlense, 400
13566-590, Sao Carlos, SP, Brazil
oscarmhr@sc.usp.br

Marcelo Souza de Castro
Faculty of Mechanical Engineering, University of Campinas
St. Mendeleyev, 200
13083-860, Campinas, SP, Brazil
mcastro@fem.unicamp.br

Abstract. *Stratified flows have been object of study because of its common occurrence in horizontal and slightly inclined pipes, e.g., directional oil wells of the petroleum industry. Even today, the models to predict pressure drop and holdup of this flow pattern present considerable errors when compared to experimental data. One point that needs improvement is related to the shape factor of the phases of the two fluid model, which are based on the velocity profiles. Therefore a model that predicts, accurately, such profiles is necessary. In this work two velocity profiles models, based on Couette-Poiseuille flow, and a third power law model are compared with experimental data of velocity profile acquired with a LDA system from literature. The velocity profiles were acquired at the vertical center-line of the pipe, therefore, 3D effects were neglected. The two models based on the Couette-Poiseuille flow present good and similar results. The power law presented the worst average deviation and disregards the no-slip condition at the interface. The calculated average deviation was of 17.36%, 17.43% and 23.86%, respectively for the Couette-Poiseuille models and third power law. The models are able to predict some experimental information in certain conditions but more data are necessary in order to refine the models.*

Keywords: *liquid-liquid flow, stratified flow, oil-water flow, velocity profile.*

1. INTRODUCTION

In last years there has been an increasing interest in liquid-liquid flows, since its occurrence is very common in many industries, e.g., petroleum industry, where oil and water flows together inside extraction pipes. This interest have boosted many researches towards liquid-liquid flow parameters, like hold-up, pressure drop, flow patterns and stability, in order to optimize equipment, cost and performance.

Stratified flow is one of the liquid-liquid flow patterns very common in horizontal and slightly-inclined flows. In this flow pattern, the lighter and heavier phase flows at the top and bottom of the pipe, respectively. Both phases are divided by an interface that can be smooth or wavy.

A representation of stratified flow pattern is shown in Fig. 1, taken from Elseth, 2001.

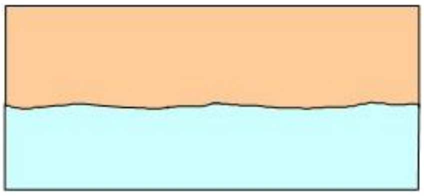

Figure 1. Stratified smooth liquid-liquid flow representation (Elseth, 2001).

Studies on liquid-liquid flows are still scanty when compared with gas-liquid flows. One might cite the work of Rodriguez, Baldani (2012) which proposes a new correlation for interfacial friction factor and a new model based on constant-curvature-arc model; the work of Rodriguez and Oliemans (2006), which presents a large database of horizontal and slight inclined oil-water flow pattern, flow maps, pressure drop and phase's holdup and a comparison of the results with models from literature. The works of Elseth (2001) and Amundsen (2011) that presents data about pressure gradient, holdup and velocity profile in liquid-liquid flows and compares models from literature to holdup results.

Studies about velocity profile in liquid-liquid flows are very scanty especially when devoted to velocity profiles models. One of the most relevant works in this area is Rodriguez, Mudde and Oliemans (2006), that proposed an equation for oil-water stratified velocity profile assuming a Couette-Poiseuille flow. Those authors used Elseth's data to fit some parameters of the equation and to compare the results.

In this work, data from Elseth (2001) and Amundsen (2011) are used to adjust Rodriguez, Mudde and Oliemans (2006) model. Also, a simplification of this model is proposed and a third power law model is used for comparisson. The three velocity profiles models were compared with the experimental data aforementioned.

2. METHODOLOGY

2.1 Database

Elseth (2001) and Amundsen (2011) database were used in the present work. Both authors measured mean velocity profile at the center-line of the pipe in oil-water flow using LDA technique. The oil used in both works was Exxsol D-60, and its viscosity is 1.64 mPa.s. Tables 1 and 2 present the experimental matrix of Elseth (2001) and Amundsen (2011).

Table 1. Experimental matrix of Elseth (2001).

Mixture flow rate [m³/h]	Mixture velocity [m/s]	Input water cut [%]
3.6	0.41	25
6	0.68	25, 50
9	1.02	15, 25, 40, 50, 60, 75, 85
12	1.37	15, 25, 40, 50, 60
15	1.71	25, 40, 50, 60
18	2.04	25, 40, 50, 60

Table 2. Experimental matrix of Amundsen (2011).

Parameter	Value
Input water cut [%]	0, 25, 50, 100
Mixture velocity [m/s]	1
Pipe inclination [º]	0, +1, +5, +10, -1, -5, -10

2.2 Velocity profile equation

Equation (1) shows the velocity profile model proposed by Rodriguez, Mudde and Oliemans (2006). This model is based on the Couette-Poiseuille flow.

$$u_k(y) = aU_m\left[\left(\frac{y}{h_k}\right)^{1/j_k} + bj_k\frac{y}{h_k}\left(1-\frac{y}{h_k}\right)\right] \tag{1}$$

where U_m is the mixture velocity, a and b are parameters to fit Elseth (2001) data, $_k$ is the phase index, h is the phase height, and j_k is a parameter related to shape of velocity profile. The interface level related to k-phase and, consequently, the *in-situ* phase velocity U_k are known quantities, calculated to each flow condition by Rodriguez and Baldani (2012) model. Thus, parameter j_k is found using the separated-flow approximation as presented in Eq. (2).

$$U_k = \frac{\int_0^{h_k} 2\pi(h_k - y)u_k(y)dy}{\pi h_k^2} \tag{2}$$

In the proposed simplified model, the j_k term was removed from the second term of the sum of Eq. (1). This change was motivated to simplify the fitting data process, and thus, making it easier to find parameters a and b.

The simplified model is presented in Eq. (3).

$$u_k(y) = aU_m\left[\left(\frac{y}{h_k}\right)^{1/j_k} + b\frac{y}{h_k}\left(1-\frac{y}{h_k}\right)\right] \tag{3}$$

The power law model used in this work to predict velocity profile is given in Eq. (4).

$$u_k(y) = U_{max\,k}\left(\frac{y}{2h_k}\right)^{1/7} \tag{4}$$

where $U_{max\,k}$ is different to each flow condition and calculated using the separated-flow approximation given by Eq. (2).

2.3 Data acquisition

The data acquisition was made via a homemade Labview® based program. This program enables the extraction of the coordinates of each points of a graph from literature saved as an image files. This program was used to catalog more than a thousand points of velocity profile and holdup present in Amundsen (2011) and Elseth (2001).

3. RESULTS

A comparison of the experimental velocity profile of Amundsen (2011) and the three models are presented in Figs. (2), (3) and (4), respectively for Rodriguez, Muddy and Oliemans (2006) model, the proposed simplified model, and the power law model. The experimental conditions chosen are *Uws* = 0.24 *m/s* (water superficial velocity), *Uos*= 0.75 *m/s* (oil superficial velocity) and β = 0° (pipe inclination). In Figs. (2), (3) and (4) the purple and blue points are the oil and water experimental axial velocities of Amundsen (2011), respectively. Vertical axis shows dimensionless value of position *y/D,* and horizontal axis shows dimensionless axis of velocity $u(y)/U_m$.

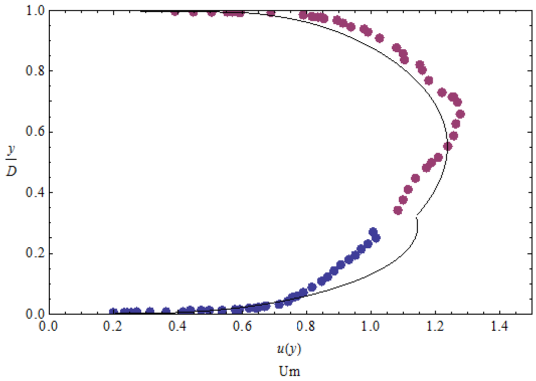

Figure 4 – Amundsen (2011) experimental data and Rodriguez, Mudde and Oliemans (2006) model velocity profile (continuous line).

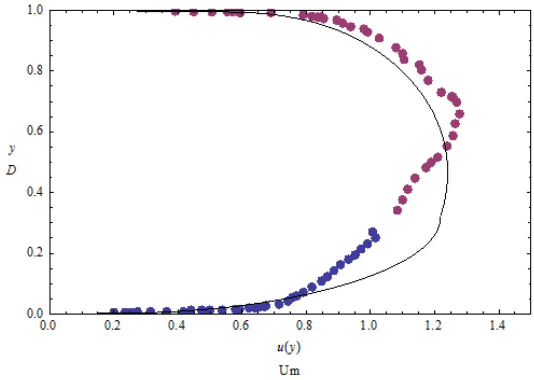

Figure 5 – Amundsen (2011) experimental data and simplified proposed velocity profile model (continuous line).

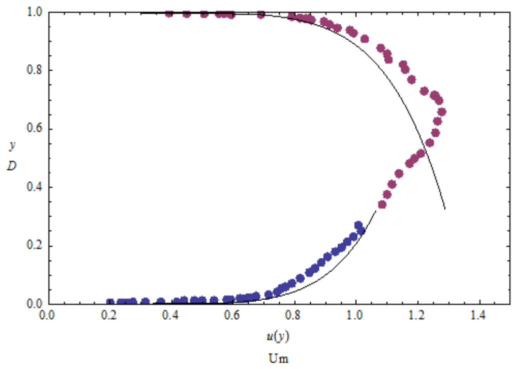

Figure 6 – Amundsen (2011) experimental data and power law model velocity profile (continuous line).

Data of seventeen flow conditions were compared with the described three models. Average deviation calculated was of 17.36%, 17.43% and 23.86%, for Rodriguez *et al.* (2006) model, proposed simplified model and power law model, respectively.

As expected, Rodriguez *et al.* (2006) model and simplified have slightly differences in the velocity profile, with a more accentuated concavity in the first model. This fact makes Rodriguez *et al.* (2006) model better to predicts maximum points of velocity. However, these two models present very similar results. They present similar average deviation, and both underestimate the water phase in downward flows, and underestimate oil phase in upward flows. Power law model presents very good predictions, especially at low water cuts. However, this model does not assure no-slip condition between phases.

4. CONCLUSION

Results presented by Rodriguez *et al.* (2006) model and the simplified model are very similar, and their trends suggests that gravitational effects are not very well predicted. However, they could reproduce some interesting results at low water cuts.

Power law model presents the worst average deviation among the tested models. This model produces a flattened concavity, increasing error in flow conditions where experimental profile velocity concavity is similar to a parabolic one. However, this model could produce very good results to water phase at low water cuts. No-slip condition is the great fail about this model.

It is interesting to remember that the data were measured only in the vertical center-line of the pipe, therefore 3D effects are neglected in three models.

More data of velocity profile in different vertical lines, with different geometries pipes, and distinct fluids are needed in order to better understanding governing phenomena in velocity profiles.

5. ACKNOWLEDGEMENTS

The authors are grateful to CNPq for the financial support.

6. REFERENCES

Amundsen, L., 2011. *An experimental study of oil-water flow in horizontal and inclined pipes*, Ph.D. thesis, Norwegian University of Science and Technology, Norway.

Elseth, G., 2001. *An experimental study of oil-water flow in horizontal pipes*, Ph.D. thesis, Telemark University College, Norway.

Rodriguez, O.M.H., Baldani, L.S., 2012. Prediction of pressure gradient and holdup in wavy stratified liquid-liquid inclined pipe flow, *Journal of Petroleum Science and Engineering*, Vols. 96-97, p. 140-151.

Rodriguez, O.M.H. and Oliemans, R.V.A., 2006. Experimental study on oil-water flow in horizontal and slightly inclined pipes, *International Journal of Multiphase Flow*, Vol. 32, p. 323-343.

Rodriguez, O.M.H., Mudde, R.F. and Oliemans, R.V.A., 2006. Stability analisys of slightly-inclined stratified oil-water flow, including the distribution coefficientes and the cross-section curvature**.** In *Proceedings of the 5th North American Conference on Multiphase Technology – BHR 2006*, p. 229-245. Banff, Canada.

7. RESPONSIBILITY NOTICE