COBEM-2017-1959
APPLICATION OF AN EMPIRICAL MODEL TO IDENTIFY STRATIFIED GAS–LIQUID FLOW IN THE WHOLE RANGE OF PIPE INCLINATIONS

Germano Scarabeli Custódio Assunção
University of Campinas
germs.scarabelli@gmail.com

João Carlos von Hohendorff Filho
University of Campinas
joao@dep.fem.unicamp.br

Denis José Schiozer
University of Campinas
denis@cepetro.unicamp.br

Marcelo Souza de Castro
University of Campinas
mcastro@fem.unicamp.br

Abstract. The objective of this work is to apply an empirical model to predict the transition stratified/nonstratified gas-liquid two-phase flow in the whole range of inclinations. A previous work proved the efficiency of this empirical model to predict the transition in horizontal and downward pipe flows. In this work, we showed that this empirical model can also be accurate to identify stratified flow pattern in upward inclined pipes, hence it may be applied for the whole range of pipe inclinations. Moreover, we also compared the prediction of the empirical model with a traditionally used mechanistic model.

Keywords: Stratified Flow, Empirical Model, Flow pattern transition, Mechanistic Model

1. INTRODUCTION

Multiphase flows have wide applications in different fields: evaporators, boilers, distillation towers, chemical reactors, condensers, nuclear reactors and oil and gas pipelines. When multiple phases jointly flow in the pipes, different flow patterns can be observed. The manifestation of a certain flow pattern depends of several variables, e.g. pipe inclination and diameter, fluid rates and properties. Once each flow pattern presents specific characteristics, the correct identification of the flow pattern is a crucial step to accurately predict the pressure drop of the flow and consequently to sizing and design multiphase flow systems.

Due to complexities to identify flow pattern transitions, since several data must be evaluated, over the years models have been proposed to identify flow patterns in specific conditions, mainly related to pipe inclinations. We highlight Eaton et al. (1967), Beggs and Brill (1973) and Taitel and Dukler (1976), which are models applicable for horizontal and near horizontal (±10º) flows and Hagedorn and Brown (1965) and Taitel et al. (1980) for vertical or sharply inclined flows.

However, for industry applications, fluids are transported upwards from vertical or deviated wells, through hilly-terrain pipelines to downstream processing facilities (Zhang et al., 2003), that is, in different pipe inclinations. Thus, aiming to mitigate the need to apply different models for the different flow configurations, some studies addressed models that can be used for any pipe inclination, namely, $-90^{o} \leq \theta \leq 90^{o}$. Example of these models, a.k.a. unified models, can be found in literature in the works developed by Spedding and Nguyen (1980), Barnea (1987), Petalas and Aziz (1996), Gomez *et al.* (1999) and Zhang et al. (2003).

The challenge in unified models is to develop closed-loop methodologies that predict the correct flow pattern transition and then, accurately calculate the pressure drop. From several possible flow patterns, one often observed is the stratified flow, which occurs with the liquid flowing on the bottom and the gas flowing above it. Such pattern is the dominant flow over a wide range of inclination angles, namely, between 0° up to -80°, covering a wide range of gas and

liquid flow rates (Shoham, 2006). For upward flows, only for certain ranges of operating parameters the stratified pattern exists. However, as stated by Barmak et al. (2016), upward stratified flow also has practical importance, since it can be observed in experiments with low liquid and high gas flow rates. Moreover, for upward inclinations, we can note that multiple steady state configurations can be observed, hence, the characterization of this pattern can be challenging.

In literature, we can find lots of studies addressing stratified flow prediction and modeling, namely, Wallis and Dobbins (1973), Taitel and Dukler (1976), Persen (1984), Baker and Gravestock (1987), Wu et al. (1987), Xiao *et al.* (1990), Woods et al. (2000), Muller-Steinhagen (2000), Hurlburt and Hanratty (2002), Bhagwat and Ghajar (2015). Those models to predict the stratified flow pattern are separated in two approaches: (1) empirical and (2) mechanistic (phenomenological). The former is based on development of empirical equations that fits observations from experimental data. The latter is modelled on a theoretical basis, reducing the dependence on empirical data (Muller-Steinhagen, 2000).

A typical problem faced by engineers is the difficulty of which empirical correlation or mechanistic model should be used to evaluate stratified flow (or any other flow pattern), since a particular correlation or model may be applicable for a specific condition but not to others. To overcome the problem of choosing the most appropriate model, engineers usually apply the model directly found in commercial softwares. In this context, a widely used model both in commercial softwares and in research laboratories is the one developed by Taitel and Dukler (1976). Although initially developed to horizontal and near horizontal flows, it was extrapolated and used to sharply inclined pipes by Barnea (1987), presenting relatively good agreement in comparison to observed data.

One of the most recent works addressing stratified transition was proposed by Bhagwat and Ghajar (2015), who developed an empirical model for horizontal and downward inclined pipes, testing against sixteen experimental data sources. In this empirical model, flow inclination angle was applied using its module. Since the inclination angle is negative downwards, the proposed model may also be accurate for upwards flow, since only the absolute value of inclination angle is applied. Given that, the objective of this paper is twofold. Firstly, analyse the performance of the empirical model proposed by Bhagwat and Ghajar (2015) for upward inclined pipes. Secondly, this paper compares Bhagwat and Ghajar (2015) experimental model to Taitel and Dukler (1976) mechanistic model, regarding accuracy to predict the stratified flow for the whole range of pipe inclinations.

2. STRATIFIED TO NONSTRATIFIED TRANSITION MODELS AND EXPERIMENTAL DATA

In this section we present both models used, as well as the description of experimental data acquired to perform the present study.

2.1 Taitel and Dukler (1976)

Taitel and Dukler (1976) model is applicable for steady-state, horizontal and near horizontal ($\pm 10°$) flows. It is a mechanistic model based on equilibrium of the stratified flow. A stability analysis is performed to determine whether or not the flow is stable. If so, stratified flow occurs, otherwise, nonstratified flow is predicted.

They used the Kelvin-Helmholtz instability theory to provide the solution of the stability analysis, adopting the inviscid analysis, neglecting fluid viscosities and consequently interfacial shear stresses. Two forces are regarded: (1) the gravity force, which tends to stabilize the flow and (2) the suction pressure force over the wave, which tends to destroy the stratified structure.

Considering those forces, from mass and momentum conservation, the authors proposed transition stratified-nonstratified flow presented by Eq. (1), in dimensionless form. In this equation, F is the Froude number, defined by Eq. (2), $\tilde{h}_L$ is the dimensionless liquid holdup (h_L/D), $\tilde{U}_G$ and $\tilde{A}_G$ are dimensionless parameters calculated by Eqs. (3) and (4).

The dimensionless liquid holdup is function of Lockhart–Martinelli parameter (X) and the inclination angle dimensionless parameter (Y). The determination of dimensionless liquid holdup can be performed graphically, using the multi-curve plot proposed by Taitel and Dukler (1976) and shown in Figure 1, or iteratively, using the momentum balance equation, presented in Eq. (5).

All the tilde dimensionless variables in Eq. (5) are only functions of the dimensionless liquid holdup. Their names are described in the nomenclature section and relationships between the tilde dimensionless variables and dimensionless liquid holdup are detailed in Taitel and Dukler (1976).

Although developed for specific inclinations, $\pm 10°$, Barnea (1987) tested the model against experimental data and concluded that an extrapolation of the model for the whole range of inclinations can be satisfactory.

$$F^2 \left[\frac{1}{\left(1 - \tilde{h}_L\right)^2} \frac{\tilde{U}_G \sqrt{1 - \left(2\tilde{h}_L - 1\right)^2}}{\tilde{A}_G} \right] < 1 \qquad (1)$$

$$F = \frac{U_{SG}}{\sqrt{g.D\cos\theta}}\sqrt{\frac{\rho_G}{\rho_L - \rho_G}} \tag{2}$$

$$\tilde{U}_G = \frac{\pi}{4\tilde{A}_G} \tag{3}$$

$$\tilde{A}_G = 0.25\left[\pi - \arccos\left(2\tilde{h}_L - 1\right) + \left(2\tilde{h}_L - 1\right)\sqrt{1 - \left(2\tilde{h}_L - 1\right)^2}\right] \tag{4}$$

$$X^2\left[\left(\tilde{U}_L\,\tilde{D}_L\right)^{-n}\tilde{U}_L^2\frac{\tilde{S}_L}{\tilde{A}_L}\right] - \left[\left(\tilde{U}_G\,\tilde{D}_G\right)^{-m}\tilde{U}_G^2\left(\frac{\tilde{S}_G}{\tilde{A}_G} + \frac{\tilde{S}_I}{\tilde{A}_G} + \frac{\tilde{S}_I}{\tilde{A}_L}\right)\right] + 4Y = 0 \tag{5}$$
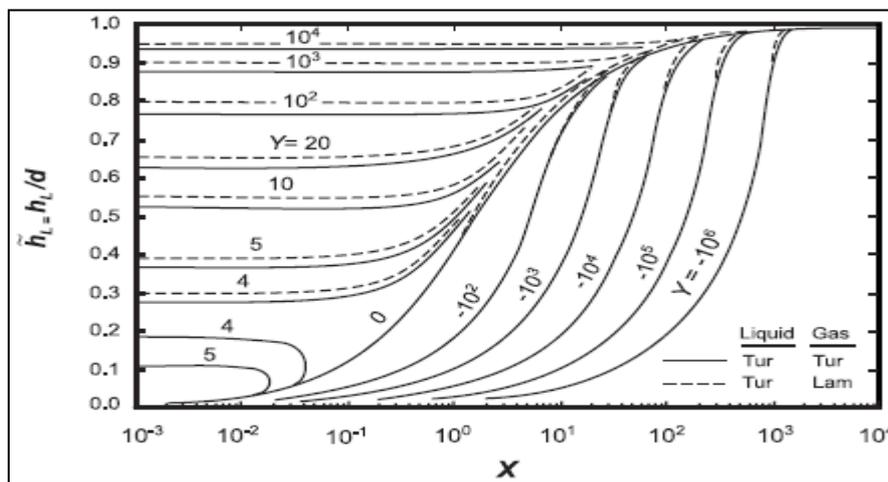

Figure 1. Graphical solution for liquid holdup in function of X and Y (Shoham, 2006).

2.2 Bhagwat and Ghajar (2015)

The model proposed by Bhagwat and Ghajar (2015) is an empirical model to predict the stratified/nonstratified transition. They used four coefficients, presented in Eqs. (6) to (9): C_1 is function of the pipe diameter (D) and reference pipe diameter ($D_{REF} = 25.4$ mm); C_2 is calculated using C_4 (Eq. 9) and pipe inclination; C_3 is function of reference liquid density ($\rho_{REF} = 1000$ kg/m^3), gas-liquid density difference ($\Delta\rho = \rho_L - \rho_G$), D and D_{REF}; C_4 establish a relationship between D and D_{REF}. As highlighted the authors, C_1, C_2 and C_3 control the slope of the transition line in buoyancy-driven regions (large values of X), while C_4 controls the slope of transition line in the inertia-driven regions (small values of X). Note that we modified a term in coefficient C_2. Instead of multiple the hyperbolic tangent term by 10 (Eq. 7), we observed that using only the unity as multiplier, better results were obtained. For that reason, we changed this term in relation to original paper from Bhagwat and Ghajar (2015).

These coefficients create the relationship between the modified Froude number ($Fr_{SG} = F.\sqrt{\cos\theta}$) and the Lockhart–Martinelli parameter (X), generating the physical model of Eq. (10) that determines the stratified/nonstratified transition. The stratified flow exists for all values of Fr_{SG} that satisfy Eq. (10).

This empirical model was initially proposed for a specific range of experimental data: pipe diameter from 8.9 to 300 mm; pipe inclination from 0° to -90°; liquid density from 780 to 1420 kg/m^3; gas density from 1.2 to 35 kg/m^3 and liquid viscosity from 0.0002 to 0.08 Pa.s

$$C_1 = 1.3\ln\left(\frac{D}{D_{REF}}\right) + 2.5 \tag{6}$$

$$C_2 = \frac{C_4^{0.65}}{\left[1 + 2\sin(2|\theta|).\left(1 + 1\tanh\left(\frac{1}{|\theta|}\right)\right)\right]} \tag{7}$$

$$C_3 = \begin{cases} \rho_L \leq 1000\dfrac{kg}{m^3} \Rightarrow 0.65.\left(\dfrac{\Delta\rho}{\rho_{REF}}\right).\left(\dfrac{D}{D_{REF}}\right)^{-0.15} \\[4mm] \rho_L > 1000\dfrac{kg}{m^3} \Rightarrow 0.65.\left(\dfrac{D}{D_{REF}}\right)^{-0.15} \end{cases} \tag{8}$$

$$C_4 = 0.2\sqrt{\frac{D_{REF}}{D}} \tag{9}$$

$$Fr_{SG} \leq (0.6 + C_2).\left[\frac{\exp\left(-C_1 C_2 X^{C_3}\right)}{X^{C_4}}\right] \tag{10}$$

2.3 EXPERIMENTAL DATA

There are no experimental tests developed in the present study. We used experimental data conducted by some studies published in the literature and the summary of them is presented in Table 1. We highlight that in all data listed in Table 1 the observed flow pattern was the stratified.

Table 1. Stratified Experimental data used in the present work.

Data	Reference	Fluids	θ (deg.)	D (mm)
Upward				
Data 1	Mukherjee (1979)	Kerose-Air	5	50.8
Data 2	Manabe (2001)	Oil-Natural Gas	1	55.0
Data 3	Weisman and Kang (1981)	Glycerol-Air	10	25.0
Data 4	Chupin (2003)	Oil-Air	1	60.0
Horizontal				
Data 5	Barnea et al. (1980)	Glycerol-Air	0	38.0
Data 6	Meng (2001)	Oil-Air	0	50.1
Data 7	Brito (2012)	Oil-Air	0	50.8
Data 8	Andritsos (1986)	Glycerol-Air	0	95.3
Data 9	Agrawal et al. (1973)	Oil-Air	0	30.4
Data 10	Abdul-Majeed (1996)	Kerose-Air	0	50.8
Downward				
Data 11	Nicholson et al. (1978)	Oil-Natural Gas	-5	30.5
Data 12	Nicholson et al. (1978)	Oil-Natural Gas	-9	30.5
Data 13	Mukherjee (1979)	Kerose-Air	-70	50.8
Data 14	Mukherjee (1979)	Kerose-Air	-20	50.8

3. RESULTS AND DISCUSSIONS

In the present work, we searched to (1) expand to upward inclined pipes the empirical model initially proposed by Bhagwat and Ghajar (2015) for horizontal and downward inclined pipes and (2) compare the applicability and accuracy of this empirical model to a mechanistic model proposed by Taitel and Dukler (1976).

To reach these objectives, the first step was to program the Taitel and Dukler (1976) model. Once we are using it to calculate in several conditions, against 14 data sources (more than 800 data points), the graphical solution would be impraticable. For this reason, we used the iterative solution presented in Eq. (5). The iterative solution consists in determine a value for $\tilde{h}_L$ that solves Eq. (5). Lockhart–Martinelli parameter (X) and the inclination angle dimensionless parameter (Y) are input data and the other variables are function of $\tilde{h}_L$.

There are several methods to solve such problem, e.g.: secant, Newton's, false position, Brent's and bisection method. To perform the solution of this problem, we applied the last one, for two reasons: (1) the bisection method is the simplest root-finding algorithm, since iterations involve simple calculations and (2) it is robust and always converges.

To test the accuracy of our algorithm, we generated the multi-curve plot proposed by Taitel and Dukler (1976), presented in Figure 1. Applying our program, we obtained the plot shown in Figure 2. The result was very similar to the plot from Figure 1. Thus, we guarantee that the model was correctly implemented. Note that multiple solutions are obtained for upward configurations in both figures.

We then implemented the method proposed by Bhagwat and Ghajar (2015), which is much simpler to program, since no iterative solution is required, only the solution of an inequality must be implemented (Eq. 10). After that, we used the experimental data from Table 1 and applied both models. Figure 3a presents the results of the Bhagwat and Ghajar (2015) model to identify stratified flow pattern in upward inclined pipes. We can observe that this model predicted with good accuracy the stratified flow. Comparing those results with Taitel and Dukler (1976) model, also presented in Figure 3a, we can observe the better performance of the former model.

Figure 3b shows the results for horizontal pipes. Comparing both models, we can also conclude that the experimental model also predicted more accurately the stratified flow than the mechanistic model. Note that the differences found were lower, i.e., both models have good performance for horizontal pipes.

Observing Figure 3c, which used experimental data for downward inclined pipes, Bhagwat and Ghajar (2015) also performed better than Taitel and Dukler (1976). The difference more significant was for data acquired from Mukherjee (1979); for sharply downward inclinations, the empirical model performed much better than the mechanistic one.
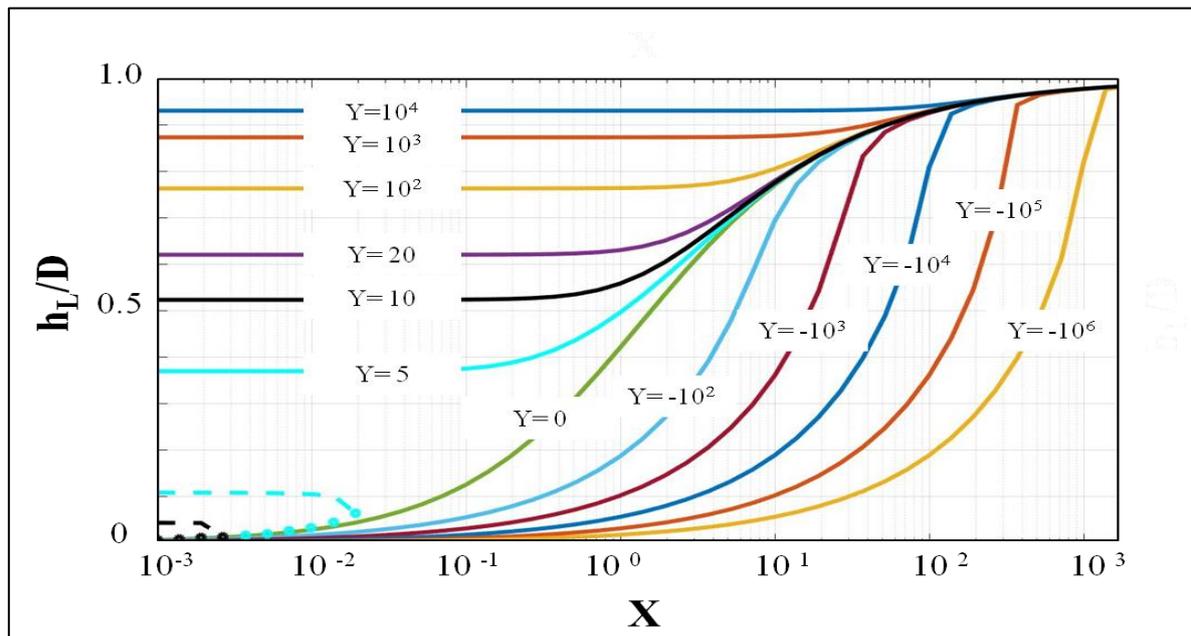

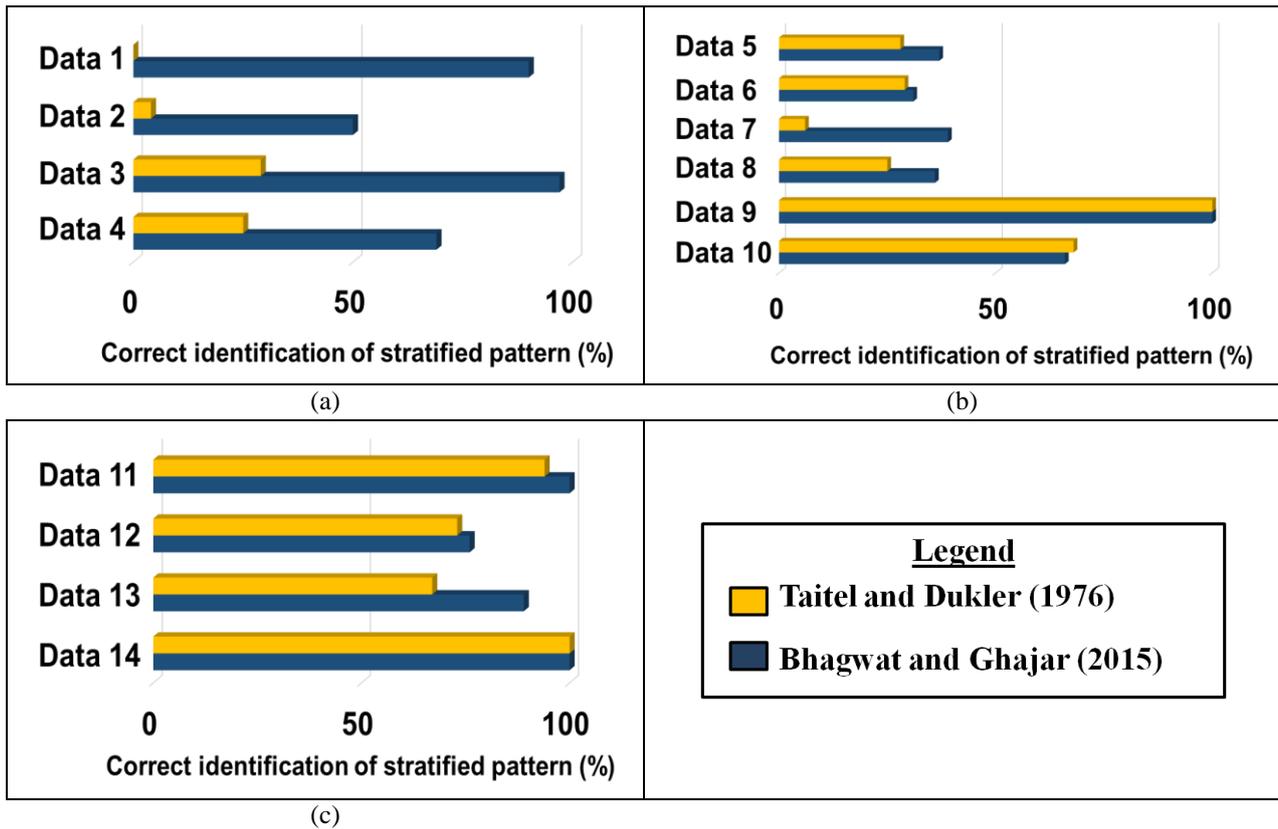Figure 2. Equilibrium liquid level for stratified flow.

(a)

(b)

(c)

Figure 3. Comparing both models: (a) upward, (b) horizontal and (c) downward inclined pipes.

In order to verify the empirical transition proposed by Bhagwat and Ghajar (2015) for upward flows, we also reproduced a map comparing the response from the empirical model and the observed points. We showed stratified and nonstratified data, thus, we could compare the observed boundary and the modeled one.

Figure 4 presents data acquired from Mukherjee (1979), for kerosene-air at 5 degrees. Although this model performed better than Taitel and Duckler (1976), as observed in Figure 3a, we can observe that the modeled curve fails for some nonstratified points, since below the curve we expected only observe stratified data, however, approximately 35% nonstratified points are erroneously identified as stratified. The same behavior was observed in data from Manabe (2001), at Figure 5, for oil-natural gas at 1 degree. The empirical model correctly identified most of the stratified points, nonetheless, the trend showed for nonstratified point did not follow the observed nonstratified flow.

In Figure 6 we reproduced measured data from Weisman and Kang (1981), for glycerol-air at 10 degrees. As we can see, the empirical model correctly identified most of the observed stratified data, per contra, still fails in identify approximately 30% of the nonstratified data. For Chupin (2003), the only data available is stratified observed points. As we can observe in Figure 7, it presented acceptable accuracy for identify stratified flow.
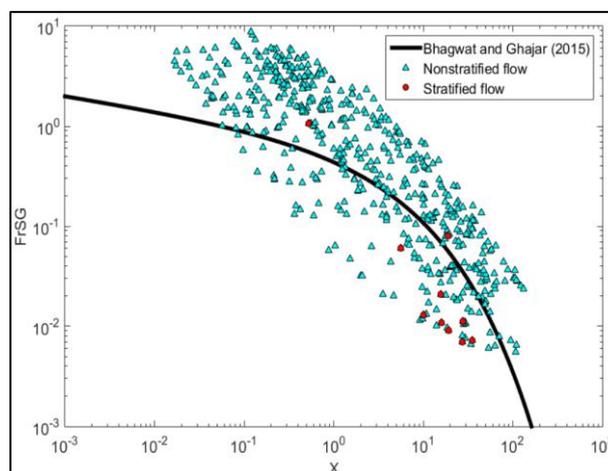

Figure 4. Prediction of stratified/nonstratifed flow using data from Mukherjee (1979).
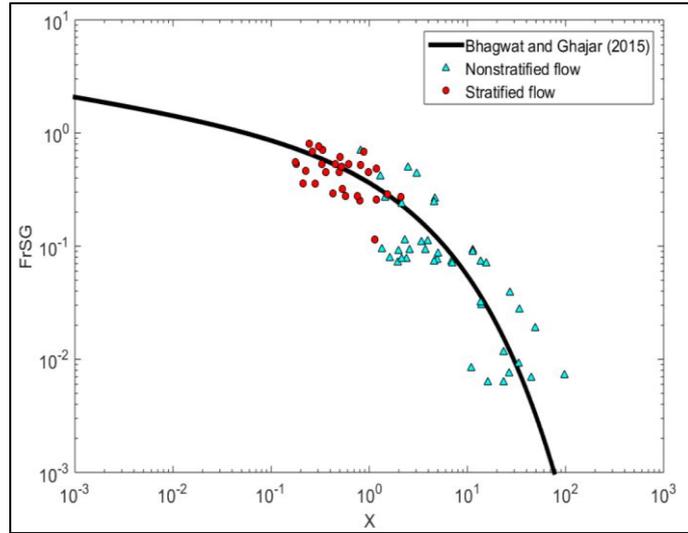
Figure 5. Prediction of stratified/nonstratifed flow using data from Manabe (2001).

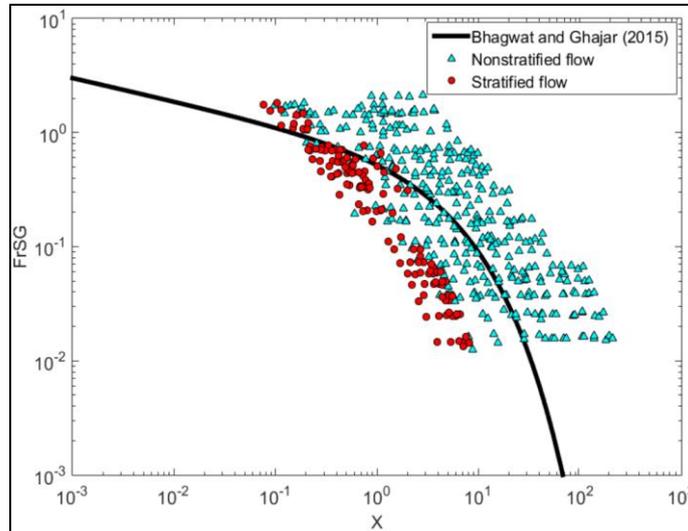
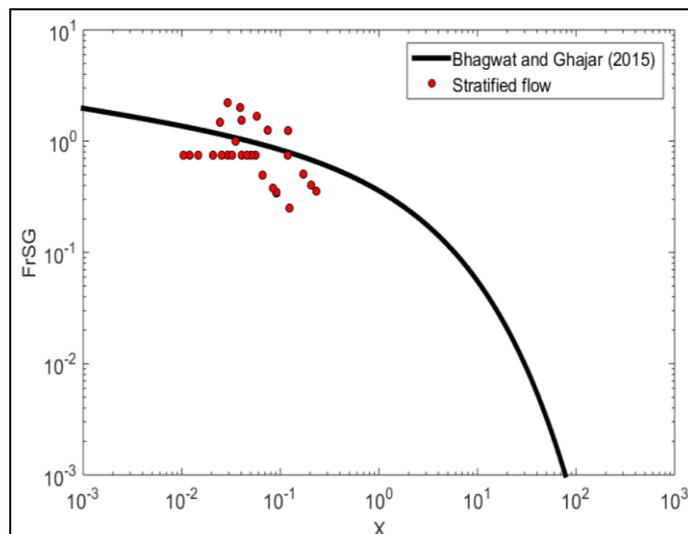Figure 6. Prediction of stratified/nonstratifed flow using data from Weisman and Kang (1981).

Figure 7. Prediction of stratified flow using data from Chupin (2003).

4. CONCLUSIONS

We studied the performance of an empirical model proposed by Bhagwat and Ghajar (2015) to predict stratified flow in upward flows. As shown in results section, the proposed model presented good accuracy in predict such flow, nonetheless, accuracy presented in the original paper to predict the boundary between stratified and nonstratified flow was not observed here for upward flow. Moreover, comparing this model with the mechanistic model proposed by Taitel and Dukler (1976), against 14 data sources, the empirical model performed better than the mechanistic one. Another important point is that the empirical model is simpler to implement, since it is an explicit equation, while the mechanistic model requires an iterative solution that can be more computationally costly.

5. NOMENCLATURE

A	area for flow, m^2
D	pipe diameter, m
$Dref$	reference pipe diameter (0.0254 m), m
F	Froude number, dimensionless
Fr_{SG}	modified Froude number, dimensionless
h_L	liquid level (under equilibrium conditions), m
g	gravitational acceleration, m/s^2
S	wetted perimeter, m
S_I	interface length, m
U	phase velocity, m/s

Greek Symbols

ρ	phase density, kg/m3
ρ_{ref}	reference value of phase density (1000 kg/m^3), kg/m^3
$\Delta\rho$	phase density difference ($\rho_L - \rho_G$), kg/m^3
θ	pipe orientation, degrees

Subscripts

G	gas phase
L	liquid phase
i	gas–liquid interface
S	superficial

Superscripts

$\sim$	dimensionless quantity
m,n	Blasius equation exponents (m=n=1 for laminar flow and m= n = 0,2 for turbulent flow), dimensionless

6. ACKNOWLEDGEMENTS

7. REFERENCES

Andritsos, N., 1986. *Effect of pipe diameter and liquid viscosity on horizontal stratified flow*. Ph.D. thesis, University of Illinois at Urbana-Champaign.

Agrawal, S.S., Gregory, G.A., and Govier, G.W., 1973. "An analysis of horizontal stratified two phase flow in pipes". *The Canadian Journal of Chemical Engineering*, 51, p. 280-286.

Abdul-Majeed, G.H., 1996. "Liquid holdup in horizontal two-phase gas—liquid flow". *Journal of Petroleum Science and Engineering*, Vol. 15, p. 271-280.

Barmak, I., Gelfgat, A. Yu., Ullmann, A., and Brauner, N., 2016. "Stability of stratified two-phase flows in inclined channels". *Physics of Fluids*, Vol. 28, p. 084101

Barnea, D. Shoham, O. Taitel, Y., 1980. "Flow Pattern Transition for Gas-Liquid Flow in Horizontal and Inclined Pipes, Comparison of Experimental Data with Theory". *International Journal of Multiphase Flow*, Vol. 6, pp 217-225.

Bhagwat, S.M. and Ghajar, A. J., 2015. "An Empirical Model to Predict the Transition Between Stratified and Nonstratified Gas–Liquid Two-Phase Flow in Horizontal". *Heat Transfer Engineering*, Vol. 36:18, p. 1485-1494.

Brito, R., 2012. *Effect of Medium Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes*, Master's dissertation, The University of Tulsa.

Chupin, G., 2004. *An Experimental Study of Multiphase Gas-Liquid Pipe Flow at Low Liquid Loading*. Ph.D. thesis, Norwegian University of Science and Technology.

Manabe, R., 2001. *A Comprehensive Mechanistic Heat Transfer Model for Two-Phase Flow with High-Pressure Flow Pattern Validation*. Ph.D. thesis, The University of Tulsa.

Meng, W., 2001. *Low Liquid Loading Gas-Liquid Two-Phase Flow in Near Horizontal Pipes*. Ph. D. thesis, The University of Tulsa.

Mukherjee, H., 1979. *An Experimental Study of Inclined Two-Phase Flow*. Ph. D. thesis, University of Tulsa.

Nicholson, M.K., Aziz, K., and Gregory, G.A., 1978. "Intermittent two phase flow in horizontal pipes: Predictive models", *The Canadian Journal of Chemical Engineering*, Vol. 56, p. 653-663.

Persen, L.N., 1984. "Stratified two-phase flow in circular pipes". *International Journal of Heat and Mass Transfer*, Vol. 27:8, p. 1227-1234.

Taitel, Y., and Dukler, A. E., 1976. "A Model for Predicting Flow Regime Transitions in Horizontal and Near Horizontal Gas–Liquid Flow", *AIChE Journal*, Vol. 22, pp. 47–55.

Tribbe, C., and Muller-Steinhagen, H.M., 2000. "An evaluation of the performance of phenomenological models for predicting pressure gradient during gas-liquid flow in horizontal pipelines". *International Journal of Multiphase Flow*, Vol. 26, p. 1019-1036.

Wallis, G.B. and Dobbins, J.E., 1973. "The onset of slugging in horizontal stratified air–water flow". *International Journal of Multiphase Flow*, Vol. 1, p. 325-335.

Weisman, J. and Kang S.Y., 1981. "Flow pattern transition in vertical and upwardly inclined lines". *International Journal of Multiphase Flow*, Vol. 7, pp. 271-291.

Wu, H.L., Pots, B.F.M., Heelenberg, J.F. and Meerhoff, R., 1987. "Flow pattern transitions in two-phase gas/condensate flow at high pressure in an 8-inch horizontal pipe", In *Proceedings of the 3rd International Conference on Multiphase Flow,* The Hague, The Netherlands.

Xiao, J. J., Shoham, O. and Brill, J. P., 1990. "A comprehensive Mechanistic Model for Two-Phase Flow in Pipes", In *Proceedings of the* 65th Annual Technical Conference, SPE 20631.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.