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Modeling And Simulation Of Stratified Gas-Liquid Multiphase Flow

Iluska Marques[1], Itallo Sampaio[1]*, Licianne Pimentel[2]

[1](*Bachelor's degree in Petroleum and Gas engineering / Jorge Amado University, Brazil)*
[1](*Bachelor's degree in Petroleum and Gas engineering/ Jorge Amado University, Brazil)*
[2] *(Master's degree in Industrial engineering/ Federal University of Bahia, Brazil)*
Corresponding Author: *Itallo Sampaio.*

ABSTRACT *: The multiphase flow is part of oil and gas industry, as well as in other industrial branches and It is extremely important to know and model it, to avoid environmental and labor risks during the processes. Even so, researches in this area are rare, and that makes it difficult to recognize the flow patterns and to detect the changes among these standards efficiently. Thus, this paper aims to create a model of a gas-liquid flow in a stratified standard, through the Excel® / Visual Basic Action (VBA) tool, with demonstration and checking of the results through Taitel and Dukler (1976) horizontal flow map. Achieving positive results regarding functionality of this model, once the results obtained were compatible. Making visible the facility and viability to create models and simulate multiphase flow through a free and accessible tool, allowing to intensify knowledge in this area, not requiring an expensive and advanced industrial software.*

KEYWORDS -*Modeling, Multiphase flow, Stratified, Taitel and Dukler.*

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I. INTRODUCTION

The multiphase flow is often found in nature as well in industrial processes, being defined as simultaneous flow composed of two phases or more with different and immiscible properties in a pipe. In this type of flow the concept of phase and component is not strictly distinguished, but rather the number of interface present in the flow [1]. The most important parameter to characterize a multiphase flow is the ratio between the steam flow and liquid flow. This ratio determines the type of flow configuration which significantly influences the parameters of project [2].

This paper aims the modeling and simulation of a gas-liquid multiphase flow in a horizontal pipe, through the Excel® / Visual Basic Action (VBA). In this context, the behavior of gas-liquid mixture in a separate steady state stratified isothermal flow will be demonstrated through correlations created based on the Taitel and Ducker (1976) equations. Making visible the facility and viability to create model and simulate multiphase flow through a free and accessible tool, allowing to intensify knowledge in this area, not requiring and expensive and advanced industrial software.

II. MATERIAL AND METHODS

The stratified multiphase flow pattern occurs when there are phases going through in a pipe with continuous interface between them. Figure. 1 below, represents a flow map developed by Taitel and Dukler (1976), which determines the transitions between flows.

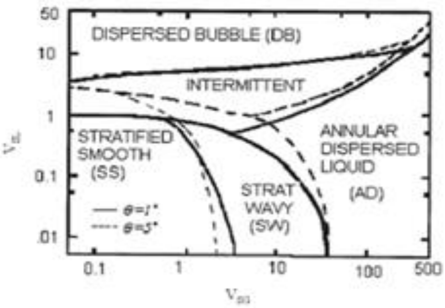

Figure 1 – Two-Phases Flow Map by Taitel and Dukler (1976)

The model of Taitel and Dukler (1976) will be used to determinate the pressure differential in each phase. The starting point is to find the steam area, which in turn inferred using geometrics relations with the pipe. Thenceforward, the fluid flow pattern and the transition between stratified flow and another one can be identified. The inclination angle (θ), of the pipe is an important factor to consider during the process of determining a multiphase flow, thus, it was considered in the approach of this article.
In this model, some characteristics were adopted for the flow to simplify the calculations. Therefore, the flow presented is stratified, multiphase, isothermal, in steady state. Fig. 2 allows show the frontal and transverse cross-section to evaluate its variables.

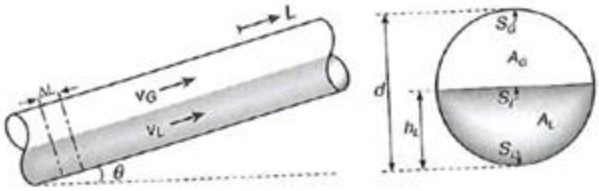

Figure 2 – Pipe section with smooth stratified fluid flow

Analyzing the models below, make visible that it can be solved in function of geometrics relations, being: A_g gas area, A_l liquid area, τ_{wg} shear stress between the gas and the pipe, τ_{wl} shear stress between the liquid and the pipe, τ_i shear stress at gas-liquid interface, s_g surface wetted by gas, s_l surface wetted by liquid, s_i surface at gas-liquid interface, ρ_g specific gas mass, ρ_l specific liquid mass, g gravity (9,8m/s), sinθ inclination angle of pipe.
Assuming a steady state flow, the balance of forces in the phases acquires the following configuration:

$$-A_l\frac{dP_l}{dx} - \tau_{wl}S_l + \tau_i S_i - \rho_l A_l g\sin(\theta) = 0 \quad (1)$$

$$-A_g\frac{dP_g}{dx} - \tau_{wg}S_g - \tau_i S_i - \rho_g A_g g\sin(\theta) = 0 \quad (2)$$

$dP_l/dx = dP_g/dx$Being, is admissible:

$$-\tau_{wl}\frac{s_l}{A_l} + \tau_i\frac{s_i}{A_l} - \rho_l g\sin\theta + \tau_{wg}\frac{s_g}{A_g} + \tau_i\frac{s_i}{A_g} + \rho_g g\sin\theta = 0 \quad (3)$$

According to Taitel and Dukler (1976), the gas area (A_g) is defined by ratio between the height of liquid (h_l) and the total pipe diameter (D):

$$A_g = 0{,}25.\,D^2.\left[\cos^{-1}\left(2\frac{h_l}{D}-1\right) - \left(2\frac{h_l}{D}-1\right)\sqrt{1-\left(2\frac{h_l}{D}\right)^2}\right] \quad (4)$$

$$A_l = A - A_g \quad (5)$$

According to Taitel and Dukler (1976), the value of liquid height required to find gas area in the Equation (4), is determined by an initial estimate, which in article was calculated by a numerical approach by a computational tool Excel® / Visual Basic Action (VBA).
The shear stresses are calculated by Fanning's friction factor (*f*), mean velocity (V) and a specific phases mass (ρ):

$$\tau_{wg} = f_g\frac{\rho_g|v_g|v_g}{2} \quad (6)$$

$$\tau_{wl} = f_l\frac{\rho_l|v_l|v_l}{2} \quad (7)$$

$$\tau_i = f_i\frac{\rho_g|v_g - v_l|(v_g - v_l)}{2} \quad (8)$$

The phases slip velocity (V) is obtained by the ratio between the surface velocity (V_s) of each one of the phases on the void fraction (α) of the same:

$$V_f = \frac{V_{sf}}{\alpha_f} \tag{9}$$

The hold up of liquid is calculated by the ration of the volume of liquid in a stretch of the section to the total volume of that section. Is admissible that empty fraction is calculated by the ration of the liquid area in this transverse cross-section to the total area of the pipe.

$$\alpha_g = \frac{A_g}{A} \tag{10}$$

$$\alpha_l = \frac{A_l}{A} \tag{11}$$

To define the Reynolds Number (Re), It is necessary to have a relation between some fluids properties, as: specific mass (ρ_g, ρ_l), slip velocity (V_{sg},V_l), viscosity (μ_g, μ_l). And the hydraulic pipe diameter (D_h).

$$Re_g = \frac{D_{hg}|V_g|\rho_g}{\mu_g} \tag{12}$$

$$Re_l = \frac{D_{hl}|V_l|\rho_l}{\mu_l} \tag{13}$$

According to Taitel and Barnea (1976), the hydraulic diameter (D_h) can be calculated by:

$$D_{hg} = \frac{4\,A_g}{S_g+Si} \tag{14}$$

$$D_{hl} = \frac{4\,A_l}{S_l} \tag{15}$$

The surfaces of pipe wetted by each phase (S_g, S_l) and the surface at gas-liquid interface (Si), are obtained by:

$$S_g = D.\cos^{-1}\left(2\frac{h_l}{D} - 1\right) \tag{16}$$

$$S_i = D.\sqrt{1 - \left(2\frac{h_l}{D} - 1\right)^2} \tag{17}$$

$$S_l = D.\left[\pi - \cos^{-1}\left(2\frac{h_l}{D} - 1\right)\right] \tag{18}$$

The friction factors between the phases and pipe (f_g, f_l), were defined according to Taitel and Dukler (1976), through a relation with the Reynolds Number of the fluid:

$$f_g = C_g(Re_g)^{-m} \tag{19}$$

$$f_l = C_l(Re_l)^{-n} \tag{20}$$

$$Re_l \leq 2300 \rightarrow 1 \quad Re_g \leq 2300 \rightarrow 16$$

Where, C_g and C_l is 16 if, else 0,046; m and n is 1 if else 0,2.

According to Taitel and Dukler (1976), the friction factor at gas-liquid interface (f_i) is equal to the gas. However, it was calculated by [3] in this paper. It created satisfactory results as soft stratified flow as wavy stratified flow.

$$f_i = f_g, \ \ toV_{sg} \leq 5\ m/s \tag{21}$$

$$f_i = f_g\left(1 + 15\left(\frac{V_{sg}}{5} - 1\right)\left(\frac{h_l}{D}\right)\right)^{0,5}, \ \ to\ V_{sg} > 5\ m/s \tag{22}$$

II.1 Determination Of Stratified Flow Pattern

According to Kelvin-Helmholtz's theory, Taitel and Dukler (1976) created an equation to determine the stability of flow in a tubular section, considering the inclination angle of pipe (θ), the Froud Number of gas (Fr_g) and the critical Froud Number of gas (Fr_{gc}), where:

$$Fr_g < Fr_{gc}\sqrt{cos(\theta)} \Rightarrow Stratified$$
$$Fr_g \geq Fr_{gc}\sqrt{cos(\theta)} \Rightarrow Not\ Stratified$$

Being:

$$Fr_g = \left(\frac{\rho_g}{(\rho_l - \rho_g)g.D}\right)^{0,5} V_{sg} \qquad (23)$$

$$Fr_{gc} = \left(1 - \frac{h_l}{D}\right)\left(\alpha_g{}^3 \frac{\pi D}{4S_i}\right)^{0,5} \qquad (24)$$

Once classified as stratified, the flow can be a soft flow with continuous gas-liquid interface or a wavy flow with waves on the gas-liquid interface, indicating a change in the flow pattern. Being the inclination angle $\theta \geq 0$, it can be a horizontal or an ascending flow. According to Taitel and Dukler (1976) the criterion to determinate this is:

$$\theta \geq 0 \begin{Bmatrix} K < K_C \Longrightarrow Soft\ Stratified \\ K \geq K_C \Rightarrow Wavy\ Stratified \end{Bmatrix}$$

Else $\theta < 0$ is a downward flow. Thus, the criterion adopted in this paper is Barnea et al (1982a):

$$\theta < 0 \begin{Bmatrix} Fr_l \leq 1,5 \Longrightarrow Soft\ Stratified \\ Fr_l > 1,5 \Longrightarrow Wavy\ Stratified \end{Bmatrix}$$

Being:

$$K = Fr_g\, Re_{sl}{}^{0,5} \qquad (25)$$

$$K_c = 2\alpha_g \left(\frac{\alpha_l\, cos(\theta)}{0,01}\right)^{0,5} \qquad (26)$$

$$Fr_l = \frac{V_l}{\sqrt{g h_l}} \qquad (27)$$

The diagram below summarizes the criteria to determine the stratified flow pattern:

$$Fr_g < Fr_{gc}\sqrt{cos\,\theta} \begin{cases} \theta \geq 0 \begin{cases} K < K_c \Longrightarrow Soft\ Stratified \\ K \geq K_c \Longrightarrow Wavy\ Stratified \end{cases} \\ \theta < 0 \begin{cases} Fr_l \leq 1,5 \Longrightarrow Soft\ Stratified \\ Fr_l > 1,5 \Longrightarrow \text{Wavy Stratified} \end{cases} \end{cases}$$
$$Fr_g \geq Fr_{gc}\sqrt{\cos\theta} \Longrightarrow \text{Not Stratified}$$

III. SIMULATION&RESULTS

The Equation (3) created by Taitel and Dukler (1976) was reproduced in Excel®/VBA. This allowed the modeling of gas-liquid flow in a horizontal tubular section as a function of the liquid height (h_l), checking if the flow is not stratified or soft and wavy stratified. The correlation adopted was validated through the flow map created by Taitel and Dukler (1976), showed in the Fig. 1. Where, it has means for checking the horizontal flow pattern in a tubular section through the slip velocity of gas (V_{sg}) and slip velocity of liquid (V_{sl}). Table 1 show the input data and their respective values adopted, necessary to modeling the flow through this tool.

Table 1 - Distribution of values to input data flow

V_{sg}	10.0 m/s
V_{sl}	0.1 m/s
ρ_g	1.14 kg/m³
ρ_l	993 kg/m³
μ_g	0.000019 Pa/s
μ_l	0.00068 Pa/s
D	0.05 m
θ	0

The Table 2 presents tests for validation of the model, comparing the results obtained with the flow map of Taitel and Dukler (1976). Where, it is necessary to vary the slip velocity of the phases on the same scale.

Table 2 – Table comparing the results obtained with the flow map created by Taitel and Dukler (1976)

		Vsl				
		0,01	0,1	1	10	100
Vsg	0,01	S-S	N-S*	N-S	N-S	N-S
	0,1	S-S	S-S	N-S	N-S	N-S
	1	S-S	S-S	N-S	N-S	N-S
	10	W-S	W-S	N-S	N-S	N-S
	100	N-S	N-S	N-S	N-S	N-S

S-S	Soft Stratified
W-S	Wavy Stratified
N-E	Not Stratified
*	Interface

The results obtained using the correlations created by Taitel and Dukler (1976), applied to the Excel® computational tool, were satisfactory and showed compatibility with the flow map of Fig. 1, mostly. Except for the test with V_{sg} being 0,01 m/s and V_{sl} being 0,1 m/s, which showed incompatibility with the original flow map, but this inconsistency is justified because it is an area close to transition between standards, as showed in Table 2.

IV. CONCLUSION

The multiphase flow is present in many industrial branches. All existing flow types are susceptible to appear at any times during industrial process, regardless of the follow-up. Making it necessary to know, dominate and predict the behavior of these flows efficiently avoiding situations of risk generation and financial loss. Nevertheless, there are few effective words in this area, which serve to model and simulate a multiphase flow, determining their flow patterns. That comes, mostly, to the difficulty of correlating the number of equations in the field of fluid mechanics of the real conditions of multiphase flow, as well as the limited conditions for laboratory tests, which, often, the empirical tests performed in laboratories usually have a different scale from the real conditions, to which these flows are submitted in industry.

Many industrial simulators used to classify flow patterns are costly. Thus, it can be seenthis study has a significant contribution, both for the literature and for practical application, and it makes possible future studies, especially regarding the application of this tool to other types of multiphase flow pattern.

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