SLUG TO CHURN TRANSITION ANALYSIS IN UPWARD VERTICAL TWO-PHASE FLOW

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Abstract. *The prediction of gas-liquid two-phase flow patterns is still an unresolved issue and has been the focus of study of a large number of authors whose efforts were directed towards the development of physical models aimed at the analytical prediction of the flow patterns and their transition boundaries. Several models to delineate the slug-to-churn flow transition have been suggested, due to the relevance of the aforementioned transition to many engineering enterprises, as it is the case of the petroleum and the chemical industries. However, there is a great deal of uncertainty over the most accurate model to predict the slug-to-churn flow transition, mainly because of the subjective methods adopted by each author to identify the slug and churn flow patterns, and also due to the difficulty in modelling this chaotic transition. The present work aims at reviewing some existing models to predict the slug-to-churn flow transitions. The performances of these models were evaluated and compared to experimental data for different flow conditions.*

Keywords: *Gas-liquid flow, flow pattern, slug flow, churn flow*

1. INTRODUCTION

Two-phase gas-liquid flows are natural phenomena also present in several human enterprises, such as the petroleum, chemical and nuclear industries. These flows are characterized by the diverse spatial configurations – called *flow patterns* – the interfaces between the phases may assume. In vertical, upward flows, four main flow patterns stand out: bubble, slug, churn and annular.

Churn flow is a highly chaotic vertical two-phase flow pattern. The oscillatory behaviour of the liquid is characteristic of this flow. The liquid phase exhibits an irregular, non-periodic behaviour that makes chunks of liquid to flow upwards and downwards in an alternate manner. The liquid usually moves in the same direction of that of the gas; however, the liquid flow may often briefly stall or even go in a direction opposite of that of the gas. This pattern occurs for gas flow rates that are intermediate to those characteristic of the slug and the annular flow patterns.

Slug-to-churn flow transition has been the focus of intensive research, due to its importance to a number of engineering applications and to its difficult prediction – according to McQuillan and Whalley (1985), accurately predicting churn flow is an endeavour with a success rate of only 36%. Yet, there has been debate on the accuracy of the models that outline this transition, due to the lack of agreement on the characterization of the flow patterns and on the determination of the transition mechanisms that trigger the onset of churn flow. The *identification* of such mechanisms has also been matter of some dispute.

Jayanti and Hewitt (1992) presented an excellent review on that what they called "schools of thought" on the mechanisms that cause the transition from slug to churn flow. According to these authors, researchers have identified four basic effects dominating this transition: the entrance effect, flooding, the wake effect and the bubble coalescence mechanism.

The *entrance effect* considers churn flow as a transition to stable slug flow. In this case, gas and liquid at the pipe inlet form short liquid slugs and Taylor-Dumitrescu bubbles. The unstable character of the liquid slugs favours their collapse and subsequent coalescence into bigger slugs. Eventually, if the pipe is long enough, the successive collapse and coalescence of these slugs result in a longer, stable slug. The oscillatory nature of this process results in a flow pattern that appears to be churn flow. Experimental work carried out by Dukler and collaborators in pipes of diameters of 0.025 and 0.05 m is the supporting basis of this theory. The well-known Dukler and Taitel (in Jayanti and Hewitt, 1992) formula (Eq. (1) in the next section) provides the entrance length required for the formation of a stable slug.

Flooding of the liquid film, or simply *flooding*, is the phenomenon that causes the breakdown of the liquid film around the Taylor bubble due to the formation of large interfacial waves. McQuillan and Whalley (1985) and other researchers endorse this theory as the basis for this transition, and there is experimental evidence supporting it. Wallis and Chaudry *et al*. (in Jayanti and Hewitt, 1992) carried out experiments where the flooding mechanism was observed.

Some researchers (Mishima and Ishii, 1984; Chen and Brill, 1997) sustained that the wake created by the ascent of a Taylor bubble would destroy its trailing liquid slug. On the verge of the slug-churn transition, liquid slugs would become very short and therefore Taylor bubbles would then be very close to each other, thus creating a strong wake effect capable of destroying the liquid slug between adjacent bubbles. In these circumstances, the void fraction at the

Taylor bubble region would be equivalent to the average void fraction in the entire pipe. This phenomenon is known as the *wake effect*.

The *bubble coalescence mechanism* associates the slug-to-churn transition to highly aerated liquid slugs. This theory sustains that the gas in the liquid slugs takes the form of dispersed bubbles due to turbulence, but as soon as the void fraction in the slug becomes bigger than 0.52, the bubbles collide and coalesce due to their proximity. Therefore, the transition to churn flow should occur at α_{LS} = 0.52, a figure 44% smaller than the maximum possible packing fraction of 0.74. This is an indication that collision between bubbles increase quickly as the bubbles get closer. Brauner & Barnea (1986) supported this kind of mechanism and developed a model which presented a more accurate expression for the transitional void fraction in the liquid slug.

In this work, a comparative analysis on the performance of slug-to-churn transition models from different "schools of thought" will be presented. Initially, the mechanisms that outline the transition and their corresponding equations will be discussed. Then outputs from computational implementations of these models will be compared to experimental data collected by Brauner and Barnea (1986) and by Costigan and Whalley (1997) in vertical, 25-mm and 32-mm ID pipes, respectively. The models here scrutinized are: Jayanti and Hewitt (1992), McQuillan and Whalley (1985) (*Flooding*), Mishima and Ishii (1984), Chen and Brill (1997) (*Wake effect*), Brauner & Barnea (1986) (*Bubble coalescence*) and Taitel *et al*. (1980) (*Entrance effects*). Also, a modification to the Chen and Brill (1997) model will be suggested and its results analyzed. Finally, it will be shown that no school has a clear predominance over the others, when it comes to accurately predicting the slug-to-churn transition.

2. LITERATURE REVIEW

A few mechanisms aimed at describing the slug-to-churn transition have been proposed and were divided into four main categories. In this section, models from these categories will be reviewed. Later on, recent models and advances on the slug-to-churn transition will be briefly introduced. In the last subsection, an alternative approach to the Chen and Brill (1997) model will be presented.

2.1 Entrance effects

Taitel *et al.* (1980) regard churn flow as phenomenon characterized by the oscillatory motion of the liquid, associated with liquid plugs that are too short to effectively form a stable bridge between two neighbouring Taylor bubbles. They also sustain that whenever churn flow is observed, stable slug units should be expected further along the pipe. As controversial as their observations might seem, experiments carried out at their labs support their remarks.

Based on an expression for the exponential decay of the liquid slug length, they proposed a stable slug length, or an entry length for churn flow, l_e, above which churn flow exists:

$$\frac{l_e}{D} = 40.6\left(\frac{u_M}{\sqrt{gD}} + 0.22\right) \tag{1}$$

where u_M is the mixture velocity, g is the gravitational acceleration and D is the tube inner diameter. This expression was later improved by Dukler and Taitel (1986) (in Jayanti and Hewitt, 1992), producing slightly better results.

2.2 Flooding

McQuillan and Whalley (1985) understood the onset of churn flow as the result of an increase in the gas flow rate until the gaseous phase "floods" the liquid film around the Taylor bubble. Based on several investigations that supported the evidence of liquid film flooding, these two researchers found out that the following semi-empirical expression (by Hewitt and Wallis, 1963) might be used to foretell the flooding gas and liquid flow rates:

$$\left(u_{BS}^*\right)^{1/2} + \left(u_{FS}^*\right)^{1/2} = C \tag{2}$$

In their work, Eq. (2) is used to determine the boundary between slug and churn flow patterns. C is a constant and the dimensionless superficial velocities of the Taylor bubble u_{BS}^* and the liquid film u_{FS}^* are defined as:

$$u_{BS}^* = u_{BS}\rho_G^{1/2}\left[gD(\rho_L - \rho_G)\right]^{-1/2} \tag{3}$$

$$u_{FS}^* = u_{FS}\rho_L^{1/2}\left[gD(\rho_L - \rho_G)\right]^{-1/2} \tag{4}$$

and the superficial velocities of the Taylor bubble u_{BS} and the liquid film u_{FS} are calculated by Eqs. (5) and (6), respectively.

$$u_{BS} = \left(1 - 4\frac{\delta}{D}\right)\left[1.2\left(u_{GS} + u_{LS}\right) + 0.35\sqrt{\frac{gD(\rho_L - \rho_G)}{\rho_L}}\right] \tag{5}$$

$$u_{FS} = u_{BS} - (u_{GS} + u_{LS}) \tag{6}$$

In eq. (5), u_{LS} is the liquid superficial velocity and δ is the film thickness in the Taylor bubble region, and is evaluated by the following expression proposed by Nusselt (1916):

$$\delta = \left[\frac{3u_{FS}D\mu_L}{4g(\rho_L - \rho_G)}\right]^{1/3} \tag{7}$$

The second work based on flooding herein discussed is due to Jayanti and Hewitt (1992). These two scientists analyzed earlier transition models and concluded that the most likely transition mechanisms were flooding and the excessive amount of bubbles in the liquid slug. However, to their judgement, the governing mechanism for the void fraction in the liquid slug was largely misunderstood. Therefore, Jayanti and Hewitt (1992) elected McQuillan and Whalley (1985) model as the basis for a new model, and made improvements on two inadequate features of the aforementioned base model. The liquid film, which was regarded as laminar, came to be modelled by the Brotz (1954) (in Jayanti and Hewitt, 1992) correlation, which is valid for a wide range of Reynolds numbers. Moreover, the liquid film length, initially neglected in the flooding rate calculations, came to be taken into account. This latter improvement corrected a known inadequacy of this model with regard to predicting transitions at high flow rates, when the liquid film lengths are smaller than the ones observed at lower liquid flow rates.

Equation (8) was proposed to evaluate the film thickness considering the Brotz (1954) correlation.

$$u_{FS} = 9.916\left(1 - \alpha_{TB}\right)\sqrt{\frac{gD(\rho_L - \rho_G)\left(1 - \sqrt{\alpha_{TB}}\right)}{\rho_L}} \tag{8}$$

where

$$\alpha_{TB} = 1 - 4\frac{\delta}{D} \tag{9}$$

An empirical correlation, Eq. (10), was suggested by the authors to take account of the falling film length on the flooding velocity.

$$\sqrt{u_{BS}^*} + m\sqrt{u_{FS}^*} = 1 \tag{10}$$

where the coefficient m is a function of L/D and is given by:

$$m = 0.1928 + 0.01089\left(L/D\right) - 3.754\times10^{-5}\left(L/D\right)^2 \qquad \text{if } L/D \le 120 \tag{11}$$

$$m = 0.96 \approx 1 \qquad \text{if } L/D > 120 \tag{12}$$

2.3 Bubble coalescence

Brauner and Barnea (1986) proposed that the formation of highly aerated liquid slugs is the main condition for the destruction of otherwise stable, well-formed slugs. Thus, the continuity of the liquid slug is hence destroyed. They used an earlier model developed by Barnea and Brauner (1985) to evaluate the void fraction in the slug, given by:

$$\alpha_S = 0.058\left[d_c\left(\frac{2f_M u_M^3}{D}\right)^{0,4}\left(\frac{\rho_L}{\sigma}\right)^{0,6} - 0.725\right]^2 \tag{13}$$

where σ is the surface tension and d_c is the characteristic bubble size for vertical flow, given by:

$$d_c = 2\sqrt{\frac{0.4\sigma}{g(\rho_L - \rho_G)}} \tag{14}$$

And the friction factor, f_M, is defined as

$$f_M = \frac{2\tau_w}{\rho_L u_M^2} \tag{15}$$

where τ_w is the wall shear stress. Brauner and Barnea (1986) then stated that the transition from slug to churn flow occurs when α_S reaches a maximum, α_{MAX}, equal to 0.52, corresponding to the bubble maximum volumetric packing.

2.4 Wake effects

Mishima and Ishii (1984) claimed that the slug-to-churn transition takes place due to the wake effect generated by the Taylor bubbles. When two bubbles are close enough, the wake effect would destabilize and destroy the liquid slug, thus causing the transition to churn flow. Their mathematical criterion evaluated the point when the void fraction of the unit cell, α_U, exceeded that of the Taylor bubble, α_{TB}. The void fraction of the unit cell is computed by applying the drift flux model and the void fraction in the Taylor bubble region is calculated by applying an analysis based on potential flow.

$$\alpha_U = \frac{u_{GS}}{\left[C_0 u_M + 0.35\sqrt{gD(\rho_L - \rho_G)/\rho_L}\right]} \tag{16}$$

$$\alpha_{TB} = 1 - 0.813\left\{(C_0 - 1)u_M + 0.35\sqrt{\frac{gD(\rho_L - \rho_G)}{\rho_L}}\left[u_M + \frac{3}{4}\sqrt{\frac{gD(\rho_L - \rho_G)}{\rho_L}}\left(\frac{gD^3(\rho_L - \rho_G)\rho_L}{\mu_L^2}\right)^{1/18}\right]^{-1}\right\} \tag{17}$$

where ρ_G and ρ_L are the densities of the gas and the liquid phases, respectively, u_{GS} is the gas superficial velocity, μ_L is the liquid dynamic viscosity, and C_0 is calculated by Eqs. (18) and (19), for round tubes and rectangular ducts, respectively.

$$C_0 = 1.20 - 0.20\sqrt{\rho_G/\rho_L} \tag{18}$$

$$C_0 = 1.35 - 0.35\sqrt{\rho_G/\rho_L} \tag{19}$$

Chen and Brill (1997) proposed a new transition model based on the wake effect occurring at the tail of a typical Taylor bubble. The authors split the liquid slug in three regions: the wake, the intermediate and the developed regions. As the gas flow rate increases the effects of the wake region on the liquid slug dominate and affects the nose of the bubble right ahead. That might result in the collapse of the slug and consequentially in the transition to churn flow.

Equation (20) represents the transition criteria proposed by the authors.

$$\beta_S \le 0.15, \quad \alpha_S \ge 0.52 \tag{20}$$

where α_S is the void fraction in the slug while $\beta_S = L_S / L_U$ is the relative length of the liquid slug. Considering the gas as incompressible, the total volumetric flow rate of the mixture is constant at any cross section. Therefore,

$$\alpha_{TB}u_{TB} - (1-\alpha_{TB})u_F = u_{GS} + u_{LS} = u_M \tag{21}$$

where u_{TB} is the gas velocity within the Taylor bubble, respectively, u_F is the liquid film terminal velocity, u_{GS} and u_{LS} are the gas and liquid superficial velocities, respectively, and u_M is the mixture velocity.

A mass balance across the entire slug unit can be approximated by:

$$u_{GS} = \alpha_{TB}(1-\beta_S)u_{TB} + \alpha_S\beta_S(u_{GS} + u_{LS}) \tag{22}$$

Considering a coordinate system moving with the Taylor bubble at a translational velocity u_T, a gas balance relative to this system yields:

$$\alpha_S (u_T - u_M) = \alpha_{TB} (u_T - u_{TB}) \tag{23}$$

The translational velocity of the Taylor bubble can be evaluated with Eq. (24), as per Nicklin *et al.* (1962):

$$u_T = 1.2 u_M + 0.35 \left[\frac{gD(\rho_L - \rho_G)}{\rho_L} \right] \tag{24}$$

The system formed by Eqs. (21) to (24) must be solved to find α_{TB}. The film thickness can then be determined by the following equation:

$$u_F = 9.916 \sqrt{\frac{gD(\rho_L - \rho_G)\left(1 - \sqrt{\alpha_{TB}}\right)}{\rho_L}} \tag{25}$$

2.5 An alternative approach to the model of Chen and Brill (1997)

In this article, a new form for Eq. (25) is proposed. Equation (26) determines the terminal thickness of the liquid film around a Taylor bubble (Chen and Brill, 1997)

$$\delta_F \left[\frac{(\rho_L - \rho_G) g}{\rho_L \nu_L^2} \right]^{1/3} = k \,\mathrm{Re}_F^m \tag{26}$$

Equation (26) can be worked out to provide:

$$\delta_F^3 \left[\frac{(\rho_L - \rho_G) g}{\rho_L \nu_L^2} \right] = k^3 \,\mathrm{Re}_F^{3m} = k^3 \left[\frac{\rho_L u_F \delta_F}{\mu_L} \right]^{3m} \tag{27}$$

Yielding:

$$u_F^{3m} = \frac{\delta_F^3 \,\Delta\rho\, g\, \mu_L^{3m}}{\rho_L\, \nu_L^2\, \rho_L^{3m}\, \delta_F^{3m}\, k^3} \tag{28}$$

Making m = 2/3,

$$u_F^2 = \frac{\delta_F\, \Delta\rho\, g\, \mu_L^2}{\rho_L^3\, \nu_L^2\, k^3} = \frac{\delta_F\, \Delta\rho\, g\, \mu_L^2}{\rho_L^3 \left(\mu_L^2 / \rho_L^2\right) k^3} = \frac{\delta_F\, \Delta\rho\, g}{\rho_L\, k^3} \tag{29}$$

$$u_F = \frac{1}{k^{3/2}} \sqrt{\frac{\delta_F\, \Delta\rho\, g}{\rho_L}} \tag{30}$$

The void fraction in the Taylor bubble region, α_{TB}, can be expressed as a function of the liquid film thickness, δ_F

$$\alpha_{TB} = \frac{\pi\left(D - 2\delta_F\right)^2}{\pi D^2} \tag{31}$$

Thus,

$$0.5D\left(1 - \sqrt{\alpha_{TB}}\right) = \delta_F \tag{32}$$

Substituting Eq. (32) in (30), gives:

$$u_F = \frac{\sqrt{2}}{2\,k^{3/2}}\sqrt{\frac{gD\left(\rho_L-\rho_G\right)\left(1-\sqrt{\alpha_{TB}}\right)}{\rho_L}} \tag{33}$$

Finally, using k = 0.0682 in Eq. (33) as suggested by Chen & Brill (1997) yields $C = \sqrt{2}\,/\,(2\,k^{3/2})$ = 39.702 and thence

$$u_F = 39.702\sqrt{\frac{gD(\rho_L-\rho_G)\left(1-\sqrt{\alpha_{TB}}\right)}{\rho_L}} \tag{34}$$

The consequences of replacing Eq. (25) by Eq. (34) into the Chen and Brill (1997) model will be discussed in the following section, and the results for both C = 9.916 and C = 39.702 will be presented.

2.6 More recent models and developments on the slug-to-churn transition

Watson and Hewitt (1999) studied the effect of pressure on the slug-to-churn flow pattern transition. The transition was determined through the analysis of void fraction probability distribution from measurements taken with impedance probes. The authors concluded that the model of Jayanti and Hewitt (1992) performed best in predicting the slug to churn transition.

Barbosa *et al.* (2001) utilized high-speed video recording to study the flow. The liquid was injected in an air flow through a porous wall in order to create counter-current flow. This condition is similar to the film flow around the Taylor bubble in slug flow. They clearly observed the flooding wave formation process, suggesting that these waves are the same that occur in the transition to churn flow.

Carvalho (2006) claimed that flooding is believed to occur at a given value of $\rho_G u_G^2$. In order to better visualize the transition at lower fluid velocities than in air-water flow, the author increased the gas density utilizing argon instead of air and tried different pressures. High-speed video cameras and fast response pressure transducers tracked a long slug that was released in an upward water flow. They observed pressure spikes as a result of flooding in the slug. When the gas density and/or liquid velocities were raised above certain levels, the flooding of the Taylor bubble at a given distance from the bubble nose was clearly observed in the video recordings.

Waltrich *et al.* (2012) investigated the development of slug and churn flows in a 42-m long vertical tube utilizing high-speed cameras, pressure transducers and conductivity probes. They observed similarities between the slug flow near the entrance of the pipe and churn flow. This may have motivated some confusion in the past about the existence of churn flow. Brauner and Barnea (1986) and Jayanti and Hewitt (1992) models showed good agreement with experimental data obtained for lower pressures.

3. RESULTS AND DISCUSSIONS

Several slug-to-churn transition models from the literature were compared to air-water experimental data obtained by Brauner and Barnea (1986) and by Costigan and Whalley (1997) in vertical, 25-mm and 32-mm ID pipes, respectively.

Figures 1 and 2 show the data as discrete, scattered points and the transitions calculated by the transition models are represented as either continuous, dashed, or dotted lines. As it can be observed, no agreement among the models in terms of either the shapes, curvatures or the flow regions their transition curves delimit was found.

Most models performed better when compared to the smallest pipe ID (25.4 mm) data, except McQuillan and Whalley's (1985) whose curves in Figs. 1 and 2 showed no detectable difference with regard to their loci, thus evidencing that changes in pipe diameter play a minor role in this model. In the opposite trend, Taitel *et al* showed a noticeable shift towards the slug flow region, that is, to lower j_G values.

For 25.4-mm ID data, all churn data points fell within the Jayanti and Hewitt (1992), Mishima and Ishii (1984) and both Chen and Brill (1997) curves. Brauner and Barnea (1986) presented a few misses, but its accuracy on transition detection was still fair.

For the 32-mm ID data, Jayanti and Hewitt (1992) and Mishima and Ishii (1984) showed the best performance among the seven models tested in this article. Both failed to explain a few churn data points, nevertheless.

The modified Chen and Brill (1997) model showed better agreement for the smallest ID (25.4 mm) than for the 32 mm pipe data. In the former case, a shift towards the slug flow region is observed for lower (j_G, j_L) pairs whereas although such shift reduces for the 32 mm data 25% of a grand total of 20 churn data points could not be explained. In general, this new approach proved to be not entirely satisfactory.

Finally, it was found that Jayanti and Hewitt (1992) model showed the best agreement with Brauner and Barnea (1986) and Costigan and Whalley (1997) experimental data.

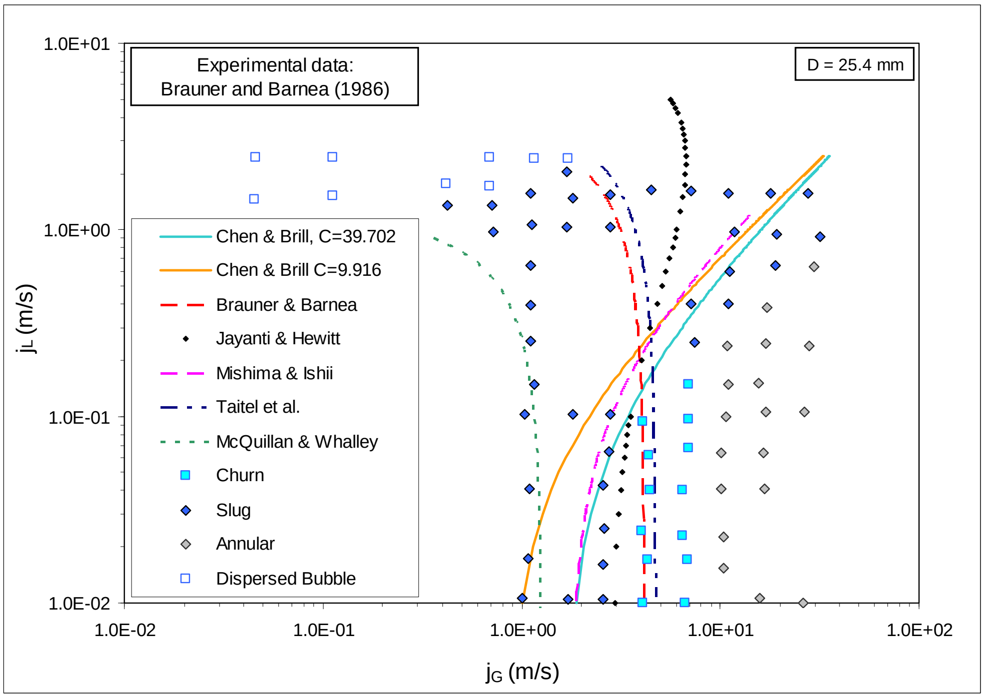

Figure 1. Different theoretical curves for slug-to-churn transition with Brauner and Barnea data (1986) (Air-water, 1.0 bar, 25ºC, 25.4 mm ID)

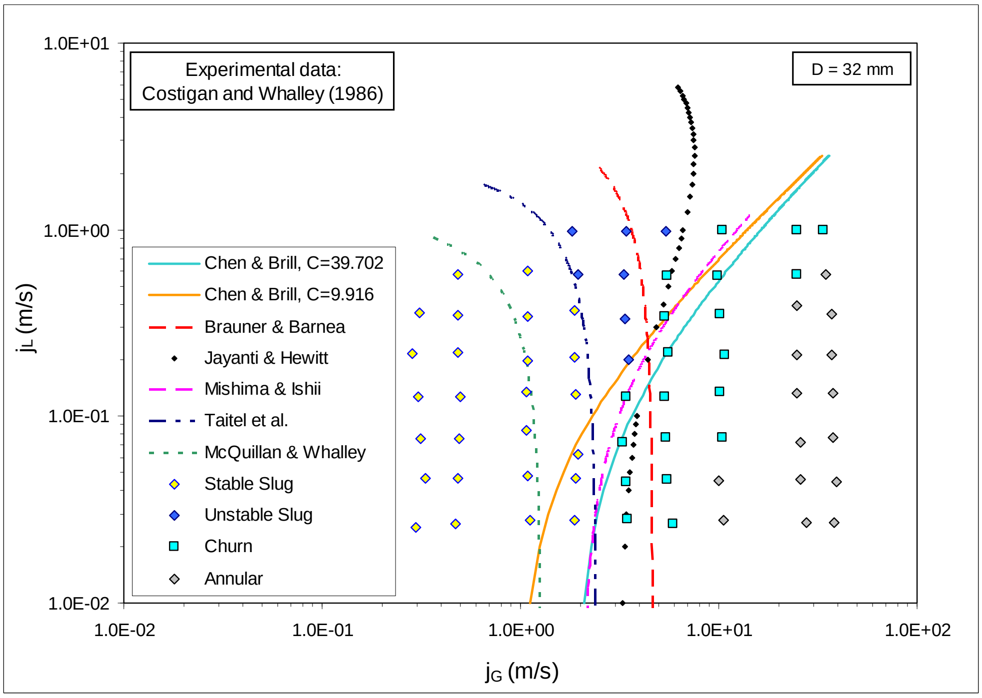

Figure 2. Different theoretical curves for slug-to-churn transition with Costigan and Whalley data (1997) (Air-water, 1.0 bar, 25ºC, 32 mm ID)

4. CONCLUSIONS

A literature review on the most relevant models for the slug-to-churn flow transitions was carried out, and a computer code to generate the transition curves according to these models was written. The outputs of that program were then compared to experimental data found in the literature. In general, a poor agreement among the transition curves outlined by these models has been found, regardless of the transition mechanisms they use – undoubtedly a consequence of the difficulty posed by accurately predicting the onset of churn flow.

Recent experimental work has clearly indicated that flooding is the main mechanism of this complex flow pattern transition, albeit not the only one. Further investigation on the liquid droplets in the gas core and the interfacial waves must be carried out.

Jayanti and Hewitt's (1992) model stoods out as the most suitable to predict the slug-to-churn flow transition. It proposes flooding as the transition mechanism and showed fair agreement with the experimental data. However, given the elusive nature of the slug-to-churn transition and its modelling, it is highly recommended that the models herein reviewed should not be used alone, but rather in conjunction with others.

A variation of Chen and Brill's (1997) transition model was proposed, tested and compared with the original formulation; yet, whichever the pipe ID investigated in the present article, the results were not entirely satisfactory.

In general, most models performed poorly, thus demonstrating that there is still fertile ground for more work in this field. Flow pattern identification and characterization via signal processing might provide the clues needed to precisely pinpointing this transition. Also, other pipe diameters and inclinations, as well as fluids with different physical-chemical properties, should be used in future experiments. All in all, slug-to-churn flow transition is seemingly an open issue worthy of further investigation and discussion.

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