

## Axial Development of Flow Regime in Adiabatic Upward Two-Phase Flow in a Vertical Annulus

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### Abstract

This study has investigated axial development of flow regime of adiabatic upward air-water two-phase flow in a vertical annulus. The inner and outer diameters of the annulus are 19.1 mm and 38.1 mm, respectively. The equivalent hydraulic diameter of the flow channel,  $D_H$ , is 19.0 mm and the total length is 4.37 m. The flow regime map includes 72 flow conditions within a range of  $0.01 \text{ m/s} < \langle j_g \rangle < 30 \text{ m/s}$  and  $0.2 \text{ m/s} < \langle j_l \rangle < 3.5 \text{ m/s}$  where  $\langle j_g \rangle$  and  $\langle j_l \rangle$  are, respectively, superficial gas and liquid velocities. The flow regime has been classified into four categories: bubbly, cap-slug, churn-turbulent and annular flows. In order to study the axial development of flow regime the area-averaged void fraction measurements have been performed using impedance void meter at three axial positions corresponding to  $z/D_H=52, 149$  and  $230$ , simultaneously, where  $z$  represents the axial position. The flow regime indicator has been chosen as some statistical parameters of area-averaged void fraction signals from impedance meters and self-organized neural networks have been used as mapping system. This information has been used to analyze the axial development of flow regime as well as to compare

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the results given by the existing flow regime transition models. The axial development of flow regime is quantified using the superficial gas velocity and void fraction values where the flow regime transition takes place. The prediction results of the models are compared for each flow regime transition. In the current test conditions, axial development of flow regime occurs in the bubbly to cap-slug (low superficial liquid velocities) and cap-slug to churn-turbulent (high superficial liquid velocities) flow regime transition zones.

**Keywords:** two-phase flow, flow regime, flow pattern, annulus, neural network

## 1. Introduction

Multiphase flows are encountered in a wide range of important industrial applications. In particular, gas-liquid two-phase flows can be observed in boilers, core and steam generators in nuclear reactors, petroleum transportation, electronic cooling and various types of chemical reactors. Two phases can flow according to several topological configurations called flow patterns or flow regimes, which are determined by the dynamic interfacial structure between both phases. The flow regime depends on a variety of parameters such as gas and liquid flow velocities, physical properties of phases and the flow channel size and geometry. The correct identification of the flow regimes and the prediction of the transition boundaries are particularly indispensable because they have a profound influence on all the two-phase transport processes. Various models have been developed to predict the transition criteria between the flow regimes. The majority of the studies in this field have been confined to circular flow geometry [1,2], although the transition criteria have been extended to mini-channel systems [3,4]. In all the cases, consistent experimental flow regime maps are needed to understand the physical phenomena involved in the flow regime transitions as well as to validate the models.

Many researchers have been working on developing objective flow regime identification methodologies. Most flow regime identification approaches have two steps in common: the first step consists of developing an experimental methodology for measuring certain parameters that are intrinsic to the flow, and are also suitable flow regime indicators (usually void fraction fluctuations) [5-10]. In the second step, a non-linear mapping is performed to obtain an objective identification of the flow regimes in accordance with these indicators.

A significant advance in the objective flow regime identification was achieved by Mi et al. [11,12]. Using the statistical parameters from the probability distribution function (PDF) of non-intrusive impedance void meters and Kohonen self-organizing neural networks (SONN), they were able to identify the flow regimes more objectively. Afterward, some improvements in the methodology developed by Mi et al. have been made. Lee et al. [13] used the cumulative PDF (CPDF) of the impedance void meter signals as flow regime indicator. The CPDF is more stable integral parameter than the PDF. Also, it has a smaller input data requirement that makes fast flow regime identification possible. Hernandez et al. [14] developed different neural network technique strategies to improve the flow regime identification results. Different types of neural networks, training strategies and flow regime indicators based on the CPDF were tested in their work. In order to minimize the effect of the fuzzy flow regime transition boundaries on the identification results, a committee of neural networks was assembled. Then the identification result was obtained by averaging the results provided by all the neural networks that integrated the committee.

Most of the studies on flow regime identification have concentrated on gas-liquid two-phase flows in tubes due to the simple geometry and many practical applications. However, in many of the chemical and nuclear systems more complex geometries exist. The annulus channel is often utilized to simulate some phenomena encountered in the complex geometries such as sub-channel of a rod bundle in a nuclear reactor core; yet, it is simple enough to perform fundamental studies. Sadatomi and Sato [15] and Furukawa and Sekoguchi [16] studied the flow regimes of gas-liquid two-phase flows in non-circular flow ducts, including concentric annulus. Kelessidis and Dukler [17] and Das et al. [18,19] investigated the flow patterns in vertical upward flow for concentric and eccentric annulus channels. They also developed flow regime

transition criteria based on phenomenological models and compared with their experimental findings. Sun et al. [20] investigated the cap-bubbly to slug flow regime transition criteria in an annulus and suggested a model for the transition criteria by modifying the study of Mishima and Ishii [2]. In the past, the axial development of the two-phase flow interfacial structures in a vertical annulus has been profoundly studied by several researchers [21,22]. However, it has focused on void fraction and interfacial area concentration development. Only the work of Jeong et al. [22] provides observation about the axial development of flow regime in an annulus. However, in their work, the flow regime map was obtained from visual information and few flow conditions were studied.

This work studies the axial development of gas-liquid two-phase flow regimes in adiabatic upward vertical flow in an annular channel. The flow regime indicator has been obtained from area-averaged void fraction signals, which are measured by impedance meters at three axial locations and artificial neural networks have been used as mapping system. The obtained information has been used to analyze the axial development of flow regime as well as to compare the predictions given by the existing flow regime transition models.

## **2. Flow regime definitions and transition boundary modeling**

### **2.1 Flow regime definitions in annulus**

Figure 1 shows typical flow patterns observed in the annulus test section with the inner and outer diameters of 19.1 and 38.1 mm, respectively. Vertical upward two-phase flows in a vertical annulus are usually classified into four basic flow regimes [17,18]. In what follows, the characteristics of each flow regime are described.

**Bubbly flow (designated as B in the following sections)**

The liquid phase is continuous and small dispersed bubbles flow in the liquid. No major difference from the bubbly flow in round tubes can be found (Fig. 1a).

**Cap-Slug flow (designated as CS in the following sections)**

The number density of small bubbles increases and bigger bubbles are formed due to bubble coalescence. The cap bubbles, which can be observed in round tubes, can not exist in the annulus if the annulus gap size is smaller than the distorted bubble limit (or minimum cap bubble limit), e.g., 10.9 mm for air–water flow under atmospheric pressure at 25°C [23]. Thus, a growing bubble is radially confined by the inner and outer walls before it reaches the maximum distorted bubble. If the bubble grows further, it becomes a cap bubble squeezed between the inner and outer walls. Also, typical large bullet-shaped bubbles (Taylor bubbles), which are observed in round tubes, have diameters close to the pipe diameter and they occupy almost the whole cross section. Such Taylor bubbles occupying almost the whole annulus cross section are observed only for stagnant liquid conditions. In most cases, Taylor bubbles in the annulus are wrapped around the inner tube, but can not cover it completely due to the long periphery in this flow channel. As a result, the cap and slug bubbles are not distinguishable in this test section and an intermediate flow regime between the cap bubbly and slug flows observed in round pipes exists in the annulus. Therefore, the “cap-slug flow” expression has been chosen for this flow regime (Fig. 1b). It should be noted that some scientists use the expression “slug flow” for this flow regime.

**Churn-Turbulent flow (designated as CT in the following sections)**

By increasing the gas flow rate, a breakdown in the partial length Taylor bubbles leads to an unstable flow regime, and the continuity of the liquid slug is repeatedly

destroyed. This liquid accumulates, forms a bridge and is again lifted by the gas. This oscillatory or alternating direction of the liquid motion is typical in the churn-turbulent flow. No major difference between the churn-turbulent flow in round pipe and annulus is observed (Fig. 1c).

### **Annular flow (designated as A in the following sections)**

The gas phase flows in the center of the gap and the liquid phase flows along the walls as a film. Generally, part of the liquid phase is entrained as small droplets in the gas core. No major difference between the annular flow in round pipe and annulus is observed (Fig 1d).

## **2.2 Existing models of flow regime transition criteria in an annulus channel**

Three models of flow regime transition criteria have been chosen and compared with the experimental data obtained in this work. Two of the models, Kelessidis and Dukler [17] and Das et al. [19], were developed for air-water adiabatic upward flows in a vertical annulus. In addition, the model developed by Mishima and Ishii [2] for vertical upward two-phase flow in round tubes has been selected, since it has been successfully applied to several flow configurations. The three models are summarized in the next paragraphs.

### **2.2.1 Kelessidis and Dukler Model [17]**

Kelessidis and Dukler investigated vertical upward gas-liquid flow in concentric and eccentric annuli with inner and outer diameters of 5.08 and 7.62 cm, respectively. The flow regime indicator was a set of some characteristic parameters of the PDF obtained from the voltage signal of two conductivity probes. The flow regime mapping was performed by applying some rules to the flow regime indicator measurements following the methodology developed by Barnea et al. [10]. The flow regime maps were

obtained for two axial locations ( $z/D_H=160$  and  $200$  approximately) and 85 flow conditions within a range of  $0.05\text{m/s} < \langle j_g \rangle < 20 \text{ m/s}$  and  $0.01 \text{ m/s} < \langle j_l \rangle < 2 \text{ m/s}$  where  $\langle j_g \rangle$  and  $\langle j_l \rangle$  are the superficial gas and liquid velocities, respectively.

Kelessidis and Dukler proposed a flow regime map model based on the phenomenological model of Taitel et al. [1] and on their experimental observations. The assumed flow regime transition criteria in the model are summarized as follows:

- Transition from bubbly to slug flow is governed by the bubble packing. For low liquid velocity conditions the transition occurs when the area-averaged void fraction,  $\langle \alpha \rangle$ , reaches 0.25. For high liquid velocity conditions flow regime remains bubbly flow due to bubble breakup caused by strong turbulence force even at  $\langle \alpha \rangle \geq 0.25$  and the void fraction at the finely-dispersed bubbly to slug flow transition is set at  $\langle \alpha \rangle = 0.52$ . The transition from bubbly to dispersed bubbly is given by a maximum stable bubble diameter criterion derived by a force balance between the surface tension and turbulent fluctuations.
- Slug to churn turbulent flow transition is governed by stable liquid slug length criteria similar to that proposed by Taitel et al. [1] in round pipes. It is proposed that the stability of the liquid slug in an annulus is associated with the liquid falling as a film around the slug bubble. It is postulated that the liquid slug is stable if it is long enough such that the liquid jet around the slug bubble is absorbed by the liquid slug and the velocity of the liquid jet slows down to that of the surrounding. The fact that the Taylor bubbles in the annulus can not cover the flow channel completely is not considered in the model. It should be noted here that axial coordinate dependence is considered in the flow regime transition boundary criterion.

- Churn-turbulent to annular flow transition occurs when the void fractions of churn-turbulent flow and the void fraction for annular flow are equal. The void fraction for the annular flow can be obtained based on geometric considerations and a force balance between interfacial shear, gravity and axial pressure drop. The void fraction of churn-turbulent flow is estimated based on the ratio of superficial gas velocity and bubble rise velocity.

### 2.2.2 Das et al. Model [19]

Das et al. carried out experiments on air-water upward flow through three concentric annulus geometries with inner and outer diameters of 2.54, 1.27, 1.27cm and 5.08, 3.81, 2.54 cm respectively. The flow regime indicator was a set of some characteristic parameters of the PDF obtained from the voltage signal of two parallel type conductivity probes. The flow regime mapping was performed by applying some rules to the flow regime indicator set. The flow regime maps were obtained for two axial locations, entrance and developed flow regions, but no quantitative information about its location was available. More than 150 flow conditions within a range of  $0.04 \text{ m/s} < \langle j_g \rangle < 9 \text{ m/s}$  and  $0.08 \text{ m/s} < \langle j_l \rangle < 2.8 \text{ m/s}$  were obtained.

They developed a phenomenological model of the flow regime boundaries as functions of the annulus dimensions, physical properties and the velocities of the two phases. The assumed flow regime transition criteria in the model are summarized as follows:

- The transition from bubbly to slug flow is postulated to occur due to an onset of asymmetric phase distribution from the symmetry prevailing in bubbly flow. This asymmetry persists in the entire range of slug flow and occurs due to the typical shape of cap and Taylor bubbles. Experimental observation [18] revealed that the coalescence of cap bubbles rather than the spherical ones played a major role in

this flow regime transition. Consequently, it is assumed that the slug flow appears when the elongated bubbles formed from the coalescence of cap bubbles have attained the nose dimensions of the Taylor bubble. This approach provides a transition void fraction,  $\langle \alpha \rangle = 0.2$ , lower than the maximum bubble packing criterion followed by several authors [1,2]. However, for high liquid flow rate (dispersed bubbly flow) this criterion is replaced by the one given by Kelessidis and Dukler [17].

- The slug to churn-turbulent flow regime transition results from the collapse of the Taylor bubbles. Experimental results showed that the flooding in the Taylor bubble region would be the main mechanism underlying the flow regime transition. Wallis flooding correlation is used for the basis of the governing equation of this phenomenon [24]. The fact that the Taylor bubbles in the annulus cannot cover the flow channel completely is not considered in the model.
- No criterion is given for the transition from churn-turbulent to annular flow.

### **2.2.3 Mishima and Ishii Model [2]**

Mishima and Ishii considered different mechanisms for the flow regime transition criteria between bubbly to slug, slug to churn-turbulent and churn-turbulent to annular flow. These criteria were compared to experimental data under steady-state and fully-developed flow conditions by using relative velocity correlations and can be summarized as;

- The transition criteria between bubbly to slug flow is based on the maximum bubble packing before significant coalescence occurs, which is estimated as  $\langle \alpha \rangle = 0.3$ . No finely-dispersed bubbly flow regime is considered.

- Slug to churn-turbulent flow transition occurs when the mean void fraction over the entire flow channel exceeds that over the Taylor bubble section. Under this condition, the liquid slugs become unstable to sustain its individual identity due to the strong wake effect.
- The criteria for churn-turbulent to annular flow transition are modeled by postulating two different mechanisms. They are flow reversal in the liquid film section along large bubbles and destruction of liquid slugs or large waves by entrainment or deformation. The second criterion from the onset of entrainment is applicable to predict the occurrence of the annular-mist flow or to predict the churn-to-annular flow transition in a large diameter tube.

### **3. Experimental methodology**

#### **3.1 Two-phase flow loop**

Figure 2 shows the schematic diagram of the experimental facility. The main components of the facility were the test section, separator tank and the circulation pump. The air-water separation tank was open to the atmosphere.

In the primary loop, water was held in the separator tank with an internal volume of approximately  $0.2 \text{ m}^3$ . A stainless steel vertical centrifugal pump circulated the water in the loop. The pump speed was controlled by a frequency inverter. A globe valve was installed at the upstream of the inlet piping, which was utilized to control the flow rate together with the pump controller. The flow rate measurement was performed by using a magnetic flow-meter with an uncertainty of about 1%. Finally, the water entered into the test section through a header where the water flow was evenly divided into four separate lines. In order to maintain constant pressure boundary conditions, i.e. constant

flow rate across the test section, the bypass section was designed such that it carried 5-10 times of the flow rate through the test section. Filtered and chemically treated water with conductivity of  $60 \mu\text{S}$ ,  $\text{pH}=8.5$  and surface tension of  $0.073 \text{ N/m}$  was used in the experiments.

Air was supplied from an air compressor. The air flow rate was controlled by four rotameters with different maximum ranges of volumetric flow. A measurement accuracy of each rotameter was  $\pm 3 \%$  when the flow rate was greater than  $50 \%$  of the full scale. The air line was divided into four separate lines in the header. Figure 3 shows the schematic of the air-water mixing unit in the header, which was composed of a tee, a sparger with mean pore size of 10- micron, and a nipple. In this unit, air bubbles were sheared off from the spargers by the water in the nipple. The bubble sizes at the mixing unit were about  $2 \sim 3 \text{ mm}$ .

The test section was about  $4.37 \text{ m}$  high and composed of an injection port, an annulus section, and three measurement ports. The annulus consisted of an inner rod with a diameter of  $19.1 \text{ mm}$  and a transparent Pyrex glass tube with the inner diameter of  $38.1 \text{ mm}$ . The measurement ports were located at  $z/D_H=52, 149$  and  $230$ . Pressure and temperature were measured at each measurement port as well as at the injection port. The temperature measurements were performed by using T-type thermocouples with an uncertainty of  $\pm 0.7 \text{ }^\circ\text{C}$ . The local pressure at each port was measured by using a differential pressure transducer. A pressure tap located at each port was connected to one sensing line of a differential pressure transducer. The other sensing line of the transducer was connected to the injection port. An absolute pressure transducer was used to measure the pressure at the injection port. Thus, pressure was measured at each measurement port in reference to the injection port. The pressure transducers have an

uncertainty of 0.5% of the measured value. The averaged combined error for the local pressure in the measurement ports is 3.9%.

Area-averaged void fraction was measured by an impedance void meter at each measurement port simultaneously with a sampling rate of 1 kHz and an acquisition time of 60 s. The inner tube wall made of stainless steel was used as one electrode while a stainless steel ring, flush-mounted against the outer wall at each port, was employed as another electrode. An alternate current circuit transfers the impedance information between the two electrodes into voltage output such that the voltage output was proportional to the measured impedance. The uncertainty of the impedance meter is about 3%.

### **3.2 Flow regime identification methodology**

The flow regime identification procedure used in this study is based on the methodology developed by Mi et al. [12] and used by Sun et al. [20] in an annulus. However, significant improvements have been made. In this study, the area-averaged void fraction CPDF distribution is used as a flow regime indicator. The flow regime mapping was performed by a SONN. This neural network architecture was trained without supervision but the number of the flow regime categories should be specified. In this study, flow regime is classified into four categories.

The steps followed in the flow regime identification methodology are depicted in Fig. 4. This figure is interpreted from left to right. The first column provides examples of images of the typical four flow regimes considered in this study (B, CS, CT and A). The first step in the identification procedure consists of obtaining the non-dimensional impedance signal,  $G^*$ , defined by

$$G^* = \frac{G_m - G_g}{G_f - G_g}, \quad (1)$$

where  $G_m$ ,  $G_g$ , and  $G_f$  are the impedances of the two-phase mixture, single-phase air, and single-phase water, respectively, which are directly related to the voltage output of the impedance probe circuit. It should be noted here that selected flow conditions to be utilized for neural network training must contain all the considered flow regimes with sufficient amount from each flow regime. If this condition is not satisfied, biased identification results are obtained [14]. In order to meet this requirement, sensitivity analysis to identify the effect of data points and their flow conditions on flow regime identification was performed by changing the amount of data points and their flow conditions for a certain flow regime. It was concluded that the number of data points and their flow conditions determined in this study was sufficiently large. The second column of Fig. 4 shows examples of typical  $G^*$  time series for the flow regimes considered in the present study. The PDF of the signals are also plotted in the third column of the figure. From the plots, one may realize that the non-dimensional impedance signals possess some characteristics of the flow regimes that can be used as flow regime indicators and the characteristics may be represented by the statistical parameters of the signals.

The next step in the identification procedure consists of selecting the set of statistical parameters of the  $G^*$  statistical distributions that will be used as flow regime indicators. Usually, the mean, standard deviation and skewness of the PDF have been used for this purpose [12,20]. However, in this study the distribution has been characterized by the  $G^*$  values where CPDF values are 0.25, 0.5, 0.75 and 1 (4 indices method), see solid squares in the fourth column of the figure. A set composed of a 4 indices vector for each flow condition is used as a flow regime indicator. This method

represents a simple and fast procedure to characterize a CPDF and has been successfully tested in two-phase flow regime identification procedures [14] providing similar results that those obtained using more sophisticated flow regime indicators [25].

Once the set of flow regime indicator vectors is obtained, a blind training process is applied to the SONN. The set of flow regime indicator vectors are divided into two separated groups used for training the neural network (training group) and for obtaining the identification results (identification group). The training group contains the 90% of the vectors and the identification group has the other 10% of the vectors (two last columns in Fig. 4). The blind training process assures unbiased identification results and increased objectivity of the final result. The vectors are selected randomly, but a minimum amount of flow conditions for every flow regime is needed in the training group in order to avoid biased results. Since the training group contains the 90% of the vectors this minimum amount is obtained without additional procedures. This process is applied several times until all the flow regime indicator vectors, i.e. flow conditions, have been identified. It is imposed that any flow condition can be identified twice. In addition, in order to minimize the effect of the unclear flow regime transition boundaries on the flow regime identification results, a committee of 50 neural networks is assembled. The same training and identification groups are used for all the neural networks that integrate the committee. Finally, the identification result is obtained by averaging the results provided by all the neural networks that integrated the committee. In this way, flow regime map repeatability greater than 95% can be achieved. If a single neural network is used, some of the flow regime identification results are unstable, mainly in the flow regime transition zones. More details about the neural network methodology used in this work can be found in Hernandez et al. [14].

#### 4. Flow regime identification results and axial development

Since the pressure drop by gravity and friction was not negligible in the present test conditions, an averaged increase of the superficial gas velocity between  $z/D_H=52$  and 230 was 28 % for all flow conditions. This entailed the expansion of air resulting in a continuous flow development along the test section. In the present study, axial development of a flow regime map within a range of  $0.01\text{m/s} < \langle j_g \rangle < 30\text{ m/s}$  and  $0.2\text{ m/s} < \langle j_l \rangle < 3.5\text{ m/s}$  have been investigated based on the neural network flow regime identifications for 216 conditions (72 flow conditions times 3 axial locations at  $z/D_H=52, 149$  and 230). Figure 5 shows the axial development of flow regime map obtained with the identification methodology presented in the previous section. In order to make the information more compact, only one flow regime map is used for the three axial locations and the superficial gas velocity in the map represents the value measured at  $z/D_H=52$ . Each symbol in the map displays the information of the flow regimes identified at the three axial locations. For example B-CS-CT means bubbly flow regime at  $z/D_H=52$ , cap bubbly flow regime at  $z/D_H=149$  and churn-turbulent flow regime at  $z/D_H=230$ . The black and gray symbols represent flow conditions where the flow regime does not and does present axial change, respectively. The flow conditions where the axial development took place were located in the boundaries between two flow regimes. Most of the flow conditions with axial development of flow regime occurred in the B to CS transition zone. Axial development in the CS and CT transition zone was observed at high superficial liquid velocity conditions. Axial development in the CT to A flow regime transition zone occurred in only two flow conditions. Table 1 provides the complete information of the identification results including the superficial gas velocity at each axial location.

In order to analyze the results in detail, quantitative information of the axial development of the flow regime is presented in Fig. 6. Figures 6a), b) and c) show the flow regime transition boundaries at the three axial locations for the B to CS, CS to CT and CT to A transitions, respectively. Figures 6 d), e) and f) show the critical void fraction,  $\langle \alpha_c \rangle$ , at the flow regime transitions corresponding to Figs. 6a), b) and c), respectively.

The axial development of the flow regime represents a decrease of the critical superficial gas velocity along the axial distance. The axial development at the B to CS flow regime transition is observed for superficial liquid velocities lower than 2 m/s (Fig. 6a). For higher  $\langle j_l \rangle$  conditions, no noticeable change in the critical superficial gas velocity as well as critical void fraction is observed. This effect was also observed by Kelessidis and Dukler [17] in their experiments. Although quantitative information was not given in their work, it is inferred that the effect of the axial development of flow regime on the critical superficial gas velocity is not as important as the observed in the present study and they did not include it in their model. In addition, Jeong et al. [22] confirmed the B to CS axial development using conductivity probes in the same annulus two-phase flow loop and similar experimental conditions. However, their study was limited to a small number of flow conditions and the flow regime identification was done using the visual information. Hibiki and Ishii [26] pointed out the axial development of flow regime based on the adiabatic vertical upward two-phase flow experiment performed in a 10.2 cm inner diameter pipe. Their study focused on the bubbly to slug flow regime transition at three axial positions such as  $z/D_H=12.8$ , 26.6 and 41.8.

For low  $z/D_H$  and  $\langle j_l \rangle$  conditions, the critical void fraction at the boundary of B to CS (Fig. 6d) is between 0.25 and 0.3 as suggested by the maximum bubble packing

criteria [1,2]. However, the critical void fraction is reduced to 0.2 at further downstream. This value is closer to the one predicted by the asymmetric phase distribution hypothesis proposed by Das et al. [19]. Similar results were obtained by Hibiki and Ishii [26] with critical void fraction values of 0.3 and 0.16 at axial positions of  $z/D_H=12.8$  and 41.8, respectively. A weaker effect of the axial position on the critical void fraction can be observed when the  $\langle j_f \rangle$  is increased. The critical void fraction values are about 0.4, which is lower than the one at the finely-dispersed bubbly flow to S or CT flow regime transition modeled by Taitel et al. [1] ( $\langle \alpha_c \rangle = 0.52$ ) and adopted by Kelessidis and Dukler [17] and Das et al. [19] models.

The reduction of the  $\langle \alpha_c \rangle$  along the axial position observed for low liquid velocity conditions can be explained by the increased bubble coalescence rate due to the increased bubble residence time inside the flow channel. This explanation seems feasible since the B to CS transition is generally associated to coalescence phenomena. Thus, for low liquid velocity conditions, the bubble interaction time, namely, axial length from the inlet is important for flow regime transition and thus the history of the inlet flow regime is sustained even at a long distance from the inlet. Hibiki and Ishii [27] discussed the inlet history effect on the interfacial structure using the interfacial area transport equation. For  $\langle j_f \rangle$  higher than 2 m/s, the axial development is not observed because sufficient bubble interaction is attained even within a short distance from the inlet. The critical  $\langle j_f \rangle$  observed in this study coincides with the liquid velocity at the flow regime transition boundary between bubbly and finely-dispersed bubbly flows, which is predicted to be  $\langle j_f \rangle \sim 1.8$  m/s in an annulus by Kelessidis and Dukler [17].

The CS to CT flow regime transition also represents axial development (Fig. 6b) for  $\langle j_f \rangle > 0.5$  m/s. Kelessidis and Dukler [17] considered the axial development in the

slug to churn turbulent flow regime transition, but it indicated that an increase of critical  $\langle j_g \rangle$  along the axial location occurred only  $\langle j_l \rangle < 1$  m/s, differing from the experimental evidence obtained in the present study. For high  $\langle j_l \rangle$  conditions, the finely-dispersed bubbly to churn-turbulent flow regime transition was proposed with no consideration of axial development in their model. The decrement observed in the critical void fraction was up to 20%, (Fig. 6e), and it usually occurred near the test section inlet. Only the model proposed by Mishima and Ishii [2] can explain the decrement observed in the critical void fraction. In their model, the critical void fraction is decreased with increased mixture volumetric flux,  $\langle j \rangle$ . Due to the pressure drop along the flow direction, the gas velocity is increased and, thus, the mixture volumetric flux is increased with the axial coordinate. The pressure drop is more important for high  $\langle j_l \rangle$  conditions, so a larger decrement of the critical void fraction is expected for this flow regime map zone as experimentally observed. Since the critical superficial gas velocity for high  $\langle j_l \rangle$  conditions is also decreased along the flow direction, the critical gas velocity ( $=\langle j_g \rangle / \langle \alpha \rangle$ ) appears to be about constant along the flow direction, see Fig. 7.

Finally, the CT to A flow regime transition zone does not present appreciable axial development (Fig. 6c) and the critical void fraction is almost constant (Fig. 6f).

## 5. Comparison of flow regime identification results with existing models

In this section, the existing models of the flow regime transition criteria summarized in Section 2.2 are compared with the flow regime identification results obtained in this study. Figures 8a), b) and c) compare the flow regime map with the transition boundaries modeled by Mishima and Ishii [2], Kelessidis and Dukler [17] and Das et al. [19], respectively. In the computation of B to CS transition boundary by Mishima and Ishii model, a distribution parameter is set at 1.1 obtained for a vertical

annulus [28]. In Kelessidis and Dukler map, CS to CT flow regime transition boundary at  $z/D_H=149$  is shown.

In order to quantify the model applicability, we propose a concurrence ratio,  $\xi$ , defined as the number of flow conditions correctly predicted by the boundary divided by the total number of flow conditions identified in the two flow regimes considered. High concurrence ratio indicates higher prediction accuracy. The concurrence ratio is utilized only for comparative purposes between the existing models and it is not intended to provide the exact prediction accuracy of them. Figures 8 d), e) and f) show the dependence of the concurrence ratio on the axial position for the models proposed by Mishima and Ishii [2], Kelessidis and Dukler [17] and Das et al. [19], respectively. In the last two models, the dispersed bubbly flow regime is considered as bubbly flow.

All the models show a high concurrence ratio for the B to CS flow regime transition. The best prediction results are obtained for the Mishima and Ishii [2] model,  $\xi > 0.9$  for all  $z/D_H$  conditions. A weak dependence of  $\xi$  on the axial location is observed and  $\xi$  value becomes lower at  $z/D_H=230$ . The opposite result is obtained for the Das et al. [19] model,  $\xi > 0.8$  for all  $z/D_H$  conditions and the concurrence ratio is improved at higher  $z/D_H$  values. The concurrence ratio of Kelessidis and Dukler [17] model is about 0.8 with almost no dependence on the axial location. These results are in concordance with the critical void fractions measured in Fig. 6d), since Mishima and Ishii, Kelessidis and Dukler and Das et al. models predict a critical void fraction of 0.3, 0.25 and 0.2, respectively. This result implies that the channel geometry does not play a major role in this flow regime transition boundary. A decrement of the critical void fraction along the flow direction should be modeled by considering the bubble contact time or developing length.

The concurrence ratio for the CS to CT flow transition computed by Mishima and Ishii model [2] is below 0.5 and many flow conditions identified as CT are located in computed CS region. This shows that the flow regime transition criteria provided by Mishima and Ishii [2] does not predict the geometry effect observed in this study since it was mainly developed for pipe flows. A considerable decrement of the superficial gas velocity at the CS to CT flow regime transition in the Mishima and Ishii model may be obtained if partial Taylor bubbles are considered. In this way, the concurrence ratio given by Mishima and Ishii may be significantly improved. A similar approach was used by Sun et al. [20] to model the B to CS flow regime transition in an annulus. Although Kelessidis and Dukler [17] and Das et al. [19] models do not consider the fact that the Taylor bubbles in the annulus can not cover the flow channel completely they can predict the CS to CT flow regime transition reasonably well for  $\langle j_g \rangle$  values lower than 1 m/s. The Kelessidis and Dukler model provides an average concurrence ratio of 0.87 showing better results for low  $z/D_H$  values. The best prediction results are obtained by Das et al. [19] with  $\xi > 0.98$ . This result may validate the destruction of the Taylor bubbles by the flooding in the Taylor bubble region assumed by Das et al model.

For the CT to A transition only the Mishima and Ishii [2] and Kelessidis and Dukler [17] models are available. Mishima and Ishii model suggests that in the current flow channel the CT to A transition occurs due to flow reversal for low  $\langle j_g \rangle$  conditions. For  $\langle j_g \rangle$  higher than 1 m/s, the transition is governed by droplet entrainment and the slug to annular-mist flow regime transition takes place. When the flow regime transition occurs due to flow reversal, the concurrence ratio is 1 for all the axial positions. The concurrence ratio for high  $\langle j_g \rangle$  conditions (droplet entrainment) is also high with  $\xi > 0.8$  for all the axial locations. It should be noted that in the latter case, flow conditions identified as CS and CT have been used to compute the concurrence ratio. If only CS

flow conditions are considered, the concurrence ratio values are almost zero. This fact is supported by Mishima and Ishii work [2] since they point out that the flow behavior in the slug to annular flow regime transition is similar to the churn-turbulent flow.

Kelessides and Dukler criterion only provides an averaged concurrence ratio of 0.64 showing a clear overestimation of the critical  $\langle j_g \rangle$ .

## 6. Conclusions

Axial development of a flow regime map in a vertical annulus within a range of  $0.01 \text{ m/s} < \langle j_g \rangle < 30 \text{ m/s}$  and  $0.2 \text{ m/s} < \langle j_l \rangle < 3.5 \text{ m/s}$  have been investigated based on the neural network flow regime identifications for 216 conditions (72 flow conditions times 3 axial locations at  $z/D_H=52, 149$  and  $230$ ). The flow regime indicator has been chosen as area-averaged void fraction signals from impedance void meter and neural network has been used as mapping system. Flow conditions that comprise bubbly (B), cap-slug (CS), cap-turbulent (CT) and annular (A) flow regimes have been identified. This information has been used to analyze the axial development of flow regime as well as to compare the existing models of flow regime transition criteria proposed by Mishima and Ishii [2], Kelessidis and Dukler [17] and Das et al. [19]. The main conclusions obtained in this study are summarized as follows:

1. Bubbly to cap-slug flow transition: although this flow regime transition presented an important axial development for  $\langle j_l \rangle$  lower than 2 m/s, the prediction accuracies of the considered models provided reasonable results. The critical void fraction measurements showed that the maximum bubble packing criteria might be used as transition criteria and modeled by considering the bubble contact time or developing length. For  $\langle j_l \rangle$  higher than 2 m/s, the dependence of the critical void fraction on the axial length was not observed.

2. Cap-slug to churn-turbulent flow transition: this flow regime transition did not present axial development for  $\langle j_T \rangle$  conditions lower than 1 m/s. From the three models considered the best prediction results were obtained by the Das et al. [19] model that assumed the destruction of Taylor bubbles by the flooding of the Taylor bubbles as the governing phenomena in this transition.
3. Dispersed bubbly, cap-slug to churn-turbulent for  $\langle j_T \rangle > 1$  m/s: this flow regime transition presented a significant axial development. Kelessides and Dukler [17] and Das et al. [19] models could not predict this flow regime transition properly since they used a constant void fraction criterion  $\langle \alpha \rangle = 0.52$ . In addition, these models predict the direct transition from dispersed bubbly to churn-turbulent flow regime differing from the experimental results. Only the Mishima and Ishii [2] model could predict the gradual flow regime transition between DB-CS-CT, but it was pointed out that the model should be remodeled by considering the flow channel geometry.
4. Churn-turbulent to annular flow transition: Axial development of the flow regime transition was not observed in this regime and Mishima and Ishii [2] model gave the best prediction results for the transition boundary.

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**Nomenclature**

$D_H$	Hydraulic diameter
$G$	Impedance
$G^*$	Dimensionless impedance
$J$	Superficial velocity
$v$	Velocity
$z$	Axial position in the flow direction

**Greek symbols**

$\alpha$	void fraction
$\zeta$	Concurrence ratio

**Subscripts**

crit	critical
f	liquid phase
g	gas phase
m	mixture

**Mathematical symbols**

$\langle \rangle$	Area average
$\langle \langle \rangle \rangle$	Void fraction weighted mean value

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