An Air-Liquid Flow Pattern for Macro- And Mini-Scale Round Channels

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ABSTRACT

In this study the flow pattern prediction method developed by Taitel and Dukler, 1976 in the mid 70's, later modified by Barnea and coworkers, 1983, is updated in order to predict flow pattern transitions in micro-scale channels (diameters smaller than 3mm). Surface tension and contact angle effects, negligible in larger tubes, were introduced in the extended method by including the Eötvos and Weber numbers. The proposed method seems to work relatively well based on comparisons against a broad database for air-water flow in round channels from 10 independent laboratories.

Keyword: *regimes, flow pattern map, Kelvin-Helmholz instability, diabatic*

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1. INTRODUCTION

It has been a long time since the first flow pattern map was proposed by Baker (1954) who defined flow pattern transitions based upon the superficial gas and liquid velocities for oil and gas flows. Since then, several maps and prediction methods to characterize flow patterns in two-phase flow have been proposed, most of them being based on observations from channels with internal diameters larger than 10mm. Combination of physical properties with superficial velocities, void fraction and, in the case of diabatic applications, the total mass velocity, and vapor quality have been used to characterize flow pattern transitions in those maps. Some maps for two-phase flow on tube bundles have also been proposed. Recently

Actually, there is a consensus among most of the researchers carrying studies on larger tube diameters that effects of pipe diameter, surface tension and contact angle are negligible on the flow pattern regime establishment for tubes in the order of 10mm or larger (Baker (1954) and Mandhane et al. (1974)). According to Tripplet et al. (1999), since the diameter of micro-scale channels are about equal to or even smaller than the Laplace length scale, the hydrodynamic interfacial process governed by the Taylor instability does not apply to capillaries and thus flow pattern prediction methods based on macro-scale channels will not work for smaller channels. Despite of the fact that macro-scale predictive methods seems to fail when applied to micro-scale channels, except for stratified flow, it seems that other major flow patterns that are common in large channels occur in micro-channels as well, although certain flow pattern details may differ significantly from those in large channels.

Table 1 shows a summary of the studies on air-water flow pattern transitions in micro-scale channels. They have been selected from macro-scale studies according to the threshold diameter of 3mm for the conventional-to-mini-channel transition suggested by Kandlikar and Grande (2003). The table describes the characteristics of the channels, the range of superficial velocities and the methods used by the authors to characterize the flow patterns. It is noted that most of the studies were performed for air-water flows inside round channels. According to this table, experiments have been performed for hydraulic diameters from 0.02mm to 5.5mm. Most of the studies involved the use of high-speed videos to characterize flow patterns. Objective methods such as pressure drop traces have also been used.

The purpose of this paper is to propose modifications on the predictive flow pattern method of Taitel and Dukler later modified by Barnea in order to predict flow patterns in micro-scale channels, based on the data described in Table 1 for air-water flows inside round tubes having tube diameters down to 1mm. Such modifications are based mainly on the introduction of the Eötvos and Weber numbers. The proposed modifications in the transitions from stratified and intermittent to annular seem to predict reasonably well the database.

1.1 Flow-Pattern Characterization

From the studies described in Table 1, only those for air-water flow in horizontal round channels having diameters down to 1mm were considered. Experimental observations for halocarbon refrigerants were not included since these fluids present surface tension of almost one order of magnitude lower than that of air-water. Significant differences in the liquid viscosity are also observed. These physical properties may affect considerably the flow pattern as pointed out by Yang and Shieh (2001) when performing flow pattern visualizations with R134a and air-water. Moreover, there is not enough data available in the literature in such way that the effect of the fluid on the flow pattern transition could be reasonably investigated and then incorporated in a prediction method.

Table 1. Flow pattern studies in single micro-scale channels.

Author/ flow orientation*	**Channel shape**	**d_h, (mm)**	**j_L, (m/s)**	**j_G, (m/s)**	**Identification method**
Damianides and Westwater (1988) /H	round tubes	1, 2, 3, 4, 5	0.0024 - 5.72	0.015 - 125.3	Photographs+ pressure traces
Fukano et al. (1989) / H, V	round-tubes	1, 2.4, 4.9	0.02 - 2.2	0.07 to 27	photographs + differential pressure traces
Barajas and Panton (1993) / H	round tubes	1.6	0.003 - 2	0.1 - 100	photographs
Mishima and Hibiki (1996) /V	round tubes	1, 2,3, 4	0.0116 - 2	0.09 - 79	high speed video camera
Yang and Shieh (2001) /H	round tubes	1 ,2 , 3	0.006 - 2.1	0.014 - 91.5	photographs
Chen et al. (2002) / H,V	round tubes	1, 1.5	0.399 - 3.52	0.502 - 11	high speed video camera
Kawahara et al. (2002) / H	round tube	0.1	0.02 – 4	0.1 - 60	video camera
Serizawa et al. (2002) / H	round tubes	0.020, 0.025, 0.100	0.003 – 17.52	0.0012 - 215.3	high speed video camera
Chung and Kawagi (2004) / H	round tubes	0.05, 0.10, 0.25, 0.53	0.01 - 5.77	0.02 -73	video camera
Vaillancourt et al. (2004) / H	round tubes	0.8, 1, 3	0.02 - 1	10 - 100	photographs
Zobeiri (2006)/H	round tubes	1, 3, 6	0.006 - 4	0.03 - 100	high speed video camera and + the variation in the intensity of a micro-laser beam through the two-phase flow within the glass tube

* H => horizontal flow; V=> vertical flow

** superscripted Roman number identify the condition for which individual experiments have been performed.

Figure 1 illustrates the flow pattern terminology adopted by Zobeiri (2006) and obtained at the LTCM-

EPFL. As shown in this figure, Zobeiri (2006) identified the following flow patterns: stratified, elongated bubbles, slug, churn, slug-annular, annular and bubbly flows. Different flow pattern classification and terminology have been used by distinct authors as follow:

- Damianides and Westwater (1988): stratified smooth, stratified, bubbly, plug, pseudo-slug, slug, annular and dispersed flows;
- Fukano et al. (1989): bubbly, plug, slug and annular flows;
- Yang and Shieh (2001): bubble, plug, wavy, slug, slug-annular (similar to pseudo-slug of Damianides and Westwater (1989)) and annular;
- Chen et al. (2002): bubbly, slug (elongated bubbles), bubbly train slug, churn and annular flows;
- Vaillancourt (2004): bubbly, intermittent, churn and annular flows.

Barnea et al. (1983) modified the Taitel and Dukler predictive method taking into account the following flow patterns for horizontal tubes: dispersed bubble, annular, intermittent, stratified and stratified wavy. Such a characterization was based on a technique presented in a previous study (Barnea et al. (1980)) by combining visual observations and signal processing from conductance probes. Damianides and Westwater (1988) also used an objective method based on traces of the pressure signal to characterize slug, annular and dispersed flows. In order to use a common flow pattern terminology, the following flow pattern characterization is applied in the present study based on Barnea et al. (1983):

- *Dispersed flow* that includes such configurations as bubbly and mist flows, with the gas bubbles in the liquid having smaller diameter than the tube, and gas dispersed in a continuous liquid phase and all the liquid detached from the wall and flowing as small droplets within the gas core;
- *Annular flow* that is characterized by a gas core surrounded by a liquid film on the tube wall;
- *Intermittent flow* that occurs when the flow geometry has an periodic or time varying character;
- *Stratified flow* (smooth + wavy) that is observed when the two phases flow separately with the liquid in the lower region of the tube due to gravitational effects.

Thus, the flow pattern identified by previous authors that were included in our database was classified based on these four flow patterns. Churn, slug, elongated bubbles, plug and pseudo-slug flows have been characterized as intermittent flows. Annular and slug-annular have been considered as annular flows. Coleman and Garimella (1999) defined a wavy-annular flow when waves in stratified-wavy flow grow to the extent that they touch the top of the tube wall. Such a definition seems to the present authors somewhat inaccurate since this is a kind of an intermittent flow and does not resemblances an annular flow pattern. Moreover, the pictures presented by these authors revealed the occurrence of churn flow and not a typical wavy-annular flow when ripples are observed on the surface of the liquid film. Thus, it has been decided to consider their wavy-annular flow pattern as an intermittent one.

1.2 Air-water Flow Pattern Maps Comparisons

Figures 2 and 3 illustrate the effect of the tube diameter on the flow pattern transitions according to the results of Damianides and Westwater (1988) and Yang and Shieh (2001), respectively. In Fig. 2 it is shown that there is almost no change in the intermittent - dispersed flow transition line when varying the tube diameter between 1 to 3mm and 4 to 5mm. However, when increasing the diameter from 3 to 4, this transition line moves to higher liquid superficial velocities. Yang and Shieh (2001) results from Fig. 3 indicate negligible effect of the diameter on this transition. According to the results of Coleman and Garimella (1999), the transition from intermittent to dispersed flow occurs at lower liquid superficial velocities with increasing the tube diameter. In the case of Tripplet et al. (1999) it is not clear at which point churn flow passes from an periodic behavior (intermittent flow) to a "continuous pattern", designated as "dispersed flow" in the present paper. According to the results of Tripplett et al. (1999), the transition superficial liquid velocity from intermittent to dispersed flow (only bubbly) decreases with the tube diameter, a trend similar to that proposed by Coleman and Garimella (1999).

According to Figs. 2 and 3, stratified flows have been observed for tube diameters larger than 2mm. A similar behavior was observed by Coleman and Garimella (1999). In the study by Barajas and Panton (1993), stratified flows were observed even for an internal diameter of 1.6mm. Here, it is important to note that these diameters are smaller than the conventional to mini-channel threshold proposed by Kandlikar and Grande (2003) of 3mm and also smaller than the value of 5.5mm based on the "Confinement Number" as proposed by Kern and Cornell (1997). Fukano et al. (1989), although performing experiments for internal tube diameters from 1 to 4.9mm, did not observe stratified flow. According to Fig. 3 and the visualizations of Coleman and Garimella (1999), it seems

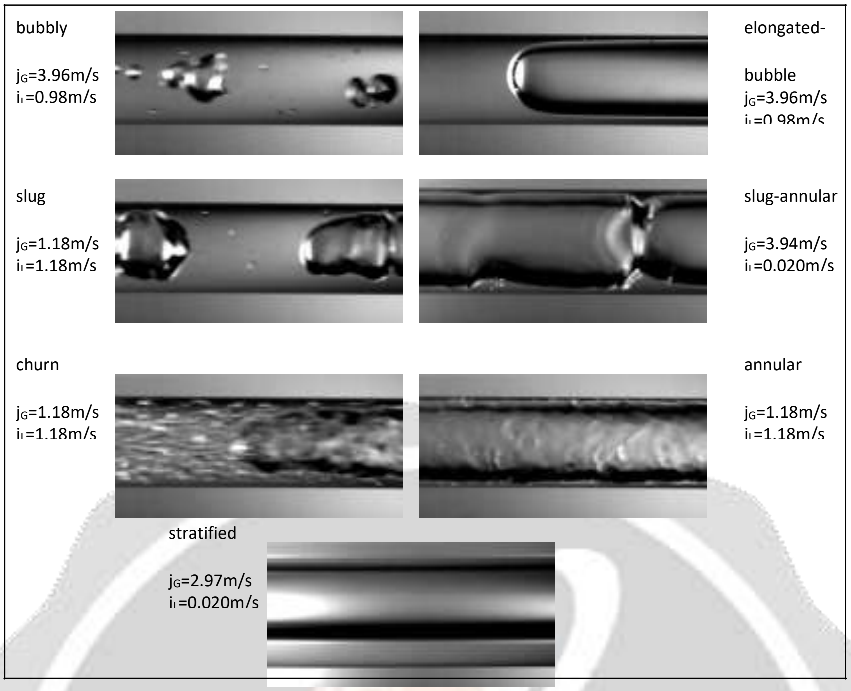

Figure 1. Flow pattern classification adopted by Zobeiri (2006).

that there is no effect of the tube internal diameter on the transition from intermittent to annular. The flow pattern maps of Fukano et al. (1989) indicate that the tube diameter effect on the transition from intermittent to annular flow is not clear. Contrary to these results, Fig. 2, based on the results of Damianides and Westwater (1988), suggests that the transition superficial velocity of the gas diminishes with the tube diameter.

Figure 4 compares the flow pattern maps obtained for air-water flows inside round tubes by different authors. Generally speaking, it can be concluded that the scattering of the transition lines decreases with the tube diameter being minimal at tube diameters of the order of 5mm.

2. Barnea's Flow Pattern Predictive Method

To the best of the authors' knowledge, there is no model for flow pattern transition in micro-scale channels. Generally, in the literature concerning micro-scale channels, only curve fitting of dimensionless numbers based on restricted databases studies have been found as, for example, the one by Revellin and Thome (2007), for halocarbon refrigerants, Vaillancourt et al. (2004), and Akbar et al. (2003), for air/water, besides flow pattern maps developed for specific experimental conditions. Thus, they cannot be considered generalized methods.

Barnea et al. (1983) were the first to implement a flow pattern prediction method to be used for small channels. They considered as reference the theoretical analysis of two-phase flow transitions by Taitel and Dukler (1976) for macro-scale channels. According Taitel-Dukler, transitions are based on the following physical mechanism: i) Transition between stratified and intermittent or annular flow patterns: it takes place when the interface becomes unstable as a result of Kelvin-Helmholz instability and a finite amplitude wave on the liquid surface grows; ii) Transition between intermittent and dispersed regimes: taking place when the turbulent fluctuations are strong enough to overcome buoyant forces acting in the gas; iii) Transition between intermittent and annular regimes: from the stratified flow pattern, depending on the liquid level, either intermittent or annular flow will develop, 0.5 being the threshold value of the ratio between the liquid level and the tube diameter.

Instead of Kelvin-Helmholz instability assumed by Taitel and Dukler, Barnea et al. (1983) proposed surface tension effects as the leading transition mechanism from stratified to intermittent flows in micro-scale channels. They modeled this transition by comparing gravity and surface tension forces. Based on a previous study (Barnea et al. (1982), they also proposed a new threshold value of 0.35 for the ratio between the liquid level and the tube

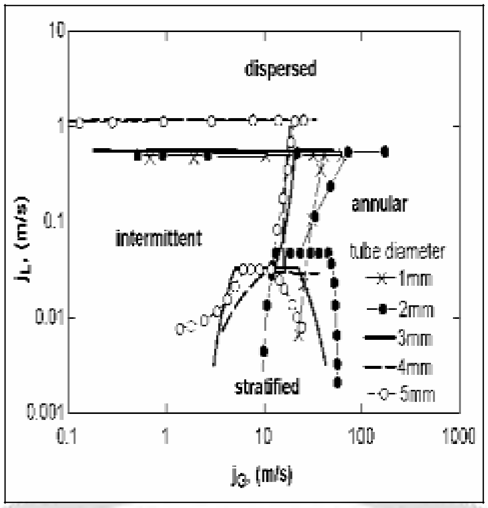

Figure 2. Illustration of the effect of tube diameter on the flow pattern transitions according to the results of Damianides and Westwater (1988) for air-water flows.

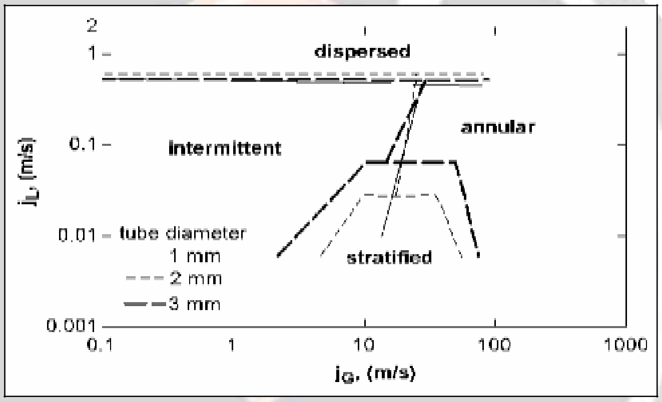

Figure 3. Illustration of the effect of tube diameter on the flow pattern transitions according to the results of Yang and Shieh (2001) for air-water flows.

diameter in the transition between intermittent and annular flows. This method predicted reasonable well their air-water data covering tube diameters from 4 to 12.3mm. A comparison of the Barnea et al. method against some micro-scale air-water flow patterns maps from the literature is shown in the maps of Fig. 4. According to these maps, for a tube diameter of 2mm, the method by Barnea and her coworkers predicts relatively well the intermittent-dispersed transition, while fails to predict stratified flow range and the transition between intermittent and annular flow patterns. In the case of the 5mm tube, the transition from intermittent-dispersed and intermittent-annular are better captured. However, the transitions intermittent-stratified and stratified-annular are still poorly predicted.

Thus, based on the conclusions revealed by the comparisons shown in Fig. 4, modifications to the Barnea's method are proposed in order to capture the wetting and inertial effects which seem to be relevant on the transitions from intermittent and stratified to annular flow for small channels.

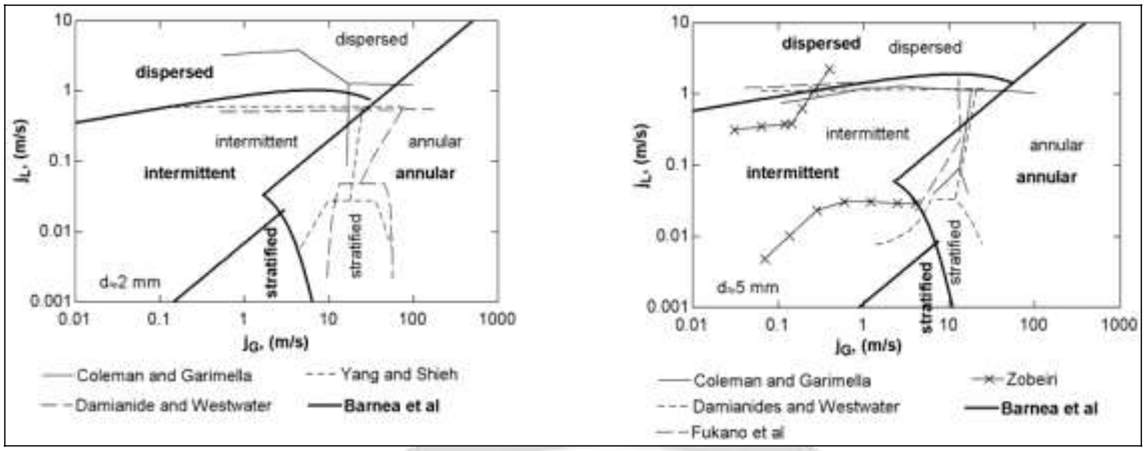

Figure 4. Comparisons of the predictions by Barnea et al. (1983) and the experimental data from the literature.

3. Comparison of Predictions with Data from Literature

Figures 5 and 6 display comparisons of the proposed flow pattern map with data from the literature. It can be concluded that the proposed modifications to the Taitel and Dukler (1976) map worked reasonably well in predicting the present database. Noteworthy is the striking coincidence of the Damianides and Westwater (1988) intermittent to annular transition with the proposed model for the 1mm tube as observed in Fig. 5. Stratified flows are also reasonably well predicted though the data available for this flow pattern are scarce, as noted in figure 6.

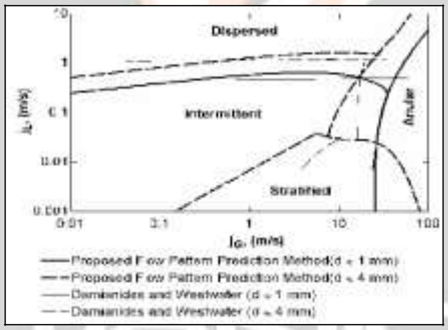

Figure 5. Comparison of the proposed predictive method and the transition lines proposed by Damianides and Westwater (1988).

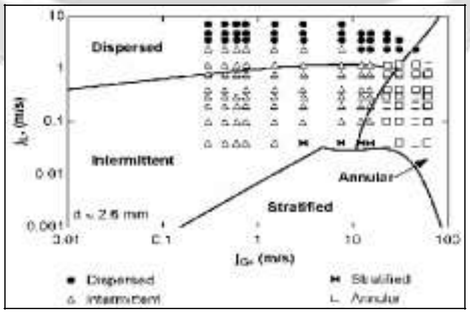

Figure 6. Comparison of the proposed predictive method (lines) and the experimental data by Coleman and Garimella (1999) (symbols).

4. CONCLUSIONS

A broad flow pattern database was gathered from the literature covering tube diameters from 1 to 5mm. A substantial scatter of the flow pattern transition lines from different authors has been observed when comparing results from different authors. Such a scatter is in part related to the subjectivity in the flow pattern characterization and also on the differences of the terminology adopted by the authors. For simplifying purposes, the following four patterns have been considered in the present study: stratified, intermittent, dispersed and annular. Using this flow pattern characterization, the available database has been introduced in map by Taitel and Dukler (1976) modified by Barnea et al. (1983). However, these procedures failed to predict transitions from intermittent and stratified to annular flow patterns for tubes of small diameters. As a result, modifications to those procedures have been proposed consisting in the introduction of wetting and surface tension effects, through the Weber and Eötvos numbers, into the physical mechanism involved in the aforementioned transitions. The proposed method seems to predict reasonably well flow patterns transitions for channels of diameter varying between 1 and 5mm.

Despite their reasonable behavior in predicting flow pattern transitions, the authors recognized that the proposed modifications are only an initial step toward a better understanding of the mechanisms acting on the flow pattern transitions in micro-scale channels. The development of a broad database including different surface/liquid combinations in order to investigate the effects of the contact angle on the transition from stratified to annular is still necessary.

5. REFERENCES

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