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Experimental Study on Gas-Viscous Liquid Mixture Flow Regimes and Transitions Criteria in Vertical Narrow Rectangular Channels

F. J. Sowiński, and M. Dziubiński

***Abstract*—In the study the influence of the physical-chemical properties of a liquid, the width of a channel gap and the superficial liquid and gas velocities on the patterns formed during two phase flows in vertical, narrow mini-channels was investigated. The research was performed in the channels of rectangular cross-section and of dimensions: 15 x 0.65 mm and 7.5 x 0.73 mm. The experimental data were compared with the published criteria of the transitions between the patterns of two-phase flows.

***Keywords*—Two-phase flow, flow regimes, mini-channel, viscosity.

I. Introduction

TWO-PHASE flows in micro and mini-channels present the potential possibilities of the intensification of heat and mass exchange processes and the selectivity and miniaturisation of those processes. In micro and mini-channels one may observe the various patterns of two-phase liquid-gas flow. The occurrence of the particular two-phase flow patterns is demonstrated in the form of diagrams called the flow maps. The area of such a diagram is divided with the boundaries into the regimes in which there is one defined predominant structure of two-phase flow.

In comparison with the channels of large cross-section in mini and micro-channels apart from the classical patterns of two-phase flow such as bubble – slug, churn, annular and disperse, one could observe the occurrence of additional patterns such as bubble-slug, annular-drop, slug-churn and chain flow [1,2]. In the literature concerning two-phase gas-liquid flows in micro- and mini-channels one can notice the predominance of the research in which water or liquids of similar to water physical – chemical properties were used [3-7]. Nevertheless, one can notice no research in which the liquids of higher viscosity are used as the continuous phase.

The aim of the study was the identification of the flow regimes formed during two-phase liquid-gas flow in vertical narrow mini-channels for the liquids of viscosity being higher than water viscosity. The experiments were performed for different dimensions of the channels, the superficial gas and liquid flow velocities and liquids of different viscosities. The experimentally determined limits of occurrence of the two-phase patterns were compared with the present in the literature criteria describing the conditions of flow pattern transitions.

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II. The Criteria of Two-Phase Flow Pattern Transitions

The flow patterns occurring during two-phase flows exert an influence on the phenomena of mass and heat exchange, determine the intensity of the processes and their energy-consumption. Hence, the determination of occurrence conditions of the particular two-phase flow patterns in narrow channels has become the subject of research [4-6]. In the study the transitions from bubble to slug flow patterns, from slug to churn flow patterns and from slug to annular flow patterns were analysed.

A. The Criterion of the Transition from Bubble to Slug Flow Patterns

To establish the criterion of the transition from bubble to slug flow patterns the dependence based on a drift model was used [4]

$$\frac{u_{SG}}{\alpha} = C_0(u_{SG} + u_{SL}) + v_b \tag{1}$$

After transformation of the equation (1) one obtains the criterion equation

$$u_{SL} = \left(\frac{1}{\alpha_{cr} \times C_0} - 1\right) \times u_{SG} - \frac{v_b}{C_0} \tag{2}$$

The constant C_0 was defined by [6]:

$$C_0 = 1.35 - 0.35\sqrt{\frac{\rho_G}{\rho_L}} \tag{3}$$

The velocity of a gas bubble in relation to the liquid (the drift velocity) v_b was determined from the dependence proposed by Hibiki [5]

$$v_b = \sqrt{2}\left(\frac{\sigma g \Delta\rho}{\rho_L^{\ 2}}\right)^{0.25} \left(1-\alpha_{cr}\right)^{1.75} \tag{4}$$

During two-phase flow in narrow mini-channels above a certain value of the gas phase share the frequency of the bubbles formed is so high that due to the coalescence one may observe the occurrence of greater bubbles forming the regular liquid slugs. According to Hibiki and Mishima [5] the limiting value of the gas phase share α_G changes from 0.2 to 0.3. The limiting gas phase share is principally determined by the width of a channel gap. The smaller the dimension of the gap, the smaller the values attained for the limiting gas phase share.

B. The Criterion of the Transition from Slug to Churn Flow Patterns

The criterion is based on the condition that an average gas phase share flowing in a two phase mixture coincides with the value of the gas phase share in a gas phase slug. This is equal in effect to the disturbances of the slug flow patterns characterised by sudden changes of the local gas phase share, in other words, the formation of churn flow patterns.

For the channels of a gap greater than 2.4 mm Hibiki and Mishima [5] described the limiting value of the gas phase share using the dependence above which one may observe the churn flow

$$\alpha_G \geq 0.813 X^{0.75} \tag{5}$$

Where

$$X = \frac{(C_0 - 1)(u_{SG} + u_{SL}) + v_b}{(u_{SG} + u_{SL}) + \gamma\left(\left(\frac{\rho_L D_h}{\mu_L}\right)^{-m} \frac{C_L \rho_L}{\Delta\rho g s}\right)^{\left(\frac{1}{m-2}\right)}} \tag{6}$$

m and γ depend on the value of the Reynolds number for the laminar flow m=1, γ= 0.15 after substituting the parameters m and γ one obtains:

$$X = \frac{(C_0 - 1)(u_{SL} + u_{SG}) + v_b}{(u_{SG} + u_{SL}) + \gamma\left(\frac{C_L \mu_L}{D_h \Delta\rho g s}\right)^{\left(-\frac{1}{2}\right)}} \tag{7}$$

Where C_L is a coefficient dependent on the Reynolds number and for the laminar flow in narrow mini-channels it was determined from the equation proposed by Wang et al [7].

C. The Criterion of the Transition from Slug to Annular Flow Patterns

In the case of the transition from slug to annular flow patterns the criterion proposed by Hibiki i Mishima [7] was used:

$$u_G = \sqrt{\frac{3\Delta\rho g D_h}{2\rho_G}}(\alpha_G - 0{,}11) \tag{8}$$

III. Experimental Set – Up

In order to examine the structures of two-phase gas liquid flow in vertical mini-channels the experimental set-up was assembled. Its main element was a vertical channel of rectangular cross-section. In the experiment two channels of different dimensions of cross-section were used: the channel I of dimensions 15 x 0.65 mm, of an equivalent diameter D_Z=0.00125 m, the channel II of dimensions 7.5 x 0.73 mm, of an equivalent diameter $D_{Z=}$0.00113 m.

The height of the channel in the two cases was equal to 400 mm. The mini-channel was made of polycarbonate which enabled to carry out the observations of the two-phase gas – liquid flow structures.

During the experiment the liquid was flowing in the closed circulation, the constant temperature of the examined liquid being maintained by a thermostat of volume 15 dm^3.

The liquid from the thermostat was supplied to the vertical channel using a pump. Before supplying the liquid into the channel the volumetric flow of the liquid was measured. In the first part of the channel the process of gas and liquid phase mixing occurred using an air distributor. The air was supplied to the distributor by a compressor and its parameters were measured and controlled by a gas flow meter. During the flow of the two-phase gas-liquid mixture through the channel the image of the flow structure was recorded using a digital camera. In the upper part of the channel the separation of the gas phase from the mixture occurred with its simultaneous supplying to the atmosphere. The liquid was directed to a vertical pipe of height equal to 1.5 m so as to attain the separation of the gas phase and, next, it was returned to the thermostat.

The superficial gas and liquid flow velocities used in the experiment changed from 0.0085 to 0.75 m/s and from 0.005 to 7.2 m/s respectively. As the continuous phase, water and two aqueous saccharose solutions (saccharose I and saccharose II) were applied. The air constituted the gas phase. The physical chemical properties of the liquids used in the experiment are demonstrated in Table I.

TABLE I
THE PROPERTIES OF THE MEDIA USED IN THE EXPERIMENT

	Viscosity [Pa·s]	Density [kg/m³]
water	$9.7\cdot10^{-4}$	998
Saccharose I	0.01	1214
Saccharose II	0.055	1274

The mini-channel was made of polycarbonate, which allowed to observe the structures of two-phase gas-liquid flow. The two-phase mixture flowing in the channel was recorded using a quick camera MV-D752 – 160 (Photonfocus) with a frequency of 314 frames per second and, subsequently, saved on the hard disc of a computer. Due to considerable film speed of the camera the photographs taken were clear which allowed to carry out accurate observations and to precisely define the structure of the flow. The identification of the flow patterns was performed off-line. The camera was mounted on a tripod, at a distance of 15 cm from a wider wall of the channel. Such a location of the camera as well as the dimensions of the channels brought about the fact that the structures registered were two-dimensional in practice. The gas phase share in the flowing two-phase mixture was determined on the grounds of the recorded image of the flow using the method presented in the study [8]

IV. Results and Discussion

The visual observations in the examined measurements confirmed the occurrence of the following flow patterns in the mini-channels, namely: bubble, cup bubble, bubble-slug, slug, slug-churn and annular. The cup bubble flow was observed only during two-phase flow with water. On the other hand, fully developed churn flow could not be detected. Admittedly, the observed destruction of the slugs was only partial. Therefore, the flow pattern under scrutiny was called slug-churn. The flow patterns observed in the experiment are shown in Fig. 1.

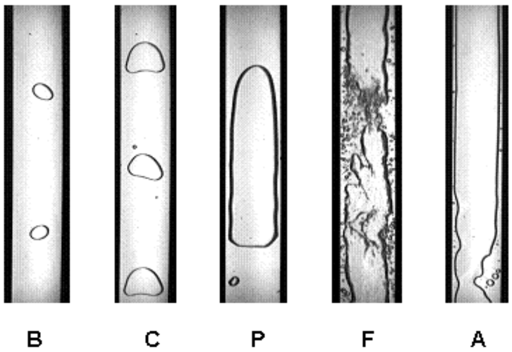

Fig. 1 The classification of the flow patterns observed in the experiment
B - bubble, C – cup-bubble, P - slug, F – slug-churn, A – annular

With the aim to examine the influence of the process parameters on the occurrence of the particular two-phase flow patterns, the results of visual observation have been presented in diagrams in the coordinate system $u_{SL}=f(u_{SG})$. The experimental results have been compared with the following criteria: the transition from the bubble to slug flow (the equation (2)), the transition from the slug to churn flow – defined by the equation (5) and from the slug to annular flow pattern – defined by the equation (8).

In Figs. 2 – 4 the flow regime maps of the two-phase mixture in the channel I has been shown. In each case of the flow the consistence of the predicted boundary between the bubble and the slug flow (the equation (2)) was observed. In must be added that cup bubbly flow patterns for water – air flow in the area of the bubble flow occurred. In contrast, in the case of a liquid of higher viscosity the consistence is present but the cup bubbly flow disappears. For the two-phase flow saccharose II – gas one may observe a new pattern of the flow, namely the bubble-slug one. Analogously, high consistence with the experimental data was observed in the case of a boundary between the slug and annular flow defined by the equation (8).

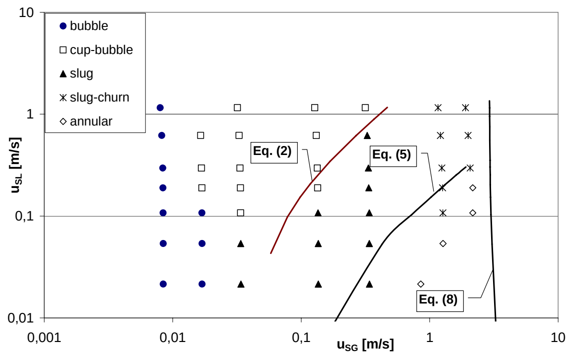

Fig. 2 Two-phase water-gas flow regime map in the minichannel I

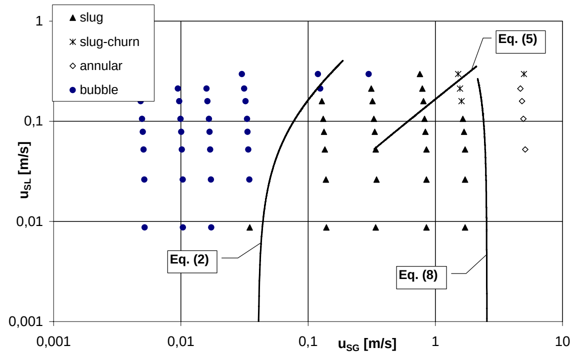

Fig. 3 Two-phase saccharose I - gas flow regime map in the minichannel I

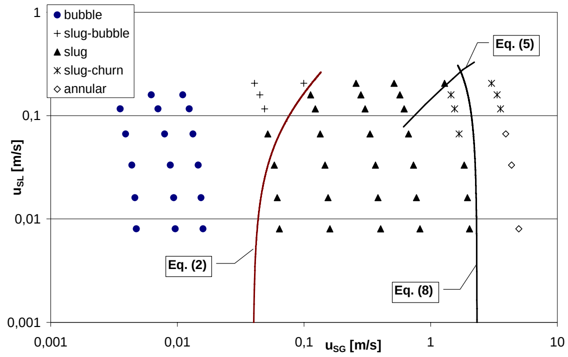

Fig. 4 Two-phase saccharose II - gas flow regime map in the minichannel I

The criterion defining the transition from the slug to the churn flow – the eq.(5) – cannot be relied on in the case of two-phase flow of the liquid of high viscosity. It is only in the case of two-phase flow with water that one may notice partial consistence with the experimental data.

In Figs. 4- 5 the maps of the two-phase flow mixture in the channel II has been shown. One may observe no essential differences connected with the occurrence of the particular flow patterns. The only change in comparison with the flow maps of two-phase flow in the channel is the separation of the slug flow from the annular flow with the slug-churn pattern. Therefore, it is vital that the boundary defined by the equation (8) separate the slug flow from the slug-churn one. The channel II is characterised by a much smaller cross-section area when compared to the channel I. Hence, it is easier for a liquid flowing along the walls to stop a gaseous core present in the central area of the channel. Simultaneously, higher superficial gas velocities are required to form the annular flow pattern. Nonetheless, disturbances in the flowing liquid are present for the similar superficial liquid velocity when compared to the channel I.

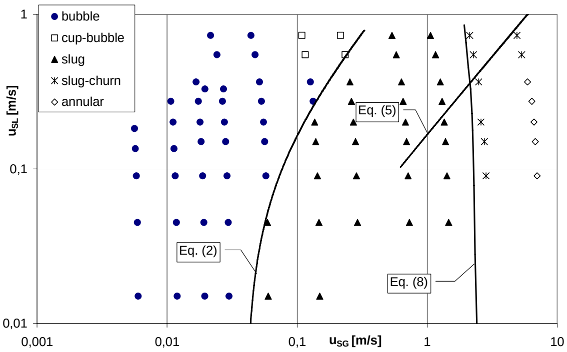

Fig. 5 Two-phase saccharose I - gas flow regime map in the minichannel II

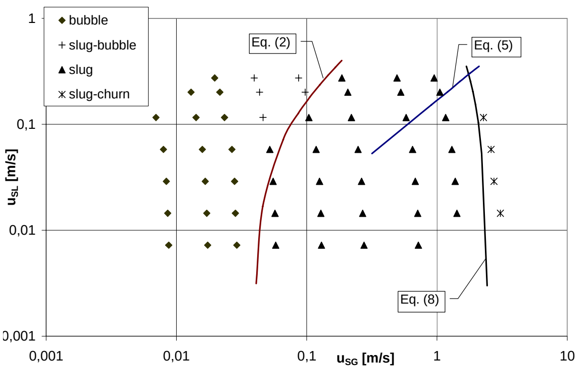

Fig. 6 Two-phase saccharose II - gas flow regime map in the minichannel II

V. Conclusion

As a consequence of the experiments performed and the comparison of the experimental results with the criteria of the transitions available in the literature it is stated that:

- High consistency between the predicted boundary (defined by the eq. (2) and the experimentally determined boundary separating the bubble from the slug flow is present.
- In the case of two-phase flow of the liquid of higher viscosity than the viscosity of water, the experimental data do not confirm the criterion (5).
- The criterion (8) defines the boundaries observed during the investigations, occurring between the slug flow patterns and the annular and slug-churn ones with high accuracy.

VI. Symbols

C_0	- distribution parameter
D_h	- hydraulic equivalent diameter of the flow channel, m
g	- gravitational acceleration, m/s^2
s	- gap width, m
u_S	- superficial flow velocity, m/s
v	- flow velocity, m/s
α	- void fraction
μ	- dynamic viscosity, Pa·s
ρ	- density, kg/m^3
σ	- surface tension, N/m

Subscripts and Superscripts

G	- gas
L	- liquid
b	- gas bubble

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