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Study of dynamics of two-phase flow through a minichannel by means of recurrences

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ABSTRACT

By changing air and water flow rates in the two-phase (air–water) flow through a minichannel, we observed the evolution of air bubbles and slugs patterns. This spatiotemporal behaviour was identified qualitatively by using a digital camera. Simultaneously, we provided a detailed analysis of these phenomena by using the corresponding sequences of light transmission time series recorded with a laser-phototransistor sensor. To distinguish particular patterns, we used recurrence plots and recurrence quantification analysis. Finally, we showed that the maxima of various recurrence quantificators obtained from the laser time series could follow the bubble and slugs patterns in studied ranges of air and water flows.

1. Introduction

Two-phase dynamics is important in many technical applications for pipe systems. In the context of minichannel flow, the complex nature of this phenomenon was studied experimentally [1–3]. The main results of the mentioned references were focused on classification of bubbles and slugs patterns in two-phase flows, however this classification schema were based on visualisation approach.

Zhao and Rezkallah [1] reported formations of two-phase air-water flow patterns at microgravity conditions during a series of parabolic flight trajectories in space. Wongwises and Pipathattakul [2] studied two-phase flow pattern, pressure drop and void fraction in horizontal and inclined upward air water two-phase flow in a mini-gap annular channel with horizontal and inclined channel. The experimental results showed that the inclination angle has a significant effect on the flow pattern transition, pressure drop and void fraction. Accurate flow visualisation experiments on adiabatic flow patterns in small tubes were carried out by Chen et al. [3]. The flow patterns were also modelled numerically by Anjos et al. [4].

Flow types were initially identified by Wang et al. [5], who used the Hurst and Lyapunov exponents, and correlation dimension. Jin et al. [6] applied the correlation dimension and Kolmogorov entropy, while Mosdorf et al. [7] discussed the results of various non-linear analyses of temperature and pressure fluctuations in microchannels. Zong et al. [8] and Gao et al. [9] characterised complex patterns resulting from horizontal oil-water two-phase flows by network recurrence quantifiers. Recently, Gorski at al. performed detailed studies of the transition from slugs to bubbles and the self-aggregation

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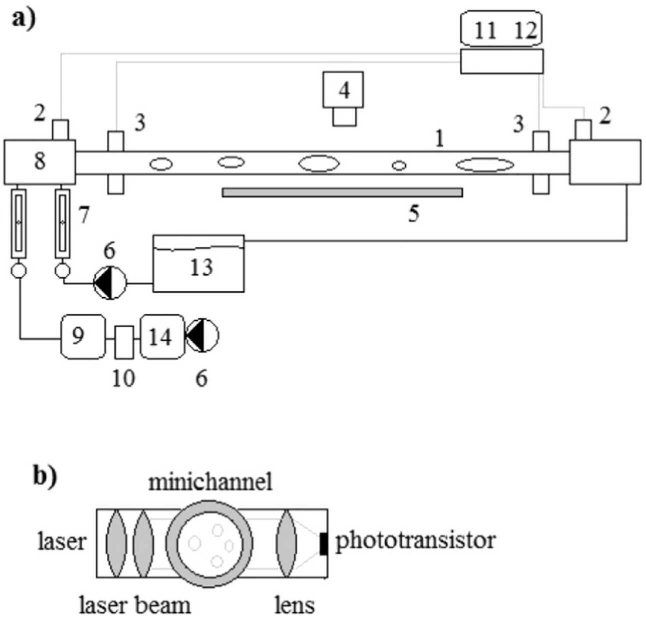

Fig. 1. Schematic plot of the experimental stand. (a) Experimental setup: 1. minichannel with a diameter of 3 mm, 2. pressure sensors (MPX12DP), 3. laser-phototransistor sensor, 4. Phantom v. 1610 camera, 5. lighting, 6. pumps (air or water), 7. flow metres. 8. mini bubbles generator, 9. air tank, 10. automatic valve to maintain a constant pressure in the tank 9, 11. data acquisition station (DT9800), 12. computer, 13. water tank, 14 air tank. The total length of the minichannel was 1 m while the laser was located 10 cm from the inlet end. (b) Laser-phototransistor sensor.

phenomenon in a similar system [10–12]. In [13] the authors performed the recurrence identification of two-phase flow patterns behaviour by analysing corresponding pressure drop time series.

In this paper, we attempt to complete a 2D map (plotted over air and water flow volumes) of different patterns by employing the Recurrence Plots Analysis. The systematic results based on laser light transmissivity measurement are compared to the standard qualitative observations made by the digital camera.

2. Experimental setup

The experiment involved analysis of data recorded for different flow patterns (water-air at 21 °C) in a 3 mm diameter circular channel. Fig. 1 shows the schematic design of the experimental stand. Given to the size of the minichannel, it was necessary to use a special generator of mini bubbles (8 - Fig. 1a) to produce bubbly flow inside the channel. The proportional pressure regulator (Metal Work Regtronic with an accuracy of 1 kPa) was used to maintain the constant overpressure in the supply tank (10 - Fig. 1a) at 50 kPa. Flow patterns were recorded using the Phantom v. 1610 digital camera at 5000 fps (1280×64 pixels). The amount of air flowing through the minichannel was measured by a laser-phototransistor sensor (3 - Fig. 1a). Data from the sensors was acquired by an acquisition system (Data translation 9800, an accuracy of 1 mV for voltages in the range of -10 V to 10 V), (11 - Fig. 1a) at a sampling rate of 1 kHz. A schematic design of the laser-phototransistor sensor is shown in Fig. 1b. It should be noted that we used various locations of the laser-phototransistor system and the obtained results were convergent.

Given size of the minichannel, the bubbly flow inside it can only be generated by a generator of mini-bubbles. The generator (Fig. 2) was made of 6 stainless steel sheets (each with a thickness of 0.5 mm). Orifices used for water and air supply and the outlet of the generator are shown in detail in Fig. 2. Slots were cut out in the sheets. The slots were used for supplying the water and air to the minichannel. Bubbles were generated in the central channel (0.5 × 0.5 mm - Fig. 2-1). Air was supplied via the channel (Fig. 2-2) to the orifice (0.25 × 0.5 mm) formed which by contact the sheets 1 and 2. Two outer channels (Fig. 2-3) were used to supplying the additional water to the minichannel.

Fig. 3 shows the classification schema of patterns based on digital camera images of the air-water flow upon changing the water and air rates. The mixture of air and water creates a flow with a non-uniform phase content. The air phase is visible as bubbles surrounded by water. As expected, the bubbles change the size and the corresponding distribution depending on the applied flow rates. It is clear that increase in the air supply leads to the formation of larger bubbles or elongated bubbles (air slugs). Additionally, there are processes of bubble aggregation and/or bubble instabilities which strongly influence the size of bubbles. Generally, for a higher q_w we observe smaller bubbles. This is the effect of increasing the flow velocity. Interestingly, at q_w=0.179 l/min and $q_a \in [0.113, 0.199]$ ln/min, we can observe a more periodic intermittency in the distribution of air bubbles in water. Some more complex periodicity can also be observed at cases (q_w=0.362 l/min and q_a=0.156 ln/min); and (q_w=0.544 l/min and q_a=0.242 ln/min). At higher values of q_w, the bubbles are

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