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Investigation of two-phase flow patterns by analysis of Eulerian space–time correlations

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ABSTRACT

This paper concerns experimental investigation of two-phase air–water flow in a 5 mm circular channel for different gas and water volume flow rates. Flow patterns are recorded using a high-speed digital camera. To investigate the spatial correlations of flow structures, we propose a new technique for extracting high resolution space–time series from video frames. For the extracted series, Eulerian space–time correlations are estimated and represented by correlation curves and spatio-temporal 2D maps for several gas and water volume flow rates as well as for different channel inclinations. The characteristic features of the flow patterns can be deduced from the correlation results.

1. Introduction

Two-phase flows in mini-channels appear in modern industrial plants, heat exchanges, and cooling systems more frequently. The characteristic structure of the two-phase flow significantly affects the results of technological processes. Therefore, mixed flows have been tested and new methods for measurement and identification of flow patterns are sought for decades. This research is concerned with analysis of video data obtained from measurements of two-phase flow in a channel with varying inclination. We present the scientific background and motivation behind this work by putting special emphasis on measurement techniques and data analysis methods which are applied in investigations performed with a high-speed camera.

To start with, Lockhart and Martinelli (1949), investigated various flow mechanisms of the two-phase air–liquid flow in a circular channel by measuring pressure-drop. The authors showed that the pressure drop in the mini-channel is correlated in means of parameter X, where X denotes the square root of the ratio of pressure drop in the pipe if only the liquid flows alone to the pressure drop if the gas flows alone. The issue of correlating two-phase flows with respect to various parameters, in particular X, has been very intensively examined in recent decades. Velocity of long bubbles in vertical tube has been derived theoretically by Dumitrescu (1943) and investigated experimentally by Davis and Taylor (1950). The shape of long bubbles in horizontal channels was studied theoretically and experimentally by Netto et al. (1999). The systematic experimental investigations of two-phase flow patterns in mini-channels were undertaken by Triplett et al. (1999b). Unfortunately, the results of the experiment showed rather poor agreement with pressure drop models. In the further part of the studies reported by Triplett et al. (1999a), the void (gas volume) fraction and pressure drop in microchannels were systematically measured and analyzed. The void fraction was estimated from photographs taken by a system of a strobe and a digital camera. Studies were also undertaken to analyze correlations in the two-phase flow based on a large number of measurements. To give an example, Li and Wu (2010) and Xu et al. (2012) use a number of correlation results from the published data to find new and more general pressure drop correlation formulas. In turn, Choi and Kim (2011) studied the two-phase flow pressure drop in rectangular microchannels with different aspect ratios and hydraulic diameters. They used a high-speed digital camera and a long-distance microscope to visualize the flow patterns. Two-phase flows were studied in various configurations. Zukoski (1966) made the experimental study of the long bubbles motion in closed tubes. He investigated the influence of viscosity, surface tension, and the channel inclination angle on the bubbles velocities. The pressure drop correlations in the two-phase flow in horizontal helicoidal mini-channels were measured by Awwad et al. (1995). They tested 32 different helicoidal pipes for a range of flow rates of the both mixture components and found the data to be well correlated. Mishima and Hibiki (1995) studied

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the characteristics of two-phase flows in vertical minichannels of different diameters while Zaidi et al. (1998) investigated the effect of channel inclination on two-phase flow using two different laser methods. Coleman and Garimella (1999) analyzed the effect of mini-channel diameter and shape on two-phase flow patterns in the circular and rectangular horizontal pipes. In this case, the flow patterns were determined by a high-speed camera analysis to distinguish flow regimes and transitions occurring between them.

Nowadays more and more sophisticated experimental techniques and theoretical methods are used to investigate two-phase flow. The methods of electrical resistance tomography are developed and used to measure flow patterns. Dong et al. (2003) applied a sensing array consisting of 16 electrodes to identify flow regimes in two-phase air–water flow. Using the polynomial regression method they were able to estimate the void fraction, whereas by exploiting the neural networks they could identify the flowing structures. A four electrode conductance array was used by Gao et al. (2013) to collect multivariate data from the oil–water two-phase flow. They derived the multivariate recurrence networks from the experimental data and proved that the cross-clustering coefficient from the multivariate recurrence network can be used to detect flow patterns. The most widely used advanced theoretical and numerical procedures for identification of flow patterns include Hurst and Lyapunov exponents: Wang et al. (2003), correlation dimension: Wang et al. (2003) and Jin et al. (2003), Kolmogorov and multiscale entropy: Jin et al. (2003) and Górski et al. (2015a), and recurrence plots: Gao et al. (2013) and Górski et al. (2015c, 2015b).

Two-phase flow patterns are often studied using complex video systems compatible with special software for image analysis. For example, Hay et al. (1998) applied a system consisting of a video camera and a strobe illumination to investigate the sizes and shapes of drops in the annular flows. Similar tests were conducted for higher pressures by Fore et al. (2002). By registering two-phase flows, they used a steel wire with lines scribed around its circumference to create a spatial reference scale visible in the video frames. The study of two-phase flow, where the video frames recorded by a high-speed camera were used to determine the cross-sectional averaged void fraction of droplets in the annular regime, were made by Serizawa et al. (2002). In the literature one can find many other examples of the use of the video techniques to study the two-phase flows. Only a few of them convert the video data into time series, which can be further analyzed using various numerical methods.

Despite many decades of research, the interest in two-phase flow continues unabated. Two-phase flow is a turbulent and non-linear process which depends on many variables. The emergence of new theoretical, numerical and experimental methods testifies to the great importance of this phenomenon for industry and non-linear science. The aim of the present paper is to introduce a new simple method that enables drawing a time series from a sequence of video frames. First of all, we want to demonstrate that the proposed technique is easy to apply when compared to the aforementioned advanced experimental methods. Despite its simplicity, this technique has a great analytical potential that is difficult to presented in a single publication. The obtained time series can then be analyzed using a number of methods for non-linear systems analysis. Out of these many methods, we decided to choose the correlation method because, in our opinion, it is well suited to study the structure of two-phase flows. Here, we perform two-gate conversion which results in two independent time series collected simultaneously. The experimental results of air–water two phase flows in a 5 mm channel are analyzed by Eulerian space–time correlations for both time series. The results of the correlation calculations are then presented on a color 2D maps. Such a presentation of the results makes it possible to read the most important information about flowing void patterns and about the changes that occur in them when the parameters and geometry of the experiment are changed. Finally, we propose some 2D maps transformation which enables reducing the graphical results to a single curve representative of the whole series. These two-dimensional graphical representations of a series of flows are then converted to a single curve by applying an inverse continuous wavelet transform. It gives a brief characterization of flow dynamics of the whole series.

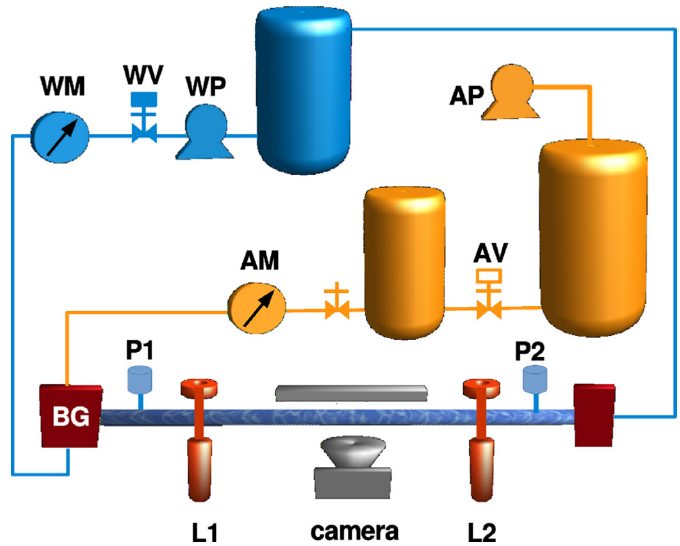

Fig. 1. Two-phase system flows in a channel. Air is provided to the water loop (blue) from a side branch (yellow). Pressure is measured by two sensors (P1, P2). Two lasers measure the perturbations of the system (L1, L2). The camera collects video frames. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Experimental setup and procedure

This work investigates various flows of two-phase systems which differ in relative amounts of the two phases. All flows were studied in a circular channel with a diameter of 5 mm for three configurations: horizontal, slope (45°), and vertical. During the measurements, the results were recorded by two pressure ports, two laser sensors and a high-speed video camera. A schematic of the experiment is shown in Fig. 1 while the design of the mixture injector is presented in Fig. 2. The generator was made of 6 sheets of stainless steel (0.5 mm thick): 2 for separation, 3 with water, and 1 with air minichannels. The total channel length was 40 cm and the part of the channel seen by the camera was 28.5 mm. The flow registered by the camera was fully developed. The pressure ports and laser probes were set up outside the area. The pressure difference between the inlet and outlet of minichannel was measured using the MPX12DP silicon pressure sensor (range 0–10 kPa, sensitivity 5.5 mV/kPa, response time 1 ms, accuracy 0.05 kPa). Data from the sensors were acquired by the acquisition system (Data Translation 9804, an accuracy of 1 mV for voltages in the range of -10 V to 10 V), at a sampling rate of 2 kHz. The analysis of the two-phase flow discussed in the paper is performed on the basis of the video data. Video frames were collected by a fast digital camera Casio EX-F1 at a rate of 1200 fps with a resolution of 336 × 96 pixels. The field of view of the camera had a size of 28.5 mm (width) × 8.14 mm (height). The size of the window where the two-phase flows were registered was 28.5 mm × 5mm in physical units, and 336 × 59 in pixels. The values of water and gas volume flow rates applied in the measurements are listed in Table 1. The flow measurements were made in series. The rate of water volume flow (column 2) was fixed for each series. The