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Dynamics of two-phase flow analyzed by multi-gate correlations

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ABSTRACT

A multi-gate cross-correlation technique is applied to analyze the dynamics of a two-phase flow. The water and air concurrent flows are measured in a 5 mm diameter circular channel inclined at an angle of 45 degrees and set vertically, with different gas-to-liquid volume rates. The Experimental results are put in series with a constant water flow rate. Several variables are measured along with capturing video frames by a fast digital camera. Time-series data are extracted from the video data by setting seven conversion gates in the camera's field of view. By calculation of the cross-correlation coefficients between the first and subsequent gates, the characteristic parameters of spatial correlation decay are measured for each flow. A comparison of the correlation decay in the modeled and experimental flows reveals some interesting aspects of the flow dynamics.

1. Introduction

A two-phase flow of a certain dynamics is created by a characteristic pattern of gas structures and its variability in time and space. Depending on the geometry of the experiment, volume flow rates of both phases, their properties, temperature, pressure and other conditions [1], a flow is assigned to a specified flow class based on its distinguishing characteristics. Therefore, flow type identification is an important reference point for both the theoretical analysis and experimental research. Given the wide spectrum of forms and phenomena of two-phase flows, the classification of flows is not regulated in detail. Many researchers establish their own classifications based on flow qualities and the type of information generated from the theoretical and experimental results of their work [2,3]. According to the most general classification, flows can be divided into four classes: bubbly, slug, churn, and annular. Since there are no sharp borders between these classes, therefore the literature often offers descriptions of other classes, located in the border areas between the above classes.

The identification of flow, that is, the distinguishing of their characteristics and assigning them to a specific class of flow, is conducted using a variety of experimental and theoretical techniques. Some research topics such as pressure drop correlations [4] were investigated thoroughly and now form some kind of standard in the studies of two-phase flows. On the other hand, some research groups [e.g. [5]] apply sophisticated experimental techniques and innovative theoretical approaches with a view to obtaining a deeper insight into this phenomenon. Among others, they include widely used experimental techniques, such as laser light transmission recorded by semiconductor photo-sensors [6] or an array of optical sensors [7], impedance measurements [8,9], ultrasonic methods [10] or methods based on the use of electrode-mesh systems [11]. Sometimes, instead of complex measurement systems and analytical methods, the researchers use simple means. For example, [12] developed an electronic system integrated with the flow duct, performing "on line" impedance measurements and numerical analysis necessary to identify the flow. On the other hand, the measurement by the optical fiber probe [13] increases the spatial and temporal resolution of the experiment yet at the expense of some interference with the interior of the system. Virtually in all experimental studies of the two-phase flows, the flows – in parallel to other measurements – are recorded by a fast digital camera. In some works, the series of images are used to produce time-series, a further numerical analysis of which provides information about the flow characteristics [14,15]. In our research we use a similar approach. Another idea of using the video data to study two-phase flows is based on direct observation of the movement of gas particles in the liquid, as in the case of the PIV (particle image velocimetry) method (e.g. [16]).

Many experimental studies of the flows are based on the correlation and cross-correlation measurements. [17] was the first to consider the correlations in turbulent fluid flows. This approach is still being developed in many scientific and practical applications, e.g. to measure the velocity of a turbulent or multiphase flow. Cross-correlations as the tool for studying the flow velocity of a gas/solid mixture were exploited by [18]. This method is also commonly employed in testing of a gas/liquid mixture [19,20]. [21] also investigated the problem of measuring the speed of a turbulent flow on the basis of cross-correlation. Their analytical model enables, among other things, determination of the correlation decrease following an increase in the distance between the probes. We call this phenomenon a "correlation decay". It is the focal

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point of our research and it provides a tool for evaluating the dynamics of the two-phase flows. The problem of correlation decay in turbulent flows attracted the attention of researchers much earlier [22]. Similar studies were also conducted for the gas–liquid mixture [23].

The main aim of this work is to study the dynamics of two-phase flows by measuring the cross-correlations decay. The tested air–water flows were measured in a 5 mm diameter circular channel at vertical and slope (45°) configurations (Section 2). The examined time series were obtained from video data through the conversion described in Section 3. The conversions was performed simultaneously at multiple locations named as gates. The first approximation consists in characterizing the dynamics of the tested flow is characterized by a curve fitted to multi-gate correlation peaks. A description of the multi-gate cross-correlations and a selection of the results obtained for the experimental data are given in Section 4. A simple model of diffusion of the gas structures (Section 5) allows us to determine an analogous correlation decay curve for the theoretical data. The parameters of the correlation decay curves calculated for the experimental results of all series are reported and discussed in Section 6. In this section, the experimental results are also compared with the model predictions. The last section offers conclusions and comments on the results.

2. Experiment

The data were provided by the experiment studying several two-phase flows for different values of water and air flow rates were investigated in a 5 mm diameter circular channel for slope (45°) and vertical configurations. A schematic design of the experiment is shown on the left in Fig. 1. The analyzed time series were obtained from video data through the conversion described in Section 3. During the flows measurements, different data were recorded by using pressure ports, laser sensors and a high-speed video camera. In this work, the video data are used to determine the cross-correlations of the system. 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, which corresponds to the dimensions of the field of view of a camera equal to 28, 5 × 8, 14 mm^2. The size of the window where the mixture flows were registered was 336 × 59 in pixels, and 28.5 × 5 mm^2 in physical units. The flow measurements were made in series. In each series, the water flow rate was maintained constant. This constant value, denoted by a symbolic name (Table 1) defines a given series. The relative air content in the system increases with the number indicating the number of a measurement in the series. The serial numbers of the measurement in the cycle denoting the gas volume flow rates are listed in Table 2. The experiments performed in the slope (45°) configuration are denoted by the letter ‘s’, and in a vertical configuration by the letter ‘v’. On the right of Fig. 1 there are shown exemplary video frames recorded in the series s-W2: s-W2-5, s-W2-8, s-W2-9, and s-W2-11, in order from top to bottom.

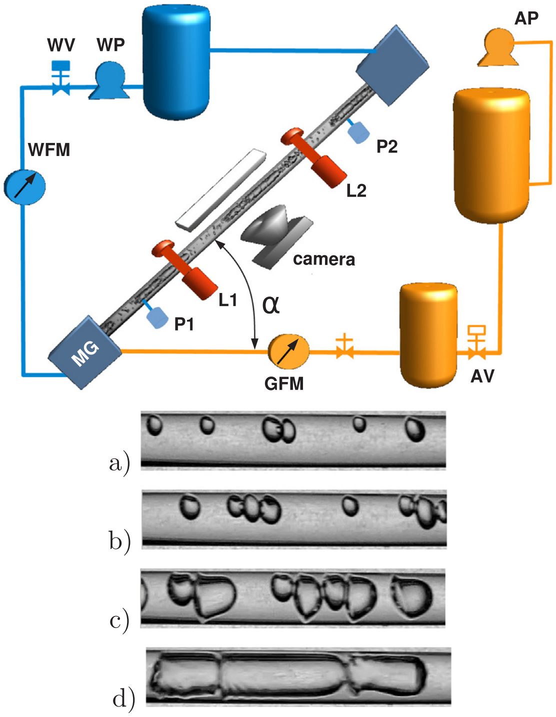

Fig. 1. Two-phase mixture flows in a channel. Air is provided to the water loop (blue) from a side branch (yellow). Pressure is measured by two sensors (P1, P2). Two lasers measure the perturbations of the system (L1, L2). The camera collects video frames. Below there are exemplary video frames collected for the slope (45°) configuration of the channel, flows: s-W2-{5, 8, 9, 11} from top to bottom, respectively. Water and gas volume flow rates are listed in Tables 1 and 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Symbolic names representing a series of two-phase flows and the corresponding values of water volume flow rates.

Flow series symbolic names	*WFR* (l/min)
W1	0.23
W2	0.38
W3	0.52
W5	0.85
W7	1.09

3. Video-data-conversion

In this work we extend the procedure of converting video data on time series for two spatial locations, which was described in the study by [24]. According to our concept, the time series are converted in locations called gates. The analysis is extended by replacing two gates $\{G^1, G^2\}$ by a system of seven equidistant gates $\{G^1, G^2, \dots G^7\}$, as shown in Fig. 2. The previously analyzed gates G^1 and G^2 correspond to gates G^1 and G^7 which are considered in this study. In the process of video data-to-time series transformation, for each video frame we determine instantaneous values at the conversion gates. For each gate, this value is equal to the number of black points lying on the line of the conversion gate, after filtering the video frame to a one-bit resolution image.

4. Multi-gate correlations

4.1. Concept

The study of fluid dynamics is based on time series converted from gates G^i, $i = 1, 2, \dots, 7$. Multi-Gate cross-correlation coefficients are

Table 2
Values of the gas volume flow rates for the subsequent flows of the series.

Flow No.	*GFR* (l/min)
1	0.0025
2	0.0063
3	0.0105
4	0.0157
5	0.0216
6	0.0295
7	0.0381
8	0.0457
9	0.1
10	0.2
11	0.3
12	0.4