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Short Communication

A new method for the study of two-phase flow patterns based on the chaotic characteristic method of image fields ☆

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ABSTRACT

The phenomenon of two-phase flow is widespread in industrial production. Different flow regimes have different mechanisms for heat-transfer and flowing. Changes of flow regimes in a channel can lead to flow resistance, a change of stability and heat transfer problems. Therefore, understanding the dynamics and identification of the flow regime in a gas–liquid two-phase flow is vital in industrial production. Because of complex interfacial effects and relative motion between the phases, it is difficult to accurately identify the two-phase flow patterns. This paper emphasizes the study of flow dynamics, and flow pattern identification. This paper also proposes a new method for extracting time series. Each frame of the video signal is divided into smaller areas. The gray scale difference of two adjacent frames is calculated to obtain the maximum points in the smaller areas and form a time series. The maximal Lyapunov exponents of time series are respectively extracted, and its matrix is composed. The videos of gas–liquid two-flow patterns are divided into different chaotic areas by the characteristics of the Lyapunov exponent. Then the overall and detailed analyses are conducted respectively by zero and one distribution map and contour map. The mechanism of gas–liquid two-phase flow is analyzed by combining the fractal box dimension, Shannon entropy, and the average value of the maximal Lyapunov exponent matrix. As there are chaotic characteristics with different intensities in the background of the gas–liquid two-phase flow video and changed phase interfaces, the results show that the extracting method of the maximum distance series of small areas combined with the maximal Lyapunov exponent can be used to distinguish the characteristics of different flow patterns, which is proven to be an effective method for analyzing the gas–liquid two-phase flow signals.

1. Introduction

The phenomenon of the two-phase flow is widely found in heating transfer equipment in the fields of chemistry, petroleum, and dynamical engineering, as well as various processing industries, such as evaporators, condensers, boilers and oil and gas transmission. The two-phase flow and heat transfer characteristics are extremely influenced by flow regimes. It is the basis of the computation of heat transfer and flow, although it cannot be described quantitatively. Different flow regimes have different mechanisms of heat-transfer and flow. Changes of flow regimes in a channel can lead to flow resistance and a change of stability and heat transfer problems. Therefore, understanding the dynamics and identification of the flow regime is very important in the gas–liquid two-phase flow [1].

Because of complex interfacial effects and relative motion between the phases, it is difficult to accurately identify the two-phase flow patterns. In particular, the mechanism of the transition from flow patterns to dynamics has not been very clear; two-phase flow is a complex, non-linear dynamic system. Since the 1990s, we have seen increasing research on the analysis of flow pattern dynamics and identification based on the chaos and fractal time series [2–6].

After nearly 5 years in the application of image processing technology in the gas–liquid two-phase flow patterns identification and dynamics, research has seen a lot of reports. Zhou et al. [7,8] extracted a gray symbiotic matrix, gray histogram statistical characteristics, and wavelet packet information entropy traits from the single frame flow pattern image made up of the feature vector, identifying the flow patterns with the neural network and support vector machine (SVM). Additionally, the Lempel–Ziv complexity characteristics, Shannon entropy, and the fractal box dimensions of single frame images were extracted; the chaos dynamic characteristics of the three complexity measures were analyzed in different gas superficial velocities [9].

However, when we analyze the dynamics of flow patterns, the method of image analysis mentioned above may lose some information. Many feature extraction methods will ignore a great deal of useful important information for single image. If the

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emphasis is on flow pattern identification, the method of image analysis mentioned above is sufficient. Although this paper's emphasis is on the analysis of flow pattern dynamics, a method that not only can play the advantages of visual images, but can also save as much of the image's information as possible is needed. In comparison to the above methods, the method put forth in this paper has greater advantages analyzing the dynamic characteristics of flow patterns. It will afford more abundant information for comprehending the dynamic characteristics of flow patterns. And through several characteristic parameters of the maximal Lyapunov exponents matrix, we can see the distribution of the flow interface of the gas–liquid two-phase flow in the pipeline; it will reflect the trends of the two-phase flow, which can help us master the flow mechanism of the gas–liquid two-phase flow patterns.

For images, gray values can be regarded as the product of incident light components and the reflected light components. The incident light, depending on the light source, is usually uniform. However, the intensity of reflected light, which depends upon the nature of the reflector, will change with different properties and the structural features of the reflector. According to the test, the gray scale video images of the single-phase flow pipelines have chaotic characteristics. While the gas appeared in the pipes, the interfaces also occurred within the pipes wherein the structure, thickness and direction were changing with the flow pattern. As reflected light is more stable than single-phase fluid, the chaotic characteristics of the two-phase flow gray image are changed in an image. With this feature, the image signal of two-phase flow is studied to reveal its inherent kinetic mechanism.

2. Data collection

Experiments were carried out by the air–water two-phase flow experimental system, composed of fluid control equipment and image acquisition equipment. The experimental liquid is water, and experimental gas is air. The scheme of this experimental system is shown in Fig. 1. A transparent Plexiglas tube was selected. Its inner diameter is 40 mm, and the length is 2 m. The range of its water volume flow is 0.007–3.180 m^3/h. The range of its air volume flow is 0.500–4.585 m^3/h. The environmental pressure is 1.01 × 105 Pa, and the environmental temperature is 20 °C. The images of six kinds of typical flow patterns were intercepted in the video of flow patterns in the horizontal Plexiglas tube. The size of the video is 1536 × 1024. The frame rate of the video is 250 frame/s. The images of six kinds of flow patterns are shown in Fig. 2.

3. Extraction and analysis of the sequence with the maximum gray distance

3.1. Maximal Lyapunov exponent (MLE)

The Lyapunov exponent λ quantifies the sensitivity to initial conditions of a dynamic system and also quantifies the predictability of system behavior. A system, which is embedded in the m-dimensional phase space, has m Lyapunov exponents ($\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_m$). Since a positive Lyapunov exponent indicates chaos, the computation of only the MLE (λ_1) is sufficient for detecting the chaos [10,11].

Therefore, in this study, the MLE was estimated as an indicator of the chaotic behavior of the Doppler signal by using the Wolf's algorithm [12], which is frequently used for the analysis of experimental data as a simple and robust method [11].

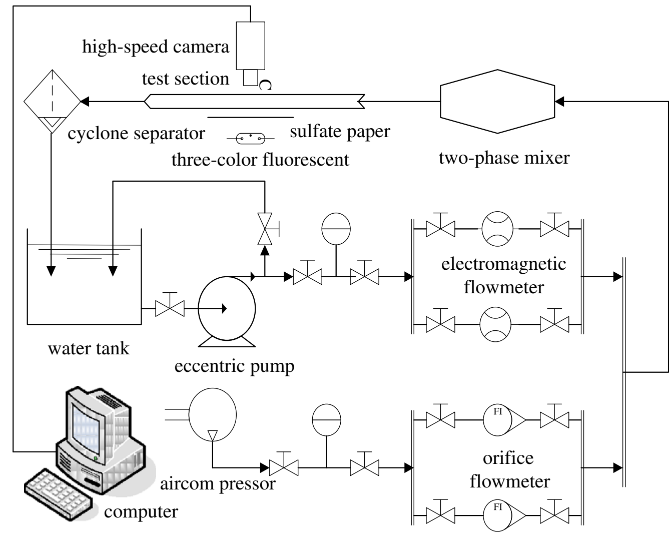

Fig. 1. Experimental system of air–water two-phase flow.

Wolf's algorithm is based on the direct calculation of divergence or convergence of the trajectories on the attractor and given as [12]

$$\lambda_1 = \frac{1}{t_N - t_0} \sum_{i=1}^{N} \log_2 \frac{L'(t_i)}{L(t_{i-1})} \tag{1}$$

where $L'(t_i)$ and $L(t_{i-1})$ are the Euclidean distances calculated between two nearest neighbor points on the different trajectories of the attractor at the t_i and t_{i-1} time steps, respectively. The ratio of these distances gives the evolution of these two points on the attractor for this time interval. This procedure is repeated by selecting the new neighbor points at the replacement points on the attractor until the end of data file. N is the number of replacement steps or iteration number. As N increases, the value of the exponent converges to a constant which is also its average value and this value is known as the true MLE value [12].

3.2. Extraction and analysis of the sequence

This method has been applied to search ships on the sea. In the video, there are regular chaotic characteristics on the surface of a sea without any ships, while there are chaotic characteristics where ships appear to be damaged. The positive and negative values of the maximal Lyapunov index can form the shapes of the ships. 100 frame images were used to detect ship target by this method. Experiment result shows that the detection rate of the proposed algorithm is 100%, and its false alarm rate is only 5%. So the algorithm is superior to the statistical analysis method which was often used.

The idea of this study is that the variation of the whole structure of the image is presented by the variation of the gray of the image block area. Based on this idea, the paper analyzes the variation of the interface in the images of the gas–liquid two phase flow. This paper extended the method and proposed to describe the different flow patterns by zero and one distribution maps. The 2D and 3D contour maps and the probability density spectrum are calculated together to analyze the mechanism of the gas–liquid two-phase flow. In addition to identifying the flow patterns, the extended method is important in that through these several characteristic parameters it can know the distribution of the flow interface of the gas–liquid two-phase flow in the pipeline, which can help master the flow mechanism of the gas–liquid two-phase flow patterns.