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Gas–water two-phase flow characterization with Electrical Resistance Tomography and Multivariate Multiscale Entropy analysis☆

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A B S T R A C T

Flow behavior characterization is important to understand gas-liquid two-phase flow mechanics and further establish its description model. An Electrical Resistance Tomography (ERT) provides information regarding flow conditions at different directions where the sensing electrodes implemented. We extracted the multivariate sample entropy (MSampEn) by treating ERT data as a multivariate time series. The dynamic experimental results indicate that the MSampEn is sensitive to complexity change of flow patterns including bubbly flow, stratified flow, plug flow and slug flow. MSampEn can characterize the flow behavior at different direction of two-phase flow, and reveal the transition between flow patterns when flow velocity changes. The proposed method is effective to analyze two-phase flow pattern transition by incorporating information of different scales and different spatial directions.

1. Introduction

Gas–liquid two-phase flow widely exists in process industries, such as petroleum exploitation and transportation, nuclear power and chemical industries [1]. The understanding on the flow behavior of gas–liquid two-phase flow is of aid to modeling two-phase flow. Gas–liquid two-phase flow is a time-variant non-linear dynamic system, the momentum, heat and even mass transfer at the interface of the two phases complicate its flow process.

Many measuring techniques have been adopted to characterize gas–liquid two-phase flow, such as by a high speed camera [2], differential pressures [3], conductance/capacitance sensors [4]. The flow information extracted by these measuring techniques are then analyzed with imaging analysis, statistical analysis, time–frequency analysis of either wavelet transform or Hilbert transform, chaotic analysis and entropy analysis [5]. These methods usually use one independent measurement data series, and hence only provide the flow information in either local or average manner. However, the single point measurement cannot obtain detailed information regarding the complex spatial distribution of two phases, thereby multiple points measurement is needed.

Considered as a transplant from medical imaging, flow imaging technique (named Process Tomography, PT) was introduced into process industries in the middle of 20th century [6]. PT is capable of providing temporal–spatial information of multiphase flow at one or multiple measuring cross sections of an opaque vessel or a pipeline. It thereby thrived in multiphase flow imaging during the past decades. PT adopts multiple projections on the measuring cross section to acquire as much information as possible to reconstruct the cross sectional phase distribution by utilizing the integral values of the sensing field projected from different directions [7]. One of the commonly used PT modalities is Electrical Tomography which can be sub-divided into Electrical Resistance Tomography (ERT) and Electrical Capacitance Tomography (ECT) [8,9]. These two electrical modalities are similar in operation but different in the sensitivity of electrical properties. ERT is sensitive to the change of resistance/conductance of fluid while ECT to the capacitance. In the case of ERT, the continuous phase of two-phase systems must be a conductive fluid, such as mineral/salted water, the second phase may be either non-conductive (gas) or highly conductive particles, e.g. metallic mineral particles [10]. ECT functions well when the continuous phase is isolative. For gas–liquid two-phase flow when the liquid phase is water, which is usually conductive, ERT is selected [11].

ERT has been used in various industrial applications for concentration profile visualization, flow velocity measurement and fluid dynamics characterization in gas–liquid two-phase flow where impedance contrast exists between the main fluid and the second phase fluid. Boundary voltages are collected between the

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electrodes by applying electrical currents into one or more pairs of the electrodes under a specific sensing strategy [12]. ERT is faster in response to flow dynamic change compared with radiation based tomography, thus provides rich information regarding dynamic flow behaviors at different directions of the measuring cross section, which potentially improves the equipment design, process control, the development of theoretical models, multiphase flow monitoring and products quality assurance [13].

The multiple electrodes could provide more information than the single point sensors. These information can be directly utilized for analyzing two-phase flow behavior without reconstructing the cross-sectional images. When applying ERT on flow process monitoring and analysis, a frame of 208 data (16 electrodes under adjacent mode) would be a high dimensional matrix if the time history of the matrix is considered. Therefore, ERT needs a synthetic tool for a thorough description and characterization of the multivariate time series provided by the multiple electrodes. A frame of ERT data is usually compressed into one feature or a vector of features to simplify analysis [14]. For instance, Tan et al. [14] extracted wavelet features from a univariate feature compressed from a 16-electrode ERT for flow pattern identification. Useful information would be lost during the averaging of the multivariate time series, thus synthetically characterizing the multi-source information for profound understanding on the analyzed process presents a challenge to the applications of ERT. For instance, Xu et al. [15] applied Independent Component Analysis (ICA) on the univariate feature extracted from a 8-electrode ERT to analyze the flow behavior of gas–liquid two-phase flow.

Entropy is a measure of complexity of a dynamic system (usually refers to the Shannon entropy [16]) or a signal. Traditionally, entropy increases with the degree of disorder of a dynamic system and reaches its maximum for a completely random system, such as approximate entropy (ApEn) [17] and sample entropy (SampEn) [18]. However, this increase in entropy is not always explicitly related to a higher degree of overall complexity as discovered by Costa et al. [19]. Therefore Multiscale Entropy (MSE) is presented to characterize the complexity of a dynamic system on different scales. MSE quantifies the interdependence between entropy and scale through evaluating sample entropy of univariate time series that coarse grained at multiple temporal scales, and has been successfully applied on analyzing the complexity of physiologic signals [20].

The MSE analysis was applied in characterizing vertical gas–water two-phase flow with a vertical multi-electrode array by Zheng and Jin [21]. They found that MSE is helpful in understanding the two-phase flow behaviors.In order to further utilize MSE method, Zhu et al. [22] adopted Multiscale Cross Entropy method by including the average phase fractions at two axial locations to study the flow behavior of inclined oil–water two-phase flow.

The aforementioned MSE algorithm analyzes scalar time series and is therefore not a practical tool for multivariate time series analysis. To further understand the detailed spatial characteristics of gas–water two-phase flow, we utilized the multi-dimensional information provided by ERT at different directions of a cross-section of pipe. The data measured by ERT are treated as a multivariate time series containing temporal–spatial flow dynamic information within one cross-section, and analyzed with Multivariate Multiscale Entropy (MMSE). In this work, we characterized the typical flow patterns with Multivariate Sample Entropy (MSampEn), and also investigated the MSampEn change when the flow velocity changes. The MSampEn reveals the inherent flow mechanics of gas–liquid two-phase flow, and the flow pattern change behavior is analyzed in a MSampEn plot.

2. Electrical Resistance Tomography

Electrical Resistance Tomography (ERT) is based on the principle that the conductivity of medium (phase) differs. The electrical response of conductive fluid includes a real part and an imaginary part. The real part is caused by the resistance of the fluid while the imaginary part is caused by the capacitance. Under low frequency exciting signals, the real part dominates; under high frequency, the imaginary part. So the exciting frequency for resistance measurement is between 10 kHz and 100 kHz in practice. In the meanwhile, the higher the frequency, the faster the sampling rate. Therefore a constant electrical current of 50 kHz and 5 mA peak–peak amplitude is adopted as the exciting signal, and the data acquisition rate is 120 frames/s. The ERT system has 16 alloy electrodes of 6 mm width and 8 mm height as adopted in our previous works.

An ERT collects boundary voltages between the electrodes by applying electric currents into one or more pairs of the electrodes under a specific sensing strategy. Then the phase distribution can be reconstructed through a specific reconstruction algorithm. The adjacent sensing strategy is adopted in the present ERT system, which operates in the following steps: the exciting current firstly injects into a pair of neighbouring electrodes and the voltages measured from successive pairs of neighboring electrodes. This process repeats until all the independent measurements have been made [23], as shown in Fig. 1. In adjacent strategy, a 16-electrode ERT obtains $13 \times 16 = 208$ voltage data (104 independent data due to reciprocal theory) to reconstruct one cross-sectional image (usually called frame). The electrode configuration in the experiments is shown in Fig. 2.

For two-phase flow analysis and characterization, a time series matrix of 208 dimensions would bring difficulties to data processing, therefore we extract a simple feature vector V_{Ri} from each electrode to reduce dimensionality:

$$V_{Ri} = \frac{1}{13}\sum_{j=1}^{13}(V_{ij} - V_{ij0}), \quad i = 1, 2, \ldots, 16 \tag{1}$$

where V_{ij} is the measured value of the jth ($j = 1, 2, \ldots, 13$) boundary voltage in the ith ($i = 1, 2, \ldots, 16$) excitation, and V_{ij0} is the V_{ij} when the pipe is full of water. This voltage is induced by the change of conductivity within the measuring cross section, as a result of phase distribution. Therefore, each V_{Ri} represents a local interrogation of the sensing field at the direction of the exciting electrode pair, along with the response of the measuring electrodes to the change of phase distribution [24]. There are hence 16 V_{Ri} in each frame of measured data, so the phase distribution change can be analyzed through a 16-variate time series obtained from ERT. An example of 16-channel signals of V_{Ri} of slug flow is shown in Fig. 3. The fluctuations of each V_{Ri} time series represent the responses of the

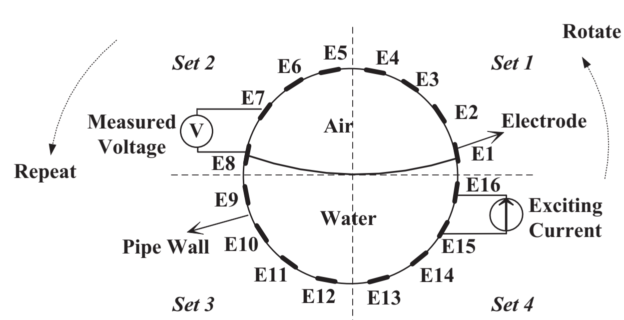

Fig. 1. Operating principle and electrode set configuration of ERT under adjacent strategy.