Entropy feature extraction on flow pattern of gas/liquid two-phase flow based on cross-section measurement

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Abstract. This paper introduces the fundamental of cross-section measurement system based on Electrical Resistance Tomography (ERT). The measured data of four flow regimes of the gas/liquid two-phase flow in horizontal pipe flow are obtained by an ERT system. For the measured data, five entropies are extracted to analyze the experimental data according to the different flow regimes, and the analysis method is examined and compared in three different perspectives. The results indicate that three different perspectives of entropy-based feature extraction are sensitive to the flow pattern transition in gas/liquid two-phase flow. By analyzing the results of three different perspectives with the changes of gas/liquid two-phase flow parameters, the dynamic structures of gas/liquid two-phase flow is obtained, and they also provide an efficient supplementary to reveal the flow pattern transition mechanism of gas/liquid two-phase flow. Comparison of the three different methods of feature extraction shows that the appropriate entropy should be used for the identification and prediction of flow regimes.

1. INTRODUCTION

The gas/liquid two-phase flow is very typical in nature and industrial applications, and the accurate measurement of its parameters is always an urgent issue that needs to be solved in engineering and science (Baker, O., 1954; Dong, F. et al., 2003). Research on two-phase flows is of great importance to scientific development, national economy and human living. The measurement of two phase flows presents a great challenge and fascination to researchers due to its inherit complexity and nonlinearity. Flow regime, a most characteristic spatial distributional parameter of the two phase mixture flows in pipes, impacts flow characteristic and the performance of heat and mass transfer. Moreover, it has a great influence on the accuracy when measuring other two-phase flow parameters. Therefore, the feature extraction and analysis, the identification and prediction of flow regimes are important.

Horizontal pipe flow is an important flow in the two-phase flows. The cross-sectional measurement based on Electrical Resistance Tomography (ERT) is a kind of process tomography that can be widely used in the measurement of multi-phase flow parameters (Fabre, J. et al., 1992; Dong, F. et al., 2005). The cross-sectional measurement system has a great potential in process applications. As a kind of Process Tomography (PT), this technique extracts spatial and temporal information of process parameters by using multiple sensors mounted around the region of interest. The characteristics of cross-sectional measurement are non-intrusive, non-radioactive, visible and etc (Dong, F. et al., 2006).
There are many methods to process the experimental data for feature extraction, such as the power spectral density functions (PSDF), signal to noise ratio (SNR), autocorrelation functions (ACF), probability density functions (PDF), fractal and chaos time series analysis, entropy time series analysis and etc. Entropy is a common concept in many fields, mainly in signal processing. In information theory, entropy is used to measure the concept of information laws. Classical entropy-based criteria matches these conditions and describes information-related properties for an accurate representation of a given signal. So the entropy is adopted to signal analysis and feature extraction for cross-sectional measured resistance information of the gas/liquid two-phase flow in this paper. Five main entropies are adopted to analyze the experimental data which is acquired by a cross-sectional measurement system in different flow regimes, and the five methods are compared in three different perspectives.

In spite of the technological development and efforts in the literatures for feature extraction of the gas/liquid two-phase flow, providing a more reliable and accurate feature is still considered a challenge. In this paper, the general information of cross-sectional measurement based on an ERT system and the notion of entropy is introduced, the five entropies and their definitions of the method are presented. The method of five entropy features analysis and extraction from the three different perspectives which cover the characteristic of cross-section measurement is given, and the three different perspectives are also analyzed. The three different perspectives of entropies feature extraction are sensitive to the flow pattern transition in gas/liquid two-phase flow, they can fully reflect the dynamics structure of gas/liquid two-phase flow and reveal the flow pattern transition mechanism of gas/liquid two-phase flow. Three different methods of feature extraction are compared to show that the appropriate entropy should be used.

2. CROSS-SECTIONAL MEASUREMENT BASED ON ERT AND ENTROPY

2.1 Cross-Sectional Measurement Based on ERT

The cross-sectional measurement system based on ERT, which is developed from the principle that the conductivity of different medium varies, is one of the process tomography techniques. By using the cross-sectional measuring technique, the medium distribution of measured field can be identified if the conductivity distribution of sensing field is obtained.

Sensitive electrode array using embedded structure is composed of 16 rectangular electrodes which are made from titanium alloy and evenly mounted in the pipe wall. The drift $\delta$ of measuring voltage in the cross-sectional measurement system is less than 1%, it meets the requirements of the qualitative and quantitative analysis. The drift $\delta$ is defined as the root-mean-square error of the 208 measurement voltage between the N-th cross-section and M-th cross-section (Dong F. et al., 2005).

$$\delta = \sqrt{\frac{1}{208} \sum_{i=1}^{208} (V_{Ni} - V_{Mi})^2} \times 100\%$$  \hspace{1cm} (1)
Fig. 2 Exciting and measurement strategy

Normally, the operating principle of the cross-sectional measurement system based on ERT is current-excitation and voltage-measurement, as shown in Fig. 2. The exciting current is applied into the measured section through a pair of electrodes and establishes the sensing field. The sensing field varies with the conductivity distribution and results in the change of the distribution of electric potential, and correspondingly the change of boundary voltage of sensing field. Therefore, the measured voltage contains the information of the conductivity of sensing field, and the internal flow status can be obtained from further information processing.

The 16-electrode sensors were adopted in the cross-sectional measurement system, shown as in Fig. 3.
Fig.2. The adjacent strategy was used in this research. According to the operating procedure of this strategy, gathering data of one frame needs 16 excitations and 13 voltage data acquire under each excitation. The data of one frame which is also known as one section will form a 16×13 array, so 208 measured voltages from 16 excitations for one frame of cross-sectional measurement are measured. When the pipe is full of water, the 208 collected voltage data are in the trend of 16 U-shape. The trends of one section data in four kinds of flow regimes are shown as Fig.3.

2.2 Concept of Entropy and Five Entropies from Information Viewpoint

In thermodynamics (a branch of physics), entropy is a measure of the unavailability of a system’s energy to do work (Coifman, R.R. et al., 1992; John A., 2003). It is a measure of the randomness of molecules in a system and is central to the second law of thermodynamics and the fundamental thermodynamic relation, which deals with physical processes and whether they occur spontaneously. Spontaneous changes, occur with an increase in entropy in isolated systems, tend to smooth out differences in temperature, pressure, density, and chemical potential that may exist in a system, so entropy is thus a measure of how far this smoothing-out process has progressed and it is one of the factors that determines the free energy of the system. In terms of statistical mechanics, the entropy describes the number of the possible microscopic configurations of the system and is a quantitative measure of disorder in a system. The statistical definition of entropy is a more fundamental definition, from which all other definitions and all properties of entropy follow. The term "entropy" is generally interpreted in three distinct, but semi-related, ways, i.e. from macroscopic viewpoint (classical thermodynamics), a microscopic viewpoint (statistical thermodynamics), and an information viewpoint (information theory).

In the wavelet packet framework, compression and de-noising ideas are identical to those developed in the wavelet framework. The only new feature is a more complete analysis that provides increased flexibility. A single decomposition using wavelet packets generates a large number of bases. The following five entropies are the different entropy criteria in the wavelet packet framework. Many others are available and can be easily integrated. On the concept of entropy from the information viewpoint (information theory), there are many definitions of the method and the selection must be based on their applied occasions. Most of them use the five main entropies: the (nonnormalized) Shannon entropy, the concentration in norm entropy, the "log energy" entropy, the threshold entropy and the "SURE" entropy. In the following expressions, $s$ is the signal and $(s_i)$, the coefficients of $s$ in an orthonormal basis. The entropy $E$ must be an additive cost function such that $E(0) = 0$ and $E(s) = \sum E(s_i)$.

(1) The (nonnormalized) Shannon entropy

\[
E(s) = \sum s_i^2 \log(s_i^2)
\]

(2) The "log energy" entropy with the convention

\[
\log(0) = 0 : E(s_i) = \log(s_i^2) \quad (4)
\]
\[ E_2(s) = \sum_i \log(s_i^2) \]  

(5)

(3) The threshold entropy
\[ E_3(s) = 1 \] if \( |s_i| > p \) and 0 elsewhere so \( E_3(s) = \# \{ i \text{ such that } |s_i| > p \} \) is the number of time instants when the signal is greater than a threshold \( p \).

(4) The "SURE" entropy
\[ E_4(s) = n - \# \{ i \text{ such that } |s_i| \leq p \} + \sum_i \min(s_i^2, p^2) \]  

(6)

(5) The concentration in norm entropy
\[ E_5(s_i) = |s_i|^p \]  

(7)

So
\[ E_5(s) = \sum_i |s_i|^p = \| s \|^p \]  

(8)

3. ENTROPY-BASED FEATURE EXTRACTION

According to the operating procedure of the cross-sectional measurement system, gathering data of one frame needs 16 excitations with 13 voltage data measured under each excitation. The 208 measured voltages in one frame of measured cross-section can be formed. The multi-section measurement data is formed by continual measurement.

For a cross-section of data, a variety of data-processing methods can be adopted. The first method is the entropies feature extraction based on the 208 measurement data from one cross-section. The second method is the entropies feature extraction based on different direction excitation electrodes, i.e. the feature is extracted from the 13 data under each pair of excitation to form 16 sets of data. The third method is the entropies feature extraction based on measurement electrodes. The 13 data which is acquired by each pair of measurement electrode is analyzed and processed to form 16 sets of data in a cross-section.

In the following sections, fivve entropies are extracted from 60 sequential frames’ data with three data-processing methods respectively in four flow regimes of the gas/liquid two-phase flow in horizontal pipe flow.

3.1 Entropies Feature Extraction Based on Section

In this perspective, the 208 data in each section is analyzed with the results shown in Fig.4. The x-coordinate denotes the sequential sections and y-coordinate denotes the values of entropy feature analysis in the subgraph. The analyzed results are also formed according to the four flow regimes of the gas/liquid two-phase flow in horizontal pipe flow.

When the pipe full of water, the Shannon entropy, the SURE entropy as well as the NORM entropy have the good characteristic, but the Log entropy and the Threshold entropy are easily influenced by disturbance.

In Bubbly flow, the Log entropy, the SURE entropy and the NORM entropy well manifest the bubble characteristic. The Shannon entropy has also manifested the bubble characteristic, but is inferior to the former three entropies. The Threshold entropy does not obviously manifest the bubble characteristic in bubbly flow, so that the threshold value must be selected carefully.

All the five entropies manifest slug flow in the characteristic. And the performances of Log entropy,
the Threshold entropy, the SURE entropy and the NORM entropy are more obvious, and manifest the appearance of bubble in the wave crest and the trough blends.

In plug flow, the Log entropy, the Threshold entropy, the SURE entropy, and the NORM entropy perform better than others, and may also manifest the wave ridge and the trough blends.

In this kind of data processing of the characteristic analysis and extraction method, the Log entropy, the SURE entropy and the NORM entropy have better performance, and well manifest the flow quality. Through proper selection of threshold value, the Threshold entropy can be used in characteristic analysis and the extraction of the flow under particular conditions. The results indicate the Log entropy may be more suitable for the identification of the four flow regimes of the gas/liquid two-phase flow in horizontal pipe flow.

![Entropy feature analysis based on 208 data measured in one section](image)

**Fig.4** Entropy feature analysis based on 208 data measured in one section

### 3.2 Entropies Feature Extraction Based on Different Direction Exciting Electrodes

In this perspective, the 13 data measured by each excitation is analyzed, the 16 analyzed results are formed in each section and the analyzed results of the 60 sequential sections are presented. The results are shown in Fig.5, Fig.6, Fig.7, Fig.8 and Fig.9. The coordinate definition of the figures refers to the nomenclature part. The x-coordinate denotes 16 excitations, y-coordinate denotes the sequential sections and z-coordinate denotes the values of entropy feature analysis in the sub graph. According to the four flow regimes of the gas/liquid two-phase flow in horizontal pipe flow and five entropies, the analyzed results are presented in 3 dimensional (3D) coordinates, and the cross-section space better reflects the characteristics of the flow.
Fig. 5  Shannon Entropy feature based on the 13 measurement data by Each Excitation in each section: (a) Pipe full of water, (b) Bubbly flow, (c) Slug flow, (d) Plug flow.

Fig. 6  Log Entropy feature based on the 13 measurement data by Each Excitation in each section: (a) Pipe full of water, (b) Bubbly flow, (c) Slug flow, (d) Plug flow.

Fig. 7  Threshold Entropy feature based on the 13 measurement data by Each Excitation in each section: (a) Pipe full of water, (b) Bubbly flow, (c) Slug flow, (d) Plug flow.

Fig. 8  SURE Entropy feature based on the 13 measurement data by Each Excitation in each section: (a) Pipe full of water, (b) Bubbly flow, (c) Slug flow, (d) Plug flow.
Fig. 9 Norm Entropy feature based on the 13 measurement data by Each Excitation in each section:
(a) Pipe full of water, (b) Bubbly flow, (c) Slug flow, (d) Plug flow.

Regarding the pipe full of water, it is similar with the above conclusion that the Shannon entropy, the SURE entropy and the NORM entropy have better performance, but the Log entropy and the Threshold entropy is easy affected by disturbance. For the bubbly flow, the five entropies well manifest the bubble characteristic. The Log entropy effectively manifests the characteristics of the flow of bubble in the process and the cross-sectional space. The threshold value of Threshold entropy must be selected suitably. The five entropies manifest the characteristic of slug flow and plug flow. In slug flow, the performance of the Log entropy, the Threshold entropy is more obvious over others, and better manifest the appearance of bubble in the wave crest and the trough blends. On the other hand, data processing of the Log entropy and the Threshold entropy is smooth, while the others are incisive.

In this kind of data processing of the characteristic analysis and extraction method, the Log entropy is considered better, and can well and smoothly manifest the flow characteristic and quality in process and the cross-sectional space of the flow.

3.3 Entropies Feature Extraction Based on Measurement Electrodes

In the perspective, the 13 data measured by each pair of the measurement electrodes is analyzed, the 16 sets of analyzed results of data measured by 16 pairs of the measurement electrodes are achieved in each section and the analyzed results of the 60 sequential sections are also presented. The results are shown in Fig.10, Fig.11, Fig.12, Fig.13 and Fig.14. The coordinate definition of the figures also refers to the nomenclature part. The x-coordinate denotes 16 excitations, y-coordinate denotes the sequential sections and z-coordinate denotes the values of entropy feature analysis in the subgraph. Corresponding to the four flow regimes of the gas/liquid two-phase flow in horizontal pipe flow and five entropies, the analyzed results and comparison groups are presented in 3D coordinates.

When the pipe is full of water and in bubbly flow, it is similar with the above analysis. For the slug flow and plug flow, the five entropies also well manifest the characteristic of the flow. This method is more capable of distinguishing slug and plug flow, but the characteristics of plug in flow are not obvious enough.

Fig. 10 Shannon Entropy feature based on the 13 data measured by each of the measurement electrodes in each section: (a) Pipe full of water, (b) Bubbly flow, (c) Slug flow, (d) Plug flow.
4. CONCLUSIONS
This paper introduces the fundamental of the cross-sectional measurement based on a ERT system. The measured data of four flow regimes of the gas/liquid two-phase flow in horizontal pipe flow were obtained. For the measured data, five entropies are extracted to analyze the experimental data in...
different flow regimes, and the analysis method is introduced in three different perspectives. From the different method of feature extraction, comparison groups are formed and they show that the appropriate entropy should be used for the identification and prediction of flow regimes. In the first method, the Log entropy, the SURE entropy and the NORM entropy have better performance in representing flow characteristic, and well manifest the flow quality. The results indicate the Log entropy is more suitable for the identification of the four flow regimes of the gas/liquid two-phase flow in horizontal pipe flow. In the second method, the Log entropy is also considered better and smoothly manifest the flow characteristic in the process and cross-sectional space of the flow. In the third method, it is not obvious between each method and all the five entropies well manifest the flow characteristic.

The results indicate that the three different perspectives of entropy feature extraction are sensitive to the flow pattern transition in gas/liquid two-phase flow. By analyzing the rules of three different perspectives with the changes of gas/liquid two-phase flow parameters, the dynamic structures of gas/liquid two-phase flow can be obtained, and an efficient supplementary to reveal the flow pattern transition mechanism of gas/liquid two-phase flow can also be provided. From three different perspectives of feature extraction, comparison groups are formed and they show that the appropriate entropy should be used for the identification and prediction of flow regimes.

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NOMENCLATURE

\[ \delta \] The drift of measuring voltage

\[ s \] The signal

\[ (s_j)_i \] The coefficients of signal \( s \) in an orthonormal basis

\[ E \] Entropy value

\[ \sum \] Summation symbol

\[ N \] the number of the cross-section

\[ M \] the number of the cross-section

\[ i \] \( i \)-th coordinates

\[ j \] \( j \)-th coordinates

Coordinates definition:
2D Coordinates The example is shown in Fig. A (a). The x-coordinate denote the sequential cross-section number and y-coordinate denote the values.
3D Coordinates

The example is shown in Fig. A (b). The x-coordinate denote the electrode number which can be exciting electrodes or measuring electrodes, y-coordinate denote the sequential cross-section number and z-coordinate denote the values.

![Graph of 3D Coordinates](image)

Fig.A. The example of coordinates definition

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