

Identification of vertical upward oil-gas-water three-phase flow pattern based on nonlinear analysis method

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Abstract: In order to study oil-gas-water three-phase flow characteristics in oil well, the vertical upward three-phase flow experiment at low velocity was carried out in a large diameter (125 mm ID) flow loop using the combination instrument of vertical multi-electrode array (VMEA) conductance sensor and mini-conductance probe array, and the conductance fluctuating signals of five three-phase flow patterns with water as the continuous liquid were acquired. The nonlinear dynamical characteristics of the five flow patterns were represented by nonlinear analysis method, which are chaotic attractor morphological description and complexity measures including Lempel-Ziv complexity and approximate entropy. The study results indicate that chaotic attractor morphological characteristics could identify three-phase flow pattern; the combination of Lempel-Ziv complexity and approximate entropy could serve as the classification criterion of the flow patterns mentioned above. The nonlinear information processing and analysis of time series provides a new approach to studying the dynamical evolution mechanism of the complex multiphase flow.

Keywords: Oil-gas-water three-phase flow, Flow pattern, Nonlinear dynamical characteristics, Complexity measure

1. Introduction

Oil-gas-water three-phase flow is extensively encountered in the process of oil well production and oil-gas transport process. The primary difficulty for the three-phase flow measurement in oil well is how to understand the complex flow characteristics and its influence on the flow measurement response. In addition, it is significant for the calculation of pressure gradient to identify three-phase flow patterns. Generally, the flow pattern has important guiding meaning in some field of the oil well production process, such as the pipeline installation, optimal design of artificial lift production device and downhole flowmeter, well test data interpretation and so on. Since the interaction of oil-gas-water interface is very complex, the categorizing of three-phase flow pattern is yet diversified for the lack of the knowledge on flow characteristics. In the field of oil-gas-water flow mechanism, most of the researchers extended the two-phase models to three-phase flow. They predicted flow pattern, liquid inversion point, pressure drop, phase volume fraction and so on by the proper conditional hypothesis and restraint on three-phase flow characteristics. But the prediction is not completely identical as a result of the disunity of the used rule on flow pattern judgment and transition. As is known, there are strongly nonlinear characteristics in the three-phase flow and the one-dimensional fluctuating signal measured by the sensor contains rich dynamical information about three-phase flow pattern evolving process. As a consequence, the nonlinear analysis method of the observed data is a significant direction

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for the studies of three-phase flow pattern. Recently, some achievements have been obtained in applying the nonlinear information processing technique to reveal the complex three-phase flow characteristics^[1-4]. The methods used to extract the feature from time series fluctuating signals are mainly based on fractal and chaos theory. These methods also provide a new way to the investigation of the complex flow characteristics. Nevertheless, these algorithms are relatively complicated and the calculation of parameters (delay time and embedding dimension) needs a long time and often depends on the selected specific algorithm. Besides, it is necessary to further study on the intrinsic dynamical characteristics of flow pattern by the novel nonlinear time series analysis method.

2. The oil-gas-water three-phase flow experiment in vertical upward flow loop

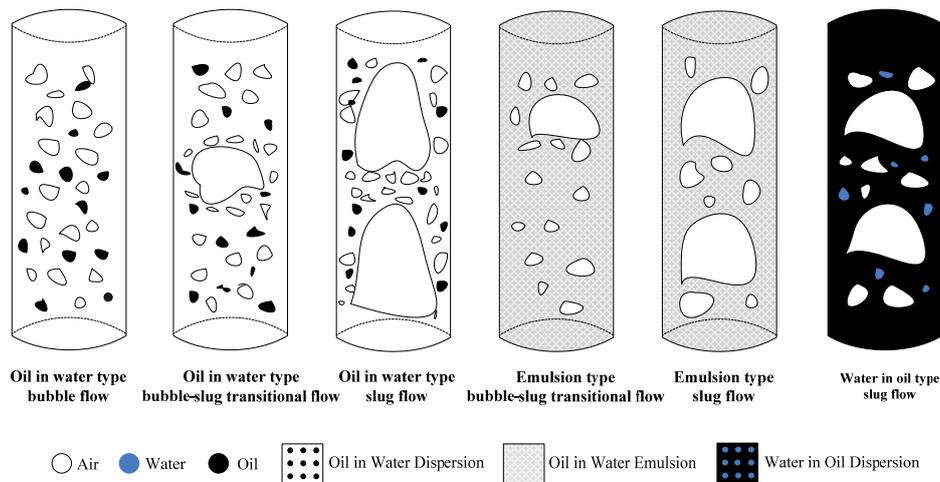


Fig. 1 Schematic diagrams of six oil-gas-water three-phase flow patterns

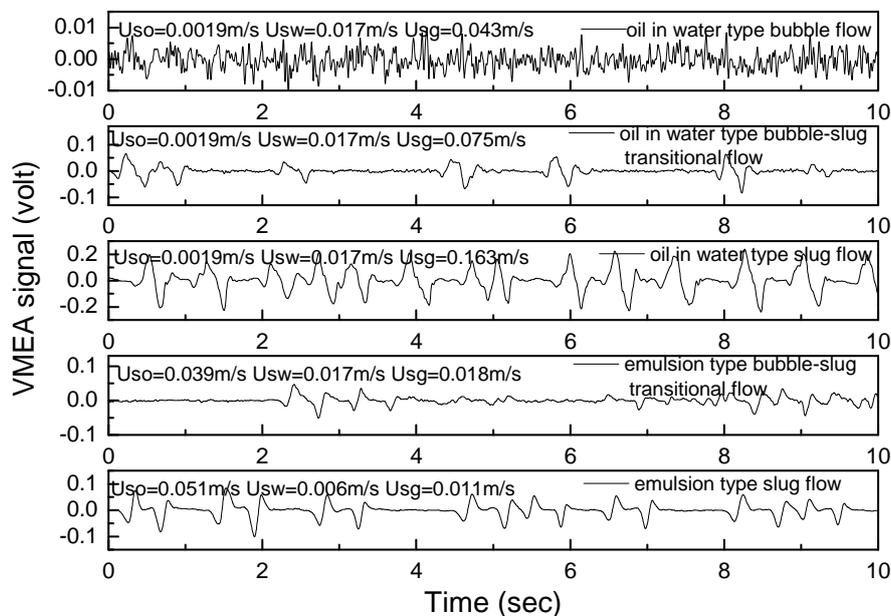


Fig. 2 VMEA sensor signals of the five typical flow patterns

The oil-gas-water three-phase flow experiments in vertical upward pipe with 125 mm ID were carried out in multiphase flow loop facility of Tianjin University. The detail description of the experimental facility refers to the literature [5]. We used mini-conductance probe array to determine oil-water flow patterns. Gas-liquid flow patterns were determined by visual observation. Six oil-gas-water three-phase flow patterns were obtained, which were named as oil in water type bubble flow, oil in water type bubble-slug transitional flow, oil in water type slug flow, emulsion type bubble-slug transitional flow, emulsion type slug flow and water in oil type slug flow, as shown in figure 1. The VMEA fluctuating signals of the first five flow patterns with water as the continuous liquid were acquired, as shown in figure 2, where U_{so} , U_{sw} , U_{sg} denotes the superficial velocity of oil, water and gas respectively.

3. Attractor morphological description of oil-gas-water flow pattern

Annunziato and Abarbanel^[6] introduced the attractor morphological description method. For the time series of acquired conductance fluctuating signal $\{x(it), i=1, 2, \dots, N\}$ (t is the sampling interval, N is the sample size), by selecting delay time τ and embedding dimension m , the vector point in phase space can be represented as follows

$$\mathbf{X}(k) = [x_1(k), x_2(k), \dots, x_m(k)] = [x(kt), x(kt + \tau), \dots, x(kt + (m-1)\tau)] \quad (1)$$

where $k=1, 2, \dots, M$, $M = N - (m-1) * \tau / t$ denotes the total of vector points.

In order to quantitatively describe the attractor shape, the definition of distance is introduced. The two-dimensional distance from each point on attractor showed in equation (1) to each reference section ($\{1, -1\}$; $\{1, 1\}$; the original point) can be defined as

$$d_1(k) = \frac{1}{\sqrt{2}} [x_1(k) - x_2(k)] \quad (2)$$

$$d_2(k) = \frac{1}{\sqrt{2}} [x_1(k) + x_2(k)] \quad (3)$$

$$d_{2o}(k) = \sqrt{x_1(k)^2 + x_2(k)^2} \quad (4)$$

Based on the distance above, attractor shape descriptors for different τ are defined, namely the single moment with respect to the different reference sections

$$M_{p,q}(\tau) = \frac{\sum_{k=1}^M d_p(k)^q}{M} \quad (5)$$

where $p \in \{1, 2, 2O\}$ denote distance class, the natural number q refer as the moment order.

The curve $M_{p,q}(\tau) \sim \tau$ increases (or decreases) to a maximum (or minimum) after certain time delaying, then the corresponding delay time is defined as the transition lag τ_f . The part before τ_f is called the first zone which represents the unfolding process of attractor from the compressed state to topology structure at suitable delay time. So the approximate slope of the zone can serve as attractor morphological characteristics denoted as $SM_{p,q}$.

Through the statistics of ten attractor morphological characteristics for all conductance fluctuating signals of five flow patterns, 3-order attractor characteristics $SM_{1,3}$ and $SM_{2,3}$ which more effectively recognize the flow patterns are chose to constitute a plane to classify the five flow patterns, as is shown in figure 3. It can be concluded that the combination of the two

characteristics could better classify the four flow patterns, such as oil in water type bubble flow, oil in water type bubble-slug transitional flow, oil in water type slug flow and emulsion type slug flow. Three dashed lines in the figure are used as the criteria of flow patterns classification and they are $SM_{1,3} = 0$, $SM_{2,3} = 10$ and $SM_{2,3} = -5$ respectively. Therefore, the region $SM_{1,3} \geq 0, SM_{2,3} \leq 10$ denotes oil in water type bubble flow, $SM_{1,3} < 0, SM_{2,3} > 10$ denotes oil in water type bubble-slug transitional flow, $SM_{1,3} < 0, -5 < SM_{2,3} < 10$ denotes oil in water type slug flow and $SM_{1,3} < 0, SM_{2,3} \leq -5$ denotes emulsion type slug flow.

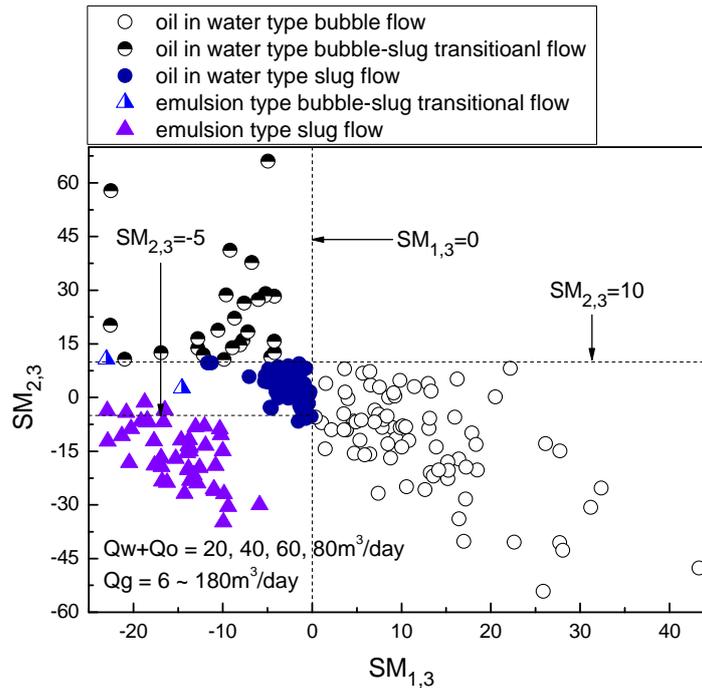


Fig. 3 Flow patterns distribution on the $SM_{1,3} \sim SM_{2,3}$ plane.

4 The complexity measure analysis

4.1 Lempel-Ziv complexity^[7]

For a finite or infinite symbolic sequence, its complexity is $c(n)$. A given string $S = s_1 s_2 \cdots s_r$ connects with Q which is one or a string of characters to form SQ . Let $SQ\pi$ denotes the string which is composed of S , Q and π which means that the last digit has to be deleted. Then we check whether Q is contained in the vocabulary of $SQ\pi$. If yes, we add the last digit to $SQ\pi$ and call the operation “to copy”. If not, we call it “to insert” and denote with “•” to separate the former from the post part. Then, we consider all the characters before the “•” as S and repeat the steps above. $c(n)$ is the total number of “•”. The relative complexity is defined as follows.

$$C(n) = \frac{c(n)}{n / \log_2 n} \quad (6)$$

It is necessary to preprocess the non-symbolic time series $\{x(it), i=1, 2, \dots, N\}$ by coarse graining to transform to the symbolic sequence. We adopt four-symbol coarse graining to reconstruct the time series in the paper.

4.2 Approximate entropy

The approximate entropy ^[8] for the time series of N points $\{x(it), i = 1, 2, \dots, N\}$ can be calculated through the following steps.

(1) The time series forms the m -dimensional template vector $\mathbf{X}_m(j)$ by ordinal

$$\mathbf{X}_m(j) = [x(jt), x((j+1)t), \dots, x((j+m-1)t)], \quad j = 1 \sim N - m + 1 \quad (7)$$

(2) Calculate the distance between the vector $\mathbf{X}_m(j)$ and the other vector $\mathbf{X}_m(j')$ for each j .

$$d[\mathbf{X}_m(j), \mathbf{X}_m(j')] = \max\{|x((j+l)t) - x((j'+l)t)| : l = 0 \sim m-1\} \quad (8)$$

(3) Given a tolerance for accepting matches r , do the statistics of $C_j^m(r)$ for each j .

$$C_j^m(r) = \{\text{number of } j' \text{ such that } d[\mathbf{X}_m(j), \mathbf{X}_m(j')] < r\} / (N - m + 1) \quad (9)$$

(4) Compute $\Phi^m(r)$, the average of the natural logarithms of the functions $C_j^m(r)$

$$\Phi^m(r) = \frac{1}{N - m + 1} \sum_{j=1}^{N-m+1} \ln C_j^m(r) \quad (10)$$

(5) Let the length of sequences to be compared is $m + 1$ and repeat (1) ~ (4) to obtain $\Phi^{m+1}(r)$.

(6) Finally, the approximate entropy is defined as

$$\text{ApEn}(m, r) = \Phi^m(r) - \Phi^{m+1}(r) \quad (11)$$

4.3 result and discussions

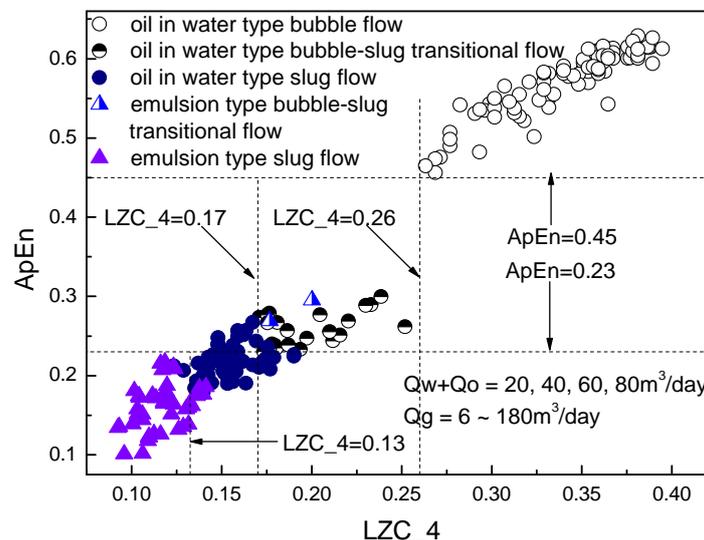


Fig. 4 Flow patterns distribution on the LZC_4-ApEn plane.

Figure 4 shows the distribution of flow patterns on the plane constituted by the two complexity measures, where LZC_4 is the Lempel-Ziv complexity measure by 4 symbols mean value coarse graining, ApEn denotes approximate entropy, the tolerance r is set 0.15 times the standard deviation of the original time series, the length of consequence to be compared (m) is 2 and the length of time series (N) is 4000. The combination criterion is able to classify four flow patterns.

The five boundaries in figure 4 are respectively: $ApEn = 0.23$, $ApEn = 0.45$, $LZC_4 = 0.13$, $LZC_4 = 0.17$, $LZC_4 = 0.26$. The dynamical complexity of oil in water type bubble flow is maximal and it mainly lies in $ApEn \geq 0.45, LZC_4 \geq 0.26$. The complexity of others is relatively small. The main region of bubble-slug flow is $0.23 < ApEn < 0.45, 0.17 < LZC_4 < 0.26$, oil in water type slug flow is $0.13 \leq LZC_4 \leq 0.17$ and emulsion type slug flow is $LZC_4 < 0.13$.

5. Conclusions

The one-dimensional fluctuating signals acquired by VMEA sensor could reflect the nonlinear dynamical characteristics of three-phase flow patterns. The combination of two attractor morphological characteristics could effectively classify four flow patterns. Lempel-Ziv complexity and ApEn of the fluctuating signal reveal that the dynamical characteristics of bubble flow is the most complex, and the next is that of the transitional flow and that of slug flow is the simplest. By comparison of complexity measure of oil in water type slug flow, the dynamical characteristics of emulsion type slug flow is simpler. The combined method of the two complexity measures makes the four flow patterns classified linearly to some extent.

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