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A scaling exponent for indicating the non-homogenous distribution of oil droplet in vertical oil–water two-phase flows

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HIGHLIGHTS

- We measure the flow structure of vertical upward oil–water two-phase flow with low velocity.
- We provide a novel multi-scale morphological analysis approach based on first-order difference scatter plot.
- The extracted scaling exponents can effectively characterize the non-homogeneous distribution of oil droplets in dispersion phase.
- The approach can roundly describe the coalescence and breakup process of dispersed droplets in oil–water two-phase flow

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ABSTRACT

The multi-scale analysis is one of the most effective tools in detecting nonlinear system. In this study, we provide a novel multi-scale morphological analysis aiming at nonlinear time series. We firstly investigate typical chaotic and fractal systems by extracting a scaling exponent from the multi-scale second-order moment in the first-order difference scatter plot, it is proved that the proposed method has a good anti-noise and signal resolution ability. In this regard, we apply it to analyze the conductance sensor signals measured from vertical oil slug flow, oil dispersed flow and very fine oil dispersed flow. We find that the invariant of scaling exponent is sensitive to the change of oil droplet size, and the trend of scaling exponent with flow conditions is helpful to understand the process of coalescence and breakup of the dispersed droplets. The research results show that the multi-scale nonlinear analysis is a useful diagnostic tool for indicating the non-homogenous distribution of the dispersed droplets in oil–water two-phase flows.

1. Introduction

Oil–water two-phase flow widely exists in the industrial process of oil production and transportation. In particular, for oil–water two-phase flow with low velocity in the oil well, the dispersed phase presents a highly non-homogenous distribution due to complex flow mechanism. In this regard, understanding the dynamical mechanism of flow pattern transition is of great importance to flow measurement in production among oil wells.

In early studies of oil–water two-phase flow in small diameter pipe, Govier et al. (1961) experimentally explored the oil–water two-phase flow and proposed four flow patterns, namely, drops of oil in water, slugs of oil in water, froth and drops of water in oil. Liu et al. (2005) applied laser-induced fluorescence (LIF) technique to investigate the phase inversion phenomenon. Jana et al. (2006, 2007) utilized conductivity probes to detect the flow structures and defined four kinds of flow patterns based on the results of probability density function and wavelet analysis. Lin and Tavlarides (2009) investigated the oil–water two-phase flow in stainless steel pipes under high temperature and pressure flow conditions, and found that the mixture velocity, pipe length, and pressure had significant impacts on flow patterns. Recently, Du et al. (2012) conducted flow loop test in a 20 mm ID pipe using conductivity method, in particular, they proposed the flow pattern transition boundaries in terms of water holdup.

Regarding the studies of oil–water two-phase flow in large diameter pipe, Flores et al. (1999) analyzed the characteristics of vertical upward oil–water two-phase flow in a 50 mm ID pipe and defined six flow patterns, i.e., dispersion oil-in-water flow, very fine dispersion oil-in-water flow, oil-in-water churn flow, water-in-oil churn flow, dispersion water-in-oil flow and very fine dispersion water-in-oil flow. Meanwhile, they proposed a physical model on flow pattern transition. Zhao et al. (2006) experimentally studied the local flow characteristics of vertical upward

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oil–water dispersed flow in a 40 mm ID pipe using dual conductivity probes. Hu and Angeli (2006) investigated the phase inversion and its associated phenomena in co-current upward and downward oil–water two-phase flow in a 38 mm ID vertical pipe. They found that phase inversion phenomenon did not happen simultaneously at all locations in the pipe cross-section by monitoring phase continuity at the pipe center and the wall. Xu et al. (2010) claimed that the frictional pressure gradient reached a lower value at the phase inversion point, and the phase inversion points were always close to an input oil fraction of 0.8 for upward flow and of 0.75 for downward flow.

In addition to the experimental studies, some researchers focused on the theoretical model of flow pattern transition. Brauner (2001) proposed a model for predicting the transition of dispersed flow patterns in liquid–liquid systems. Brauner and Ullmann (2002) combined the criterion of minimum free energy of the system with a model for droplet size in dense dispersions to predict the critical conditions for phase inversion phenomenon. Jin et al. (2003a) presented the boundaries of flow patterns in vertical upward oil–water two-phase flow by using the kinematic wave theory.

The widespread occurrence of oil–water two-phase flow in vertical pipes has prompted extensive research in this area. However, there is still a lack of adequate means to signify the non-homogenous distribution of dispersed droplets. Our ultimate goal in this work is to investigate the non-homogenous distribution of the dispersed droplets in vertical oil–water two-phase flow pipe. It is generally known that the fluctuating signals from two-phase flow contain abundant information of flow structure with temporal and spatial variations. Applying nonlinear time series analysis by extracting characteristic invariants like fractal dimension, chaotic dimension and Kolmogorov entropy is helpful to understand the dynamical evolution of two-phase flow (Oddie, 1991; Jin et al., 2003b; Zong and Jin, 2008; Zong et al., 2010; Zhu et al., 2011). In particular, nonlinear time series analysis based on difference sequence has been widely used in analyzing various physiological signals (Cohen et al., 1996; Maurer et al., 1997; Jeong et al., 2002a; Jeong et al., 2002b; Thuraisingham, 2009; Huo et al., 2012, Huo et al., 2013). Inspired by these methods, in this work, we provide a novel multi-scale analysis approach based on first-order difference scatter plot, in which we adopt the chaotic attractor morphological analysis method (Annunziato and Abarbanel, 1999; Llauro′ and Llop, 2006; Wang et al., 2010). We perform an experimental flow loop test in vertical upward oil–water two-phase flow pipe, then measure the conductance sensor fluctuating signals and calculate its second-order moment in the first-order difference scatter plot. The results presented here show that the scaling exponent extracted from conductance signals can effectively indicate the non-homogenous distribution of dispersed oil droplets and reveal their coalescence and breakup process with the change of flow conditions.

2. Multi-scale morphological analysis based on first-order difference scatter plot

2.1. First-order difference scatter plot

For constructing the multi-scale first-order difference scatter plot, we firstly obtain coarse-grained time series from the original one, and then calculate the difference sequence at each scale to acquire the first-order difference scatter plot. The algorithm is given as follows:

For a one-dimension time series $\{u(i) : i = 1, 2, ..., n\}$, the coarse-grained time series $\{y_j^s\}$ are expressed as:

$$y_j^s = \frac{1}{s} \sum_{i=(j-1)s+1}^{js} u(i), \quad 1 \le j \le n/s \tag{1}$$

where s represents the scale factor.

Then calculate the first-order difference sequence at each scale:

$$d_k^s = y_{j+1}^s - y_j^s, \quad (1 \le k \le j-1 < n/s - 1) \tag{2}$$

Thus, we can plot the scatter points after first-return of difference sequence d_k in the two-dimensional plane, i.e., (d_k, d_{k+1}).

2.2. Attractor moment

For arbitrary N-dimensional phase space, N orthogonal N-1-dimensional reference sections are constructed as N-orthogonal reference system and that is the basis for the calculation of chaotic attractor morphological characteristics (Annunziato and Abarbanel, 1999; Llauro′ and Llop, 2006; Xiao and Jin, 2007).

In the two-dimensional plane we constructed, two orthogonal unit vectors through the original point firstly are expressed as

$$\begin{aligned} \alpha_1 &= (a_{11}, a_{12})^T, \\ \alpha_2 &= (a_{21}, a_{22})^T, \end{aligned} \tag{3}$$

Then taking $\alpha_i, (i = 1, 2)$ as normal vectors to determine the two orthogonal reference lines through the original point:

$$\begin{aligned} a_{11}x_1 + a_{12}x_2 = 0 \\ a_{21}x_1 + a_{22}x_2 = 0 \end{aligned} \tag{4}$$

In order to quantitatively describe the morphological characteristics of the first-order difference scatter plot, it is necessary to introduce the definition of distance, the distance from each point to each reference line in the scatter plot can be given as

$$\begin{aligned} T_i(k) &= \langle \alpha_i, X(k) \rangle \\ &= a_{i1}x_1(k) + a_{i2}x_2(k), \end{aligned} \tag{5}$$

where $X = (x_1, x_2)^T$ is the coordinate of scatter point and k=1,2…M, M is the total number of scatter points after processed. On the basis of the distance given above, for different time scales, we define morphological parameter in the plot, i.e. attractor moment. The attractor moment of single distance can be expressed as

$$M_{i,j}(s) = \frac{\sum_{k=1}^{M} T_i(k)^j}{M} \tag{6}$$

where $M_{i,j}(s)$ represents the j-order moment of the scatter points to the i-reference line. The even order attractor moment indicates the dispersed degree of the scatter points to the investigated reference line, while the odd order attractor moment indicates the symmetry of scatter points to the investigated reference line.

The optimal reference line in two-dimensional space should satisfy that its corresponding attractor moment $M_{i,j}(s)$ attains max when j is an even number in Eq. (6). Thus we can calculate the first optimal reference line and the second reference line is orthogonal with the first one.

In order to confirm the optimal reference line that is appropriate with our research objects, Xiao et al. (2007) investigated eighty different flow conditions of gas–water two-phase flow and obtained the optimal range of the reference lines parameters, they found the bisectors of first-third quadrant and second-fourth quadrant are within this optimal range and could be the two general reference lines in the two-dimensional space which will be more comparable.