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Variability analysis of droplet distribution of oil-in-water emulsions with a multi-scale first-order difference conductance series

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HIGHLIGHTS

- We propose a novel morphological analysis based on multi-scale first-order difference scatter plot.
- We investigate flow structures of oil-in-water emulsions with low velocity and high water-cut.
- We extract a sensitive index which can effectively characterize variability in oil droplet distribution.
- We compare our proposed morphological analysis with experimental results and previous methods.

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ABSTRACT

In attempt to depict the variability of oil droplet distribution in oil-in-water emulsions, we propose an algorithm of "area discrepancy" from multi-scale first-order difference scatter plot. With the intention to assess the applicability of this algorithm, we investigate typical nonlinear systems by extracting an "inhomogeneous distribution index" (IH^s), and conclude that IH^s can satisfactorily discriminate the differences in signals as well as presents a superior anti-noise ability. In this regard, we conduct an experiment of vertical upward oil-in-water emulsions in a 20 mm inner diameter (ID) testing pipe and collect fluctuating signals of a high resolution arc type conductivity probe (ATCP), through which the effects of flow parameters on IH^s in oil-in-water emulsions are elucidated from the perspective of statistical analysis. The results indicate that the variation in IH^s with changing mixture velocity and water-cut is beneficial for understanding dynamic evolution of oil droplets in oil-in-water emulsions.

1. Introduction

Oil-in-water emulsions are frequently encountered in oilfield exploitation and industrial production. The formation of oil-in-water emulsions can be realized by injecting surfactant into oil–water mixtures. In comparison with oil–water flows, the addition of surfactant will significantly decrease interface tension between oil and water phase, which leads to the result that oil droplets exist in surfactant aqueous solution with the size of micrometer magnitude. Besides, due to the severe slippage effect, oil droplets generally present complex and inhomogeneous distribution characteristics. An investigation of oil droplet distribution is of great significance to uncover the transition in flow regime and the optimization in flowmeters.

The measurement of droplet size in emulsions has received intensive attention. With the advantages of high response speed and non-intrusiveness, multiple light scattering has been widely applied for extracting droplet size distribution in

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emulsions [1,2]. Currently, the mainstream multiple light scattering includes diffuse transmission spectroscopy [3,4], diffusing wave spectroscopy [5–7], laser light scattering [8,9] and speckle imaging [10]. Due to the direct contact with emulsions, near infrared [11–14], focused beam reflectance [15–17] and mini-probe technique [18] show obvious superiorities on the measurement of local droplet size. According to the discrepancy in relaxation time to trace particle between oil and water phase, pulsed-field gradient nuclear magnetic resonance (NMR) can be also regarded as an effective method for determining droplet size [19–23]. The observation of micrographs captured by microscope is the most direct way for analyzing droplet size distribution. Through examining the images of dispersed water droplets in horizontal water-in-oil emulsions, Al-Yaari et al. [24] addressed that with the increasing water-cut, the number of water droplets gradually increases while the size of water droplets decreases. On the basis of micrographs of emulsions under different montmorillonite concentrations, it was reported by Ganley et al. [25] that oil droplet size presents a decreasing trend with the increasing montmorillonite concentration. In order to investigate dynamic stability of emulsions, Patil et al. [26] proposed an image processing method for the acquisition of droplet size from micrographs, in terms of which they analyzed the relationship of droplet size and impeller speed. Additionally, literatures suggest that ultrasonic method performs well on studying droplet size distribution in emulsions [27–29].

So far, despite the great progress of experimental measurement on droplet size in oil–water emulsions, investigations concentrating on the underlying dynamic behavior of the variability in droplet size transition are scarce. Recently, difference-series based nonlinear analysis has been a research focus in the field of physiology [30–36]. The combination of multi-scale entropy and difference-series based nonlinear analysis facilitates the understanding of heart rate variation from the view of time scale [37,38], and an index called "multi-scale feedback ratio" is capable of characterizing the discrepancy of heart rate variation between healthy and congestive failure subjects [39]. Moreover, with first-order difference conductance series, attractor morphology analysis presents satisfied capacity for indicating non-uniform distribution of dispersed phase in oil–water/gas–liquid two-phase flow [40,41]. For the sake of detecting the variability of distribution of very fine oil droplets in oil-in-water emulsions, with sampled fluctuating signals from a high resolution arc type conductivity probe (ATCP), we introduce an algorithm of area discrepancy from multi-scale first-order difference scatter plot. An inhomogeneous distribution index (IH^s), which can sensitively indicate oil droplet size distribution in oil-in-water emulsions under different time scales, is extracted from this algorithm. Our present study provides novel insights for the instability of droplet evolution in oil-in-water emulsions.

2. Analysis of multi-scale first-order difference scatter plot

2.1. Area discrepancy from multi-scale first-order difference scatter plot

The algorithm of area discrepancy from multi-scale first-order difference scatter plot can be described as follows: For a primitive time series $\{x(i) : i = 1, 2, 3, \dots, N\}$ (N is the total number of data points) (see Fig. 1(a)), we define a consecutive coarse-grained time series $\{y^s(j) : j = 1, 2, 3, \dots, N/s\}$ as [42]:

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

where s refers to the coarse-grained scale factor. The length of $\{y^s(j)\}$ is equal to the length of primitive time series $\{x(i)\}$ divided by s. The first-order difference series under a constant scale (see Fig. 1(b)) can be expressed as:

$$d_k^s = y_{k+1}^s - y_k^s, \quad 1 \le k \le N/s - 1. \tag{2}$$

We can plot scatter points on a two-dimension plane after first-return of difference sequence $\{d^s(k)\}$, with coordinate labeled as (d_k^s, d_{k+1}^s). For a point on this two-dimension plane with the coordinate (d_k^s, d_{k+1}^s), area sequences of two circles A_k^s, A_{k+1}^s (see Fig. 1(c)) can be calculated with the absolute value of abscissa and ordinate being respective radius:

$$A_k^s = \pi \cdot \left|d_k^s\right|^2, A_{k+1}^s = \pi \cdot \left|d_{k+1}^s\right|^2. \tag{3}$$

Denote area discrepancy sequence between A_k^s and A_{k+1}^s as ΔA_k^s (see Fig. 1(d)):

$$\Delta A_k^s = \left|A_{k+1}^s - A_k^s\right| = \left|\pi \cdot \left|d_{k+1}^s\right|^2 - \pi \cdot \left|d_k^s\right|^2\right|. \tag{4}$$

Designate M as the total number of scatter points after coarse-graining, the inhomogeneous distribution index (IH^s) under scale s can be expressed in Eq. (5). Fig. 2 corresponds to the calculation flowchart for the proposed algorithm of area discrepancy.

$$IH^s = \frac{\sum_{k=1}^{M} \Delta A_k^s}{M}. \tag{5}$$