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Experimental study of interaction between liquid droplets in oil-in-water emulsions using multivariate time series analysis

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HIGHLIGHTS

- We apply a distributed mono-sensor conductance probe array to study flow instability in emulsions.
- We implement an experiment of pipeline flow of emulsions with low velocity and high water-cut.
- We investigate interaction among dispersed oil droplets on different positions at pipe cross section.
- We explore global flow instability in oil-in-water emulsions using multivariate time series analysis.

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ABSTRACT

Oil-in-water emulsions is frequently encountered in the industry of oil exploitation. The complex dynamic behavior of oil droplets brings about a great challenge in understanding its underlying flow regime. In the present study, we attempt to characterize flow instability of oil-in-water emulsions through measuring the information transfer between oil droplets. An experiment of vertical upward oil-in-water emulsions is conducted in a flow loop facility with 20 mm pipe inner diameter (ID), and multivariate time series are acquired by sampling the signals of a distributed sixteen-channel conductance mono-sensor probe array. The collected multivariate time series are firstly processed with an algorithm designated as transfer entropy (TE), through which the interaction between oil droplets at pipe cross section are investigated. Moreover, with the aid of multivariate weighted multiscale permutation entropy (MWMPE) algorithm, we also explore the global flow instability of oil droplets. Research results indicate that with the increasing distance from pipe center, the interaction between oil droplets gradually weakens. Besides, the increase in mixture velocity or the decrease in water-cut will intensify the interaction between oil droplets and global flow instability. Multivariate time series analysis can be considered as an effective method for characterizing flow instability in oil-in-water emulsions.

1. Introduction

Due to the usage of long-term water flooding, onshore oilfield exploitation in China has entered into a middle-late stage characterized by low velocity and high water-cut. With the intention to enhance oil recovery, alkali-surfactant-polymer (ASP) flooding has been widely applied in oilfields. However, the addition of surfactant will significantly decrease the interfacial tension. Consequently, the diameters of oil droplets are generally at the order of micrometer magnitude and thus oil-in-water emulsions forms. Furthermore, the added surfactant also has a remarkable impact on rheology parameters, leading to the fact that flow characteristics in oil-in-water emulsions differ much from those in oil-water flows. To date, literatures reporting on flow structure in pipeline flow of oil-water emulsions are limited. An investigation of interaction between oil droplets is of a great significance to understand the spatio-temporal evolution characteristics of flow structure in oil-in-water emulsions, which further can be a valuable guidance to the optimization of flow sensor and improve measurement accuracy of flow parameters.

Flow instability in oil-in-water emulsions has received intensive attention. Phase separation method is the earliest and simplest method for investigating flow instability. This method can be realized by metering the volume of oil phase separated from emulsions after a certain time (Wen et al., 2010; Kiran et al., 2011). The variation of size distribution in dispersed liquid phase versus time can also be an index for characterizing flow instability. In terms of the

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discrepancies in affecting light scattering intensity between oil and water phase, dynamic light scattering (Mengual et al., 1999; Höhler et al., 2014; Kanter et al., 2016) and near infrared spectroscopy (Kallevik et al., 2000; Araujo et al., 2008; Borges et al., 2015) have been demonstrated as effective techniques for extracting liquid droplet size. Additionally, as oil and water phase present obvious differences in determining the relaxation time of trace particle, pulsed-field gradient nuclear magnetic resonance (NMR) (Simon et al., 2011; Lingwood et al., 2012; Ling et al., 2017) has also been a research focus for liquid droplet size measurement. Microscope observation is the most direct method for acquiring liquid droplet size in emulsions. Through capturing the images of emulsions at different times, the change in liquid droplet size distribution can be detected with the aid of image processing technology (Youan et al., 2001; Varade et al., 2011; Kowalska, 2016; Ganley and van Duijneveldt, 2016; Patil et al., 2017). Interfacial film formed by surfactant molecule is a membrane locating between dispersed and continuous phases, and is considered as the essential factor for affecting flow instability in emulsions. The way in which interfacial film influences emulsions instability can be characterized by the variation in its mechanical strength (Yang et al., 2007; Moran and Czarnecki, 2007) and interface morphology (Fan et al., 2010; Álvarez et al., 2010). Besides, research results also indicate that both salinity (Sheng, 2010; Al-Yaari et al., 2015; Tanudjaja et al., 2017) and temperature (Ee et al., 2008) have profound influence on flow instability in emulsions.

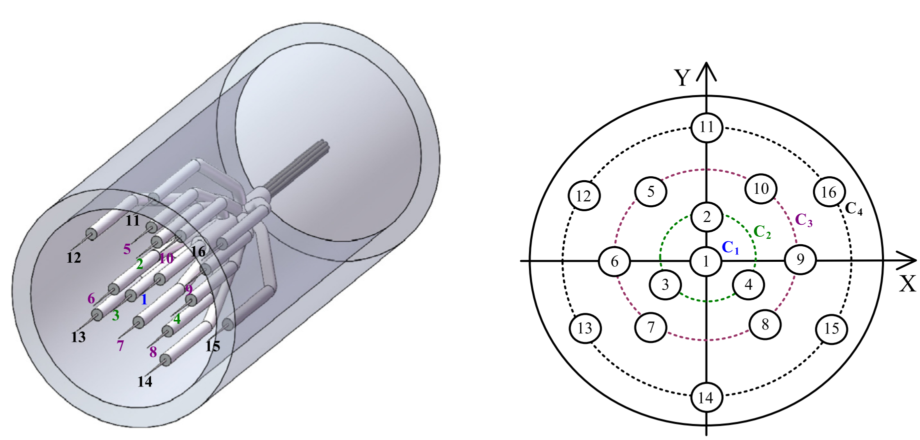
Experimental data on emulsions consists of abundant spatio-temporal evolution information in flow structure. Han et al. (2017) measured the fluctuating signals of a distributed eight-channel dual-sensors probe array and experimentally studied oil droplet size distributions on different locations at pipe cross section. It was reported that with the increasing distance from pipe center, both the number and size in oil droplets gradually decrease. Through processing the signals from a ring-shape conductance sensor with entropy algorithm, Yin et al. (2016) investigated flow instability and flow randomness in oil-in-water emulsions, on the basis of which they elucidated how the variation of flow parameters affects flow characteristics.

As aforementioned, oil droplets exist in the continuous water phase with micrometer diameters resulting from the significant decrease in interfacial tension. Therefore, in attempt to detect these tiny oil droplets using probe technique, the geometry size of probe should be elaborately designed. Aiming to understand the interactions between oil droplets in oil-in-water emulsions, we have designed a distributed sixteen-channel mono-sensor conductance probe array for a 20 mm inner diameter (ID) pipe (Han et al., 2018a) and acquired its dynamic response. It has been illuminated that TE can effectively reflect interactions between subsystems (Schreiber, 2000) and thereby have been applied in research fields such as neural system (Chávez et al., 2003; Gourévitch and Eggermont, 2007; Shovon et al., 2017), atmospheric sciences (Kleeman, 2005; Materassi et al., 2007; Verdes, 2007) and financial economy (Marschinski and Kantz, 2002; Mao and Shang, 2017). In the present study, with the sampled probe signals, we use TE to quantificationally characterize local interaction between oil droplets at pipe cross section, and investigate the effects of mixture velocity and water-cut on it. Besides, an algorithm called multivariate weighted multiscale permutation entropy (MWMPE) is also applied to uncover global flow instability of oil-in-water emulsions. The results show that the variation trend of local interaction between oil droplets versus flow parameters is in accordance with that of global flow instability. Additionally, both local and global instability indexes can satisfactorily indicate the dynamic behavior of oil droplets. Our present study provides novel insights of flow characteristics in oil-in-water emulsions.

2. Experimental facility and measurement system

The experiment of oil-in-water emulsions was carried out in multiphase flow loop facility and sensor system in Tianjin University. The total length and ID of vertical upward testing pipe are 2900 mm and 20 mm respectively. Experimental flow mediums consist of No.3 industrial white oil and aqueous solution with surfactant mass concentration equaling to 0.25%. The applied surfactant is anionic sodium dodecylbenzene sulfonate (SDBS). Surfactant aqueous solution is prepared by slowly pouring 425 g SDBS into a blender containing 170 L water. The solution is gently stirred until the dissolution of SDBS, and is left for another 2 h to guarantee complete hydration of surfactant molecules. Two peristaltic pumps are used to meter flow rate and transport oil as well as surfactant aqueous solution. These two flow mediums are introduced into the testing pipe through a "Y-junction" inlet. To ensure fully development flow, the distributed mono-sensor conductance probe array is placed at the height of 2000 mm from the mixing inlet.

Fig. 1(a and b) shows the configuration of the distributed mono-sensor conductance probe array. It can be seen that the probe array is composed by 16 identical mono-sensor probes. Specifically, Probe1 locates at pipe center (labeled as C_1). Probe2 to Probe4 (labeled as C_2) are at the position with a distance of 2.7125 mm from Probe1. For Probe5 to Probe10 (labeled as C_3), their distances



(a) 3D structure of distributed mono-sensor probe array (b) Distribution of mono-sensor probes

Fig. 1. Configuration of distributed sixteen-channel mono-sensor conductance probe array.