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The nonlinear analysis of horizontal oil-water two-phase flow in a small diameter pipe

Lu-Sheng Zhai [a,b], Panagiota Angeli [b], Ning-De Jin [a,*], Da-Shi Zhou [a], Lei Zhu [a]

[a] School of Electrical and Information Engineering, Tianjin University, Tianjin, China
[b] Department of Chemical Engineering, University College London, London, UK

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ABSTRACT

Horizontal oil-water two-phase flows are frequently encountered in many industrial processes but the understanding of the dynamic behavior underlying the different flow patterns is still a challenge. In this study, we first conduct experiments of horizontal oil-water flows in a small diameter pipe, and collect the fluctuation signals from conductance probes. The multi-scale power-law correlations of the oil-water flow structures are investigated using detrended fluctuation analysis (DFA) based on the magnitude and sign decomposition of the raw signals. The analysis reveals the scaling behavior of different flow structures; five conductive flow patterns are indentified based on the magnitude and sign scaling exponents at different time scales. In addition, the transfer entropy (TE) in a state space is used to study the information transferring characteristics of the oil-water mixture flowing past a conductance cross-correlation velocity probe. The results of TE indicate that the transferring information depends on the flow conditions and can be used to show changes in the flow patterns.

1. Introduction

Horizontal oil-water two-phase flows are frequently encountered in oil well production and oil transportation. The modelling of the flow parameters in such flows greatly depends on the multi-scale flow structures and the slippage between the two phases. Thus, investigating the nonlinear dynamic characteristics of oil-water flow structures is of significance for improving the accuracy of measurement and prediction of the flow parameters.

The flow structures forming during oil-water flows can be complex. In early studies they were directly observed via imaging (Russell et al., 1959; Hasson et al., 1970; Arirachakaran et al., 1989). Notably, Trallero et al. (1995, 1997) carried out experiments of oil-water flows in a horizontal pipe with an inner diameter of 50.8 mm and defined six flow patterns, i.e., stratified flow (ST), stratified flow with mixing at interface (ST&MI), dispersion of water in oil and water flow (DO/W&W), dispersion of water in oil and oil in water flow (DW/O&DO/W), dispersion of oil in water flow (DO/W) and dispersion of water in oil flow (DW/O). Angeli and Hewitt (1998, 2000) studied oil-water flows in both stainless steel and acrylic test sections using a high frequency impedance probe and indentified a new three-layer pattern. Lovick and Angeli (2004a) grouped all patterns where there are two continuous phases at the top and bottom of the pipe but with drops of one phase into the other to just one pattern named dual continuous (DC) flow. Chakrabarti et al., (2005) observed water-kerosene flow patterns of smooth stratified (SS), stratified wavy (SW), three layer (TL), plug (P) and oil dispersed in water and water (DO/WW), and predicted the pressure drop considering the energy minimization between the two phases. Zhai et al., (2015) from experiments in an acrylic pipe with a small inner diameter of 20 mm presented a new flow pattern map in which the ST&MI pattern is subdivided into four groups. In general the oil-water flow patterns are significantly affected by the inlet design, fluid properties, pipe diameter and material, pipe inclination and presence of additives (Brauner, 2003; Rodriguez and Oliemans, 2006; Wegmann and Rudolf von Rohr, 2006; Grassi et al., 2008; Al-Wahaibi et al., 2013; Ibarra et al., 2014; Abubakar et al., 2015). The variety and complexity of the flow structures present great challenges for their analysis and prediction.

In stratified flows the instability of the oil-water interface is associated with the flow pattern transition. Several studies have been carried out to investigate the interfacial features. Chakrabarti et al., (2007) designed a non-intrusive optical probe to investigate oil-water flows, and used probability density function analysis and a wavelet multiresolution technique to develop an indicator for stratified flows. Barral and Angeli (2014) measured the wave characteristics of stratified oil-water flows using wire conductance probes and investigated the effects of flow conditions on

* Corresponding author.
E-mail address: ndjin@tju.edu.cn (N.-D. Jin).

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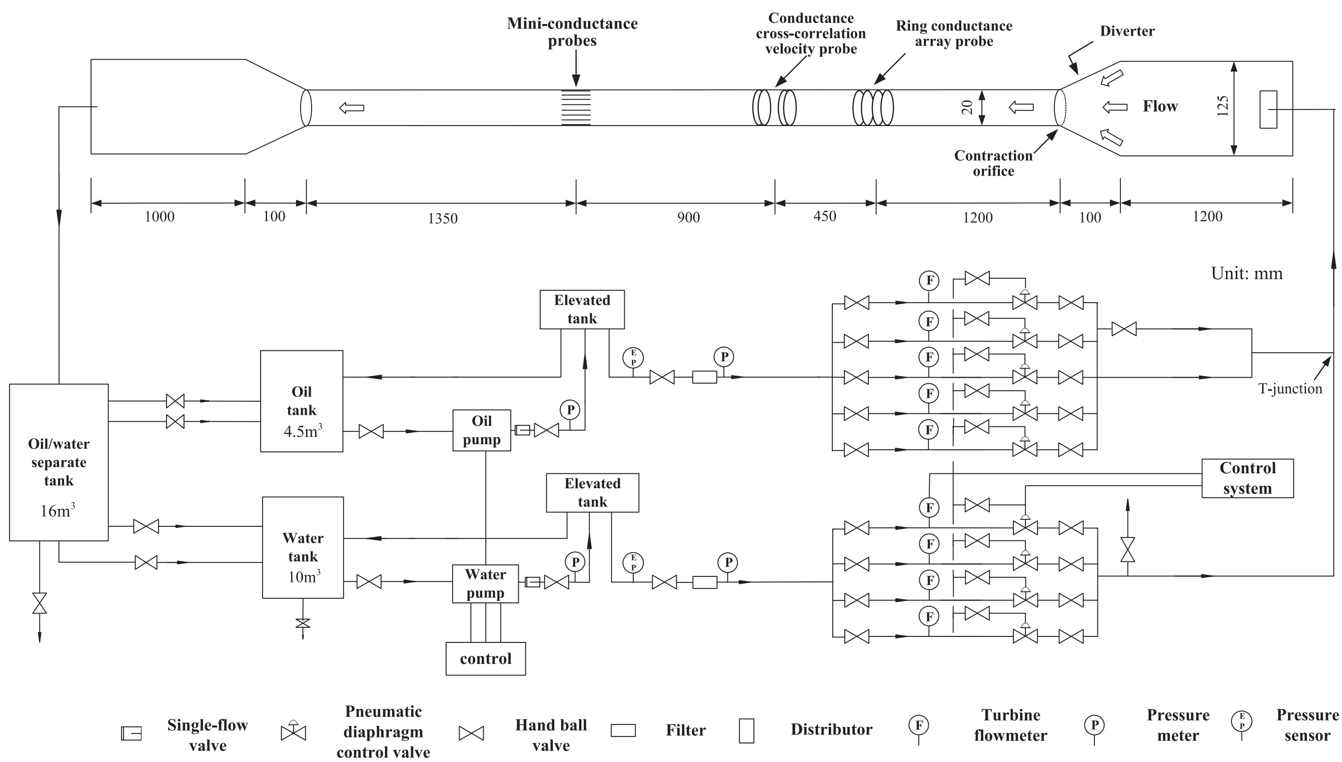

Fig. 1. Experimental set up for horizontal oil-water two-phase flows.

the power spectrum of the conductance signal. de Castro and Rodriguez (2015) found that the interfacial waves in stratified viscous oil-water flows could be correlated using the Reynolds, Froude and Weber dimensionless numbers. The interfacial wave characteristics can be used in the one-dimensional two-fluid model (Edomwonyi-Otu and Angeli, 2015; Liu et al., 2015; Picchi et al., 2015).

When dispersions occur, the local nonlinear dynamic characteristics are even more complex. Lovick and Angeli (2004b) found that in dual continuous flows droplet concentration and size decreased with increasing distance from the oil-water interface. Kumara et al., (2009, 2010) measured the local phase volume fraction and velocity distribution in a 56 mm ID steel pipe using a single-bundle gamma density meter and particle image velocimetry (PIV), and found that the degree of mixing between the phases as well as the velocity and turbulence profiles largely depend on the pipe inclination. Morgan et al., (2013) used laser-based optical diagnostic methods to measure droplet size, phase and velocity distributions in stratified and dispersed liquid-liquid flows, and found that the velocity profiles at the lower and upper parts of the pipe correspond to those of laminar flow and turbulent flow respectively. Zhai et al., (2014) developed a parallel wire capacitance probe to measure the cross-correlation velocity of segregated and dispersed oil-water flows in a horizontal pipe and indicated the dependence of the cross-correlation velocity on the flow patterns.

Despite the previous research efforts, the analysis of oil-water flow patterns and their transitions still presents significant challenges. Due to the interplay among many complex factors such as turbulence, changeable interfaces, and local relative movement between the phases, horizontal oil-water flows exhibit highly irregular, and unsteady flow structures, which give rise to dissipation, orderly and chaotic patterns. Thus, nonlinear analysis can be beneficial for exploring the flow patterns and their transitions.

Nonlinear analysis methods of two-phase flow systems have previously been studied by a number of investigators (Johnsson et al., 2006; van Ommen et al., 2011), particularly focusing on state space analysis (van Ommen et al., 2000; Llauró and Llop, 2006; Cao et al., 2009; Zong et al., 2010; Llop et al., 2012). In a recent paper, we used an Adaptive Optimal Kernel Time-Frequency Representation (AOK TFR) to investigate the flow characteristics of horizontal oil-water flows in terms of total energy and dominant frequency (Zhai et al., 2015). The AOK TFR, however, fails to distinguish the dispersed flow patterns because of their similarities in frequency and total energy.

In this current study, for the characterization of the flow patterns we introduce a multi-scale nonlinear analysis method, which is widely used in analysis of physiological signals (Ashkenazy et al., 2001). The long-range correlations of collected conductance signals are investigated by decomposing the signal increment series into magnitude and sign series and extracting their scaling behavior. Linear and nonlinear properties underlying the oil-water flows are revealed in terms of the magnitude and sign correlations. The observed oil-water flow patterns are identified using a combination of scaling exponents of the magnitude and sign series. In addition, transfer entropy analysis (Schreiber et al., Schreiber, 2000) is used to uncover the flow structure evolution of horizontal oil-water flows based on the conductance signals collected from a cross-correlation velocity probe.

2. Experiment set up and instrumentation

The experiments were carried out in the horizontal oil-water flow facility at Tianjin University, shown in Fig. 1. The test fluids used are tap water and No. 15 industry white oil with a viscosity of 11.984 mPa·s. The densities of the oil and water phases are 845 kg/m^3 and 1000 kg/m^3, respectively. The oil-water interfacial tension is 0.035 N/m. The average temperature at which the experiments were performed was 28°C. The experiments were carried out by increasing the oil flow rate at a constant water flow rate. The water flow rate was then increased to a next value and the procedure was repeated over the entire range of the oil flow rates. The oil, U_{so}, and the water superficial velocity, U_{sw}, varied from