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Characterization of oil–water two-phase pipe flow with a combined conductivity/capacitance sensor and wavelet analysis

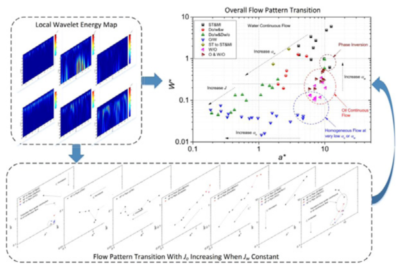
Chao Tan, Pengfei Li, Wei Dai, Feng Dong *

Tianjin Key Laboratory of Process Measurement and Control, School of Electrical Engineering and Automation, Tianjin University, No. 92, Weijin Road, Nankai, Tianjin 300072, China

HIGHLIGHTS

- Water holdup of oil–water flow is measured by a combined sensor of conductance sensor and capacitance sensor.
- Flow patterns were recorded and analyzed with continuous wavelet decomposition on holdup fluctuations.
- Flow patterns are characterized and analyzed in the local wavelet energy (LWE) coefficients maps.
- LWE Energy W^* and Scale a^* are extracted from LWE coefficients maps for overall flow characterization.
- Flow pattern transition with phase fraction and superficial velocity is studied in a W^*–a^* map.

GRAPHICAL ABSTRACT



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ABSTRACT

Flow patterns of horizontal oil–water two-phase pipe flow were studied with water holdup fluctuations provided by a set of conductivity and capacitance sensors. The in situ water fraction measured by the combined sensor was calibrated by quick-closing valves. Local wavelet energy (LWE) coefficients were extracted through continuous wavelet decomposition of the phase fraction history. The flow patterns in the horizontal pipe were identified visually and classified as water-continuous flow (oil dispersed in water flow, stratified flow with mixing at the interface, dispersion of oil in water and water flow and dispersion of water in oil, and oil in water flow) and oil-continuous flow (oil and dispersion of oil in water flow, and water dispersed in oil flow). The mechanics of flow behaviors of each flow pattern were interpreted from the LWE coefficient maps. Two features, the normalized LWE coefficient W^* and the normalized scale a^*, were extracted from the LWE coefficient maps to represent changes in flow patterns. Using these two coefficients, the flow pattern transition with superficial flow velocity of water (J_w) and oil (J_o) was investigated. An overall flow pattern transition is characterized in a W^*-a^* map, where a “triangular” distribution of flow patterns is formed and the flow pattern transition can be characterized with the change in phase fraction and overall flow velocity.

1. Introduction

Oil–water two-phase pipe flow is a typical flow phenomenon in the petroleum industry, such as in development and transportation (Thorn

* Corresponding author. Tel./fax: +86 22 27892055.
E-mail addresses: tanchao@tju.edu.cn (C. Tan), lipf12345@tju.edu.cn (P. Li), daiwei@tju.edu.cn (W. Dai), fdong@tju.edu.cn (F. Dong).

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et al., 2013). An understanding of the flow patterns, their behavior, and their flow mechanics, is of great value to the modeling, measurement and control of such flow phenomena (Angeli and Hewitt, 2000).

Characterization of two-phase flow helps in understanding the hidden mechanics of the flow process, and is also an effective tool to describe changes in two-phase flow structures in horizontal, inclined or vertical pipes (Brauner and Moalem, 1992; Angeli and Hewitt, 2000). Many sensing techniques have been used to characterize oil–water two-phase pipe flow, such as pressure transducers and conductivity probes (Trallero, 1995), gamma densitometers (Soleimani, 1999), planar laser-induced fluorescence, particle image velocimetry, particle tracking velocimetry (Morgan et al., 2012, 2013), impedance probes (Lovick and Angeli, 2004), and high speed cameras (Angeli and Hewitt, 2000). Electrical sensors are affordable, effective tools for measuring and characterizing oil–water two-phase pipe flow and have been used for decades (Trallero, 1995; Du et al., 2012). For instance, Lovick and Angeli (2004) analyzed dual-continuous flow using a conductivity probe. During the measurement of the two-phase flow phase fraction, electrical methods experience the dielectric property of the continuous flow. For instance, the conductivity sensor has a high sensitivity in conductive water-continuous flow, whereas the capacitance has a high sensitivity in the oil-continuous flow. If flow conditions can be analyzed using the same set of sensors, online analysis of the two-phase flow process would improve.

An accurate analysis of the flow process requires an objective index to characterize the flow structures, such as statistical, time–frequency, chaotic, and other nonlinear information processing methods (Jin et al., 2003; Xu et al., 2010). Because of its rheological complexity, oil–water two-phase pipe flow needs to be analyzed in the time and frequency domains. Therefore, the time–frequency representation is a promising method that characterizes a signal in the time and frequency domains by interpreting local and transient components in a time–frequency map (Du et al., 2012). These components are calculated using time–frequency decomposition techniques such as the short-time Fourier transform, wavelet transform, Wigner–Ville transform, and Choi–Williams distribution. They have a high resolution decomposition in the time–frequency plane compared with the traditional spectrum using only methods such as the Fourier transform.

Among the above time–frequency analyses methods, wavelet transform effectively analyzes and characterizes a non-stationary and transient signal on its local frequency properties in the time domain (Daubechies, 1990). Seleghim and Milioli (2001) adopted wavelet de-noising techniques to determine bubble sizes in two-phase flow. In the analysis of two-phase flow patterns: Kulkarni et al. (2001) used the multi-resolution characteristic of wavelet transforms to isolate the bubble size and velocity information from measurements of a laser Doppler anemometer. Shang et al. (2004) investigated water-vapor two-phase flow instability with wavelet decomposition. Tan et al. (2007), Tan et al. (2015) identified two-phase flow patterns using electrical resistance tomography and wavelet analysis. A thorough review of the wavelet transform in flow turbulence analysis is given by Farge (1992).

Continuous wavelet transform (CWT) emerged as one of the most favored signal processing tools since it does not contain cross terms inherent in other time–frequency methods, but it possesses frequency-dependent windowing, which allows for an arbitrarily high resolution of high frequency signal components (Addison, 2005). CWT is usually used in gas-liquid two-phase flow analysis because of the explicit fluctuating structures formed by gas bubbles of different sizes. For instance, Nguyen et al. (2010) used CWT to draw a local wavelet energy coefficient map on a time–frequency diagram, and presented an objective discrimination of flow patterns by combining the wavelet energy coefficient and corresponding bubble velocity. Kanai et al. (2012) estimated the bubble length using CWT and a wire-mesh sensor by treating the corresponding scales of local wavelet energy peaks as the bubble's effective length. Analyzing oil–water two-phase pipe flow with CWT is a challenge, because the phase fraction fluctuations caused by oil droplets are weak compared with gas bubbles, so the phase fraction time-series has a low amplitude and high frequency.

To characterize the oil–water two-phase pipe flow pattern and its transition, the water holdup (in situ water fraction) of oil–water two-phase pipe flow was measured by combined conductivity and capacitance electrodes to deal with the water- and oil-continuous flow separately. The water holdup signals under different flow patterns are characterized by CWT, and two normalized coefficients (W^* and a^*) are extracted from the local wavelet energy (LWE) coefficient map to represent the flow patterns at different flow conditions. The LWE coefficient map reveals time–frequency characteristics of phase fraction fluctuations of typical oil–water two-phase pipe flow patterns at a specific time, and the flow pattern transitions with phase fraction and flow velocity that forms a "triangular" distribution on the W^*-a^* map.

2. Experimental facility and methods

2.1. Test section

Fig. 1 shows the test section of 50 mm inner diameter. Two sets of electrodes are installed for water holdup measurement, i.e. a four-ring conductivity and a concave capacitance sensor. This configuration can deal with either oil- or water-continuous flow of oil–water two-phase flow, and provides information regarding water holdup changes from 0% to 100%.

The parallel ring structures create a linear electrical sensing field axially instead of radially (Fossa, 1998; Andreussi et al., 1988). Electrodes E1 and G1 are the exciting electrode-pair of the conductivity sensor, and an electrical sensing field between E1 and G1 is established by injecting a square electric current of 10 kHz into E1 (grounding G1). Electrodes M1 and M2 are the sensing electrodes that collect the electric potential drops between these electrodes, i.e. the voltages V_{cd}. The electric potential drops are directly proportional to the mixture conductivity, and thus to the phase fraction according to Coney (1973). The separation between the rings has been optimized so that the sensing field distribution between M1 and M2 is linear, therefore a linear (or as close as possible) response of output voltage (V_{cd}) to phase fraction is expected (Shi et al., 2010).

Two copper plate-electrodes (P1 and P2) are installed opposite and in between electrodes M1 and M2, so that the water fraction of the same fluid can be determined as is measured by the conductivity sensor. A constant 1 MHz and 20 V peak-to-peak amplitude sine voltage is applied in between P1 and P2 as the exciting signal. A sensing field is established to measure the water holdup through a decoupling of the overall capacitance of the fluid mixture.

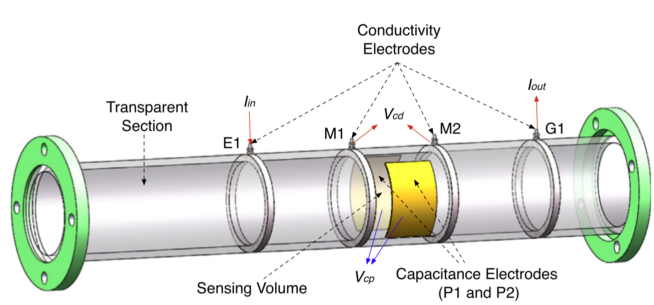

Fig. 1. Schematic view of test section with four-ring conductivity sensor and concave capacitance sensor.