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Flow pattern and holdup phenomena of low velocity oil-water flows in a vertical upward small diameter pipe

Y.F. Han, N.D. Jin *, L.S. Zhai, H.X. Zhang, Y.Y. Ren

School of Electrical and Information Engineering, Tianjin University, Tianjin, 300072, People's Republic of China

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ABSTRACT

This paper is dedicated to the investigation of flow pattern and holdup phenomena in low velocity oil-water flows through a vertical upward pipe with 20 mm inner diameter (ID). Four typical flow patterns, namely dispersed oil-in-water slug flow (D OS/W), dispersed oil-in-water flow (D O/W), very fine dispersed oil-in-water flow (VFD O/W) and transition flow (TF) were detected using a radial dual-sensors conductance probe array. We compared our experimental flow pattern boundaries with those from published physical models. To further explore the local flow structures of different flow patterns, we extracted probability density function (PDF) of oil droplet size across pipe section. In addition, slippage effect was evaluated by water holdup measurement using quick-closing valve (QCV). It was found that slippage effect generally weakens with increasing water-cut and mixture velocity. Finally, some typical drift-flux models were used to calculate water holdup, which was further compared with the measured data from published literatures. The results show that flow pattern-based modified drift-flux models proposed in the present study perform well on water holdup prediction for small ID pipes, while drift-flux models proposed by Flores et al. present superiorities on predicting water holdup in large ID pipes.

1. Introduction

Oil reservoirs with low permeability and low fluid productivity are commonly encountered in China. Considering the non-uniform distribution of the phases at cross section and variation of flow properties with time in small pipe, especially the severe slippage effect between water and oil phase with low velocity, production logging in low production oil wells is much more difficult than that in a high production because of the complex flows. A comprehensive understanding on flow pattern and holdup phenomena in low velocity oil-water flows is beneficial for the development of new measurements and its data interpretation in production logging technology.

Earlier investigations on vertical oil-water two-phase flow were mainly focused on visual observations (Govier et al., 1961; Zavarch et al., 1988). An effective method for detecting flow pattern is using mini-electricity probe. Vigneaux et al. (1988) employed a high-frequency impendence probe for distinguishing different flow patterns in oil-water flows. They indicated that oil became the continuous phase when the averaged water holdup located between 20% and 30%. Flores et al. (1999) designed six conductance probes axially placed in a 50.8 mm ID pipe to identify oil-water flow regimes. They concluded that water-dominated flows contained dispersion oil-in-water, very fine dispersion oil-in-water and oil-in-water churn flow, while oil-dominated flows were composed by dispersion water-in-oil, very fine dispersion water-in-oil as well as water-in-oil churn flow. Oddie et al. (2003) conducted flow test in a 150 mm ID vertical upward oil-water two-phase flow using electrical probes. An investigation on oil-water flow pattern implemented by Jana et al. (2006) suggested that using a parallel wire conductivity probe traversing the cross-section along a diametral plane, dispersed bubbly, bubbly, churn turbulent and core annular could be detected. Based on the outputs of a mini-conductance probe array, Du et al. (2012) detected five typical flow patterns in a 20 mm ID pipe, i.e., very fine dispersed oil-in-water (VFD O/W) flow, dispersed oil-in-water (D O/W) flow, oil-in-water slug (D OS/W) flow, water-in-oil (D W/O) and transition flow (TF). Using the signals collected from a dual-ring conductance probe array, support vector classification as well as voting methods were developed by Xu et al. (2016) to classify oil-water flow pattern in a 125 mm ID vertical pipe. As for detailed reports on flow pattern boundary determination, Brauner (2001) as well as Brauner and Ullmann (2002) predicted the transition to dispersed flows and phase inversion in oil-water flows with the models for predicting drop size. Piela et al. (2006, 2008) experimentally investigated phase inversion point in oil-water flows by seeking for the critical holdup of dispersed phase. Additionally, nonlinear analysis (Zong et al., 2010; Chen et al.,

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

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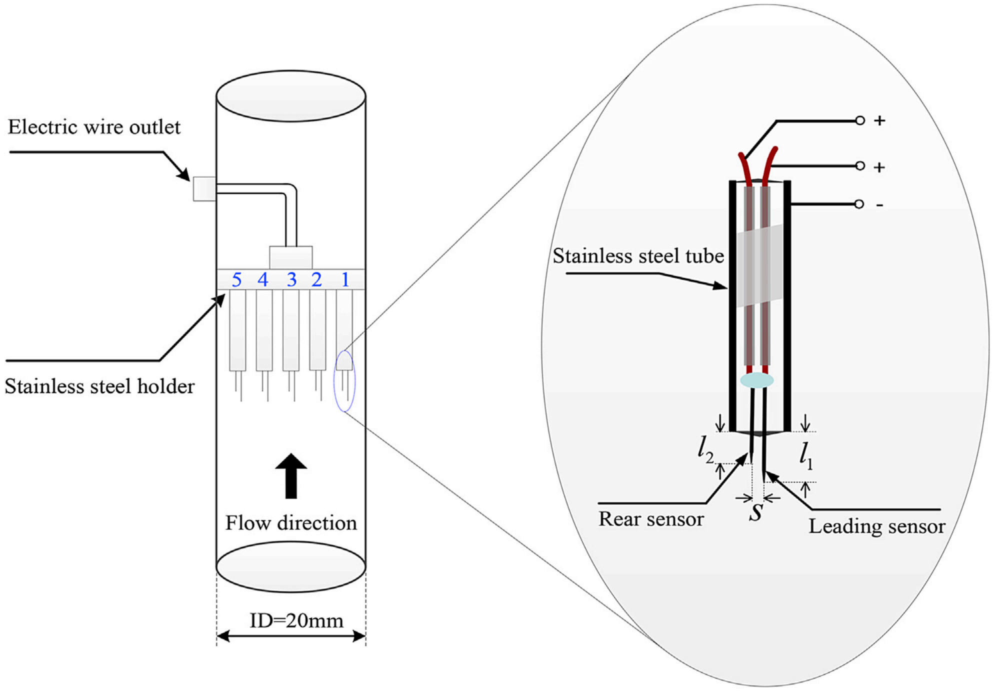
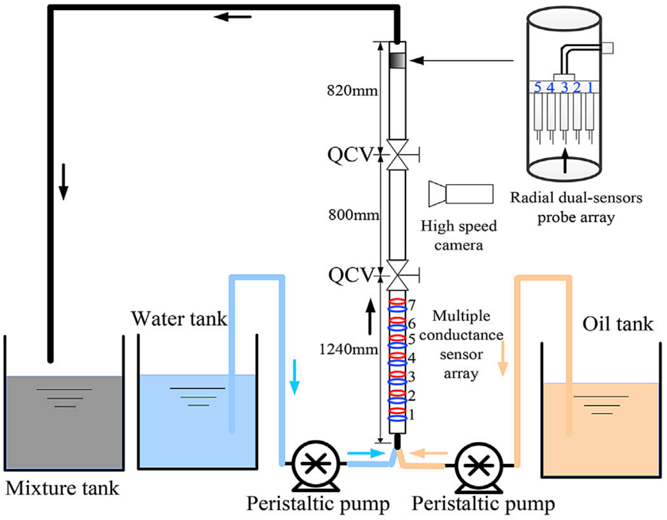
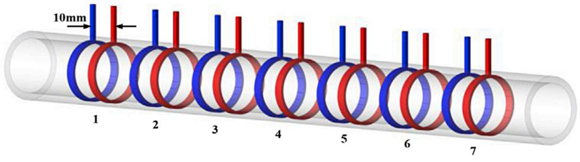


Fig. 1. Geometry structure of radial dual-sensors conductance probe array (Zhai et al., 2016).



(a) Layout of oil-water two-phase flow experiment



(b) The structure of multiple conductance sensor array

Fig. 2. Sketch map of oil-water two-phase flow experimental facility.

2015), time-frequency representation (Du et al., 2012; Han et al., 2016) are also used to characterize oil-water flows.

In oil-water flows, the amount of pipe occupied by a phase is often different from its proportion of the total volumetric flow rate. An understanding of this holdup phenomenon is central to establish physical model in two-phase flow. In upward oil-water flows, the lighter phase typically will be moving faster than the denser phase primarily because of buoyancy. Because of this fact, called the holdup phenomenon, the in-situ volume fraction of the denser phase will be greater than the input volume fraction of the denser phase, i.e., the denser phase is ‘held up’ in the pipe relative to the lighter phase (Hill, 1990). Generally, holdup phenomenon is associated with slippage effect between phases. Bannwart (1988) employed kinematic wave theory to figure out the interfacial waves of core annular flows with viscous oil and water in vertical and horizontal pipes, and they stated that the calculated water holdup and slip ratio from kinematic wave theory were consistent with the experimental results. Augier et al. (2003) investigated the slip velocity of homogeneous dispersed flow in a vertical pipe, and concluded that local phase fraction had a predominant influence on the mean relative velocity between two phases. Jana et al. (2007) pointed out that in vertical pipes with 25.4 mm ID, the homogeneous model was suitable for dispersed bubbly flow whilst bubbly and churn-turbulent flow pattern could be better predicted by the drift-flux model. Mydlarz-Gabryk et al. (2014) experimentally studied the slippage effect in vertical upward two-phase flow in a 30 mm ID testing pipe, on the basis of which it was summarized that slip ratio was dependent on flow pattern variation. To date, the most widely applied model for investigating slippage effect between phases is drift-flux model proposed by Zuber and Findlay (1965) and detailed investigations on this model will be presented in section 6.4 and 6.5.

Our group previously conducted a vertical upward oil-water flow test in a 20 mm ID pipe with mixture velocity changing from 0.442 m/s to 5.158 m/s (Du et al., 2012), while flow characteristic with low mixture velocity is still an unsolved problem. Therefore, we set up an experimental facility to investigate flow pattern and holdup phenomena of low velocity oil-water flows in a vertical upward small diameter pipe. A radial dual-sensors conductance probe array was used to detect flow pattern and its local flow structure across pipe section, Also, we applied QCV method to investigate the slippage effect in vertical upward oil-water flows. Finally, we established flow pattern-based modified drift-flux models and validated the accuracy of these models on predicting water holdup with previous experimental data.