Experimental Thermal and Fluid Science 80 (2017) 1–18

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Investigation on the effect of polymer in vertical oil-water two-phase flow using nonlinear analysis

Q.Y. Yang, Y.F. Han, W.X. Liu, H.X. Zhang, Y.Y. Ren, N.D. Jin *

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

ARTICLE INFO

Article history:
Received 22 January 2016
Received in revised form 6 August 2016
Accepted 7 August 2016
Available online 8 August 2016

Keywords:
Oil-water two-phase flow
Polymer
Flow characteristics
Recurrence plot
Multi-scale nonlinear analysis

ABSTRACT

This paper is devoted to investigating the effect of polymer on vertical oil-water two-phase flow using nonlinear analysis. For the comparison of flow characteristics in oil-water flows with different polymer dosages, an experiment in a vertical upward pipe with 20 mm inner diameter (ID) is conducted to obtain fluctuating signals of dispersed oil-in-water slug flow (D OS/W), dispersed oil-in-water flow (D O/W) and very fine dispersed oil-in-water flow (VFD O/W) using vertical multi-electrode conductance array sensor (VMEA). With the aid of recurrence plot, the effect of polymer on flow structure variation is qualitatively characterized. Then, recurrence quantification analysis and multi-scale weight complexity entropy causality plane (MS-WCECP) are respectively utilized to uncover the determinism and instability of the complex oil-water system with polymer addition. The results indicate that the recurrence plot can be effectively used to identify flow pattern and reveal the differences of flow structures in oil-water flows with and without polymer. The multi-scale weight complexity entropy causality plane can satisfactorily reflect the instability of polymer-added oil-water two-phase flow.

1. Introduction

For the purpose of enhancing oil recovery, polymer flooding technology has been widely used in oil fields in China. In comparison with water flooding, polymer flooding possesses the advantages of enlarging spread area, saving injection amount and allowing a higher utilization of water [1–3]. However, the high-molecular weight polymers added in vertical upward oil-water two-phase flow substantially change the rheological property, flow structure and further slippage effect, leading to the increasing difficulty of flow measurement. Therefore, uncovering the dynamic behaviours underlying different vertical oil-water flow patterns with polymer additives has been a challenge of significant interesting in the fields of nonlinear dynamics and fluid mechanics, which benefits to optimize production logging technology in oil wells.

During the transportation of oil over long distance, the realization of decreasing friction can reduce the economical cost and improve oil recovery to a certain degree. It is first proposed by Toms [4] that introducing small amount of long-chain and high-molecular weight polymer into a liquid flow can cause large decreases in the frictional resistance at the wall, and the degree of drag reduction is related to the polymer concentration. Thereafter, the drag-reduction performance of polymer in pipe flow has attracted extensive attention and been gradually employed in oil and gas industry. Initially, the researches on drag reduction effect of polymer mainly concentrate in single-phase flow. Choi and Jhon [5] experimentally investigated the phenomenon of drag-reduction using water-soluble polyoxyethylene and oil-soluble polyoxyethylene in turbulent flow. It was found that the maximum drag reduction requires lower concentration of polymer with the increasing molecular weight of polymer. Warholic et al. [6] found a lower drag-reduction in turbulent flow along sticky wall yet a higher drag-reduction over the cross-section of pipe induced by polymer additives. Besides, the variation of turbulent phenomenon is sensitive to the introduction of polymer solution and preparation of master polymer solution. Furthermore, a significant decrease on both Reynolds shear stresses and fluid velocity undulation in single-phase flow was reported by Luchik and Tiederman [7]. Regarding the drag-reduction caused by polymer in multiphase flows, Femandes et al. [8] conducted an experiment of gas-liquid two-phase flow in a 19 mm inner diameter horizontal pipe with the presence of poly-α-olefin. They developed a mathematical model to evaluate the effectiveness of polymer on drag-reduction, which can approvingly explain the correlations between drag-reduction and individual phase superficial velocity as well as pipe diameter.

In addition to the drag-reduction phenomenon, quantities of researches have been implemented to shed light on the stability of oil-water emulsion system with polymer addition. The stability

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

http://dx.doi.org/10.1016/j.expthermflusci.2016.08.008
0894-1777/

of dispersed oil-in-water emulsion with polymer and surfactant was investigated by Kang et al. [9]. They summarized that with the increasing concentration of either surfactant or polymer, an enhancing stability of emulsion was observed. Moreover, polymer contributes more to the stability than surfactant. Studies of the effect of polymer on flow characteristics in oil-water emulsion have been implemented by Al-Yaari et al. [10]. In line with the results of Kang et al. [9], it was found that polymer can stabilize the emulsion, while this effect weakens with the rising temperature. Zhang et al. [11] investigated the dissolving capacity of octane in oil-water emulsion with polymer. They reported in their experiment that at a certain temperature interval, higher concentration of anionic polymer facilitates the solubility of octane. Mi et al. [12] pointed out that uniform water-in-oil microspheres can be acquired when epoxy-based polymer (EP) membrane with a 3D bicontinuous skeleton structure is injected into emulsion.

The primary researches on flow characteristics and parameters in multiphase flow with polymer addition derive from gas-liquid two-phase flow. Al-Sarkhi et al. [13] conducted experiment of gas-water two-phase annular flow with polymer in a 95.3 mm horizontal pipe. A maximum drag reduction of about 48% was found with polymer concentration of only 10–15 ppm. Besides, the effectiveness of polymer is associated with the master polymer solution and the method for polymer injection. Soleimani et al. [14] carried out their research in horizontal gas-water two-phase flow to examine the effect of drag-reducing polymer on pseudo-slugs-interfacial drag and flow pattern transition boundary in regard to slug flow. The result shows the damping of small wavelength waves and an increase in liquid holdup, and transition to slug flow is delayed to a higher liquid holdup.

For the past few years, the investigation of flow patterns on oil-water two-phase flow with polymer addition in horizontal pipe has become a research focus [15–17]. Wahaibi et al. [18] implemented experiment in a 25.4 mm ID horizontal pipe. The polymer solution was prepared with an anionic co-polymer of 40:60 wt/wt NaAMPS/acrylamid and the impact on velocity and drag-reduction was examined. It was found that the concentration of polymer in the master solution presents no effect on the percent of drag-reduction. Al-Yaari et al. [19] measured water holdup with conductivity probe and concluded that drag-reducing polymer raises the water holdup when water superficial velocity locates in a certain range. Abubakar et al. [20] investigated the influence of polymer on oil-water two-phase flow patterns, pressure gradient and drag-reduction in horizontal and inclined pipe respectively. They elucidated that there exhibits little influence on flow pattern, pressure gradient and drag-reduction when polymer is injected into inclined pipe. Additionally, the effect of temperature and salinity on the performance of polymer was also reported [21].

In the present study, an experimental system is set up in a 20 mm ID vertical upward pipe to implement nonlinear dynamic analysis in oil-water two-phase flow with polymer additives. Combining the recurrence plot and the dynamic responses of VMEA sensor, three different flow patterns, namely dispersed oil-in-water slug flow (D OS/W), dispersed oil-in-water flow (D O/W) as well as very fine dispersed oil-in-water flow (VFD O/W) are identified. Meanwhile, with the aid of recurrence quantification and the evolution tendency of multi-scale weight complexity entropy causality, the nonlinear dynamics of oil-water flows with polymer addition are elaborately illuminated. This study provides a way to understand the nonlinear characteristics in the flow pattern variation induced by polymer in oil-water flows.

2. Experimental facility and materials

This experiment was carried out in the multiphase flow loop facility and sensor system in Tianjin University. The sketch map of experimental flow loop facility is illustrated in Fig. 1. The total length of testing pipe is 2500 mm.

In the experiment, polymer solution is prepared in a 200 L stainless steel blender (A) and then drained into a 300 L water rank (B) for storage. Another 300 L stainless steer tank (C) is used to store oil. Experimental fluids are pumped and metered using two industrial peristaltic pumps (D&E) and finally introduced into testing pipe through a “Y-junction” inlet (F). After flowing through testing pipe and the sensor measuring section, the mixed fluid is fed into a 600 L separation tank (G) at the end of the flow loop.

The peristaltic pumps (Model WT300F) used in the experiment are produced by Baoding Lead Fluid Technology Company. The flux

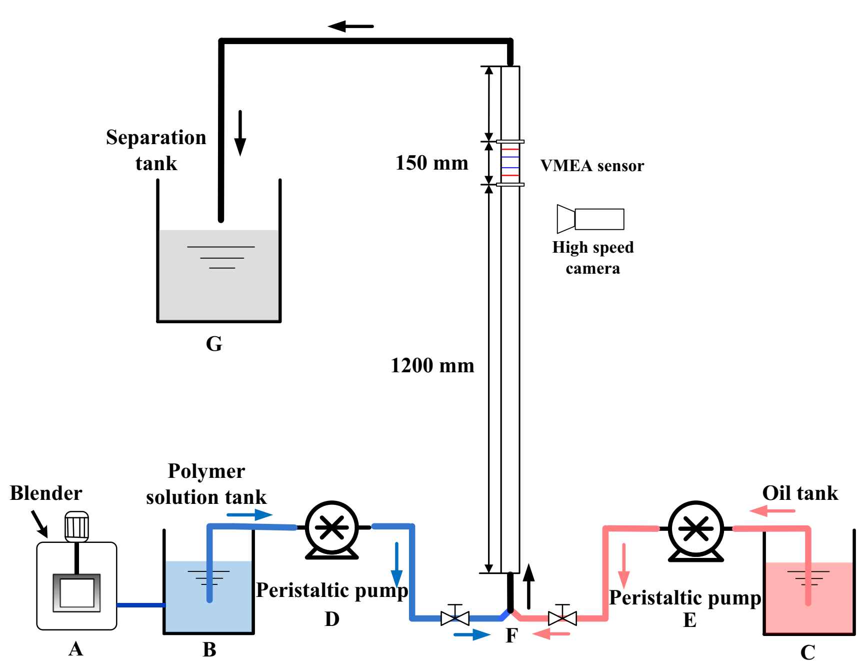

Fig. 1. Schematic diagram of oil-water two-phase flow loop facility.