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Nonlinear multi-scale dynamic stability of oil–gas–water three-phase flow in vertical upward pipe

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HIGHLIGHTS

- We design a rotating electric field conductance sensor to measure three-phase flow.
- We use recurrence plot and AOK TFR to recognize three-phase flow patterns.
- We propose a MS-WCECP to study the stability and nonlinearity of three-phase flow.
- Our analysis yields novel insights into fluid dynamics from the disequilibrium view.

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ABSTRACT

Characterizing stability and nonlinearity underlying oil–water–gas three-phase flow is a challenging problem of significant importance. We carry out experiments and measure the fluctuation signals from a rotating electric field conductance sensor with eight electrodes. We use recurrence plot and adaptive optimal kernel time–frequency representation to recognize different oil–water–gas three-phase flow patterns from experimental measurements. Then we employ multi-scale weighted complexity entropy causality plane (MS-WCECP) to explore the nonlinear characteristics for five typical oil–water–gas three-phase flow structures. The results suggest that our method enables to indicate flow pattern transitions. In particular, with the increase of scales, more information will be lost. Slug flow ends up in chaotic region, representing high complexity; Churn flow falls down from the chaotic to the random noise area, indicating the decreasing stability; while the drop degree of bubble flow is the biggest, suggesting that bubble flow has the most randomness. These findings demonstrate that multi-scale weighted complexity entropy causality plane can effectively depict the transitions of three-phase flow structures and serve as a useful tool for probing the nonlinear dynamics of the three-phase flows.

1. Introduction

The exploitation of onshore oil and gas field has come into its middle-late stage, there is going to be a big change in oil and gas reservoirs as well as the distribution of oil, gas and water. On one hand, most of the water flooded oil fields have already been in their high water-cut period, due to pumping, the pressure of flow in the reservoir is low which degases the crude oil; on the other hand, in oil deposits, the top structures and the places near fault also have gas production, this undoubtedly will lead to oil-gas–water three-phase flow in the reservoir. The complex flow structure of three-phase flow give rise to many difficulties for oil well production as well as oil gas transportation. Furthermore, pressure gradient, hold-up and the pipe parameters have a strong correlation with the flow pattern [1–4]. Any variances of flow structures will have a great influence on the industrial production, such as, artificial lift, pipe installation and many other situations. Therefore, the study of the stability and nonlinearity of flow patterns is of significant importance to both industrial production and practical application.

The conventional approaches in identifying the flow patterns include direct observation [5–8], high speed photography [9–10] and local probing [11–13]. Through estimating the existing state of different flow structures we can distinguish various flow patterns. With the development of time series analysis methods [14–16], many works dedicated to characterizing flow patterns from experimental measurements [17–18]. Wu et al. [19] adopted wavelet theory to de-noise differential pressure signals and then obtained the characteristics vectors of various flow regimes in terms of fractal theory. Wang et al. [20] used vertical

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Nomenclature

Notation

p_i	probability distribution
p_e	uniform distribution
Q	disequilibrium
Q_0	normalized constant
$J[P, P_e]$	expansion of Jenson–Shannon Divergence
C_w	statistical complexity measure
m, τ	embedding dimension, time delay
$\overline{X(t)}$	mean value of $X(t)$
p_k	weighted probability
$S[P]$	weighted permutation entropy
H_w	normalized weighted permutation entropy
$w(t)$	weight value
θ	angle of electrode
H	height of electrode
$y^s(j)$	coarse-grained time series
$\Theta(\bullet)$	Heaviside function
$\|\bullet\|$	Euclidean norm
ε	threshold value of distance
$A(t, \tau, \upsilon)$	time-localized short-time ambiguity function
$\Phi_{AOK}(\tau, \upsilon)$	Gaussion function

Greek letters

U_{sw}	water superficial velocity
U_{sg}	gas superficial velocity
U_{so}	oil superficial velocity

multi-electrode array conductance sensor to obtain signals from oil–gas–water three-phase flow and then employed chaotic attractor morphological description and complexity measures to study the dynamical characteristics of four water dominated flow patterns. Gao et al. [21–22] developed complex network-based analytical frameworks to uncover the complicated flow behaviors underlying the transitions of two-phase/three-phase flow patterns. Mukherjee et al. [23] utilized the probability density function (PDF) to identify the range of existence of different patterns from the probe signals. Dispersed flow and slug flow can be identified from the PDF analysis, and this method is particularly useful at high flow velocity where visualization techniques fail to work. There still exist significant challenges in the characterization of transitional flow behaviors underlying three-phase flow which has attracted wide attention [24–26]. A study has been made to analyze the influence of gas injection on the phase inversion between oil and water in a vertical upward pipe by Descamps et al. [27]. The results show that gas injection does not significantly change the critical concentration, but the influence on the pressure drop is considerable. Zhao et al. [28] applied multi-scale long-range magnitude and sign correlations to analyze the signals, and the results suggest that the magnitude series relates to nonlinear properties of the original time series, whereas the sign series relates to the linear properties. Despite the huge breakthrough in the researches of oil–gas–water three-phase flow, it is still a challenge to investigate the stability and determinacy of three-phase flow due to its complex structure. In this regard, a powerful tool integrating complexity and entropy remains to be developed.

Entropy is a physical quantity for describing the degree of randomness. Pincus [29] came up with the approximate entropy, which has been widely used in climate prediction, medical science as well as mechanical equipment. Balil et al. [30] developed the weighted permutation entropy by improving the permutation entropy introduced by Bandt and Pompe [31]. In the previous study of multi-phase flow, some indexes such as permutation entropy and Kolmogorov entropy have been extracted to identify flow patterns and characterize flow stability. Moreover, multi-scale sample entropy has been demonstrated to be an efficient indicator for the transitions of two-phase flow [32]. Nevertheless, neither sample entropy nor permutation entropy can describe the system from the perspective of both disequilibrium and entropy. To solve this problem, Rosso et al. [33–34] proposed the complexity entropy causality plane (CECP). Zunino et al. [35] used the complexity entropy causality plane to quantify the stock market inefficiency. Dou et al. [36] further developed the CECP by taking the advantage of multi-scale technique to map a time series into a multi-scale complexity-entropy causality plane which has enriched the knowledge of the stability and nonlinear dynamics of two-phase flow.

As a development of previous methods, we proposed a multi-scale weighted complexity entropy causality plane (MS-WCECP). Our method allows acquiring another important information about peculiarities of a probability distribution, a task that entropy-based methods fail to work and improves the performance of the CECP by combining multi-scale technique, most importantly, MS-WCECP introduce the permutation entropy into the weighted permutation entropy which performs much better in anti-noise ability as well as distinguishing different signals. The MS-WCECP has demonstrated to be a useful tool for exploring the stability and complexity of gas–liquid two phase flow [37]. In this paper we utilize multi-scale weighted complexity entropy causality plane (MS-WCECP) to analyze the signals measured from vertical upward oil–gas–water three-phase flow. Based on our analysis of experimental data, we can draw the conclusion that our method improves the signal classification ability and shows a good algorithm robustness compared to the previous work. The results indicate that the multi-scale weighted complexity entropy causality plane enables to effectively characterize the transitions of three-phase flow structures and provides an efficient analytical framework for investigating the nonlinear dynamics of the three-phase flow.

2. Multi-scale complexity entropy causality plane

2.1. Statistical complexity measure

Jaynes has established the relevance of information theory for theoretical physics [33]. Two essential ingredients of this content are: (1) Shannon's logarithmic information measure regarded as the general measure of the uncertainty associated to probabilistic physical processes. (2) Maximum entropy principle. Later, from another point of view, Kolmogoro and Sinai converted information theory into a powerful tool for the study of dynamical systems.

Ascertaining the degree of uncertainty and randomness of a system is not equal to adequately grasp the correlative structures that maybe present. Randomness and structural correlations are not totally independent aspects of this physics. It is obvious that there is no structural information of perfect order and maximal randomness. There exists a wide range of possible degree of physical structure. The characteristics of system are reflected under the probability distribution.

When the probability distribution is given, the entropy of a system is zero. We can gain the most information from it. The other way round, for a uniform distribution, very little information can