Experimental Thermal and Fluid Science 60 (2015) 165–172

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Nonlinear characterization of gas liquid two-phase flow in complex networks

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ARTICLE INFO

Article history:
Received 26 December 2013
Received in revised form 12 July 2014
Accepted 13 September 2014
Available online 22 September 2014

Keywords:
Two-phase flow
Time series
Complex networks
Nonlinear dynamics
Entropy

ABSTRACT

A new method is proposed to study nonlinear dynamic of gas liquid two-phase flow through a vertical upward pipe with the aim to make clear the two-phase flow behavior, from the complex networks perspective. The experimental test section is a transparent plexiglass pipe with inner diameter is 40 mm and the length is 1.5 m. Five kinds of flow pattern including bubble flow, bubble–slug flow, slug flow, slug–churn flow and churn flow are measured, and then constructed 178 corresponding flow pattern complex networks in order to reveal the dynamical characteristics of two-phase flow. It is found that different flow pattern complex network present different community structure, when the correspondence between the threshold and the mean of similarity matrix meet specific proportion. The results show that the power-law exponent of degree distribution and network information entropy of flow pattern complex network is sensitive to the flow pattern transition, which can be employed to characterize the nonlinear dynamics of two-phase flow. It is demonstrated that complex network approach can be an effective tool to study nonlinear dynamics of air water two-phase flow.

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1. Introduction

Gas liquid two-phase flow is widespread among the nature and industrial system. Understanding the nonlinear characterization of gas liquid two-phase flow is important significance to solve the flow problem in chemical, nuclear and petroleum industry. Due to the interplay among many complex factors such as fluid turbulence, phase interfacial interaction, and local relative movements between phases, two-phase flow shows chaos and unsteady flow structure.

Earlier research of gas liquid two-phase flow are mainly focused on experimental observations and flow pattern classification. Hoogendoorn [1] conducted air water and air oil mixtures flow experiment in horizontal smooth pipes and roughed pipes to map flow regime diagrams. Weisman et al. [2] proposed the boundary expression and dimensionless criteria of gas liquid two-phase flow on the basis of previous. Kelessidis and Dukler [3] proposed a flow pattern identification method based on probability density function, and obtained flow pattern maps. Hassan et al. [4] designed and constructed a new test rig to extend the range of the existing data on flow regimes, then created two universal flow regime maps. On the other hand, many new methods have been employed to identify the two-phase flow classification [5–12].

With the development of time-series analysis methods form nonlinear dynamics and chaos, some applications of time-series on the nonlinear characterization of complex multiphase flow have been studied [13–18]. Despite these contributions, there still exist significant challenges in the study of two-phase flow. Specifically, the previous methods fail to uncover the dynamical characteristics of bubble distribution induced by the change of Usg. So far the dynamic characteristics, which control the evolution of the flow pattern transition have not a clear understanding.

Recently, the approach [19–28] of mapping time series to complex networks which are capable of characterizing many types of systems in nature and technology that contain a large number of components interacting with each other in a complicated manner, has found wide application. In particular, Zhang and Small [21] found that noisy periodic signals correspond to random networks and chaotic time series tend to generate small-world and scale-free network features. Zhang et al. [22] pointed out that their proposed method is a transformation from the time domain to the network domain, which allows to investigate dynamics of the time series via organization of the network. Inspired by the approaches [22–28] of mapping time series into complex networks, Gao and Jin [24] did pioneering works in the investigation of two-phase flow. They introduced the approach of complex networks into study of

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http://dx.doi.org/10.1016/j.expthermflusci.2014.09.007
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Nomenclature

A	adjacency matrix
E	network information entropy
E_N	normalized network information entropy
$E_{\max}$	maximum network information entropy
$E_{\min}$	minimum network information entropy
I_s	information entropy
ID	pipe inner diameter,mm
i	node i
j	node j
k	degree
k_B	Boltzmann constant
k_i	the degree of node i
k_j	the degree of node j
L	the length of segment of time series
m	the number of segment
M_E	Euclidean distance
n	number of nodes contained in the network
N	number of sampling points
$P(i)$	importance of node i
$P(k)$	degree distribution
Q_g	gas flow rate, m^3/h
Q_l	liquid flow rate, m^3/h
r_s	threshold
S	correlation matrix
$S(i,j)$	the similarity between i and j
U_{sg}	superficial gas velocity, m/s
U_{sl}	superficial liquid velocity, m/s
X	sequence segments
y_i	ith point of time series

Greeks

γ	the power-law exponent of degree distribution
Ω	information

Subscripts

B	Boltzmann
E	Euclidean
s	shannon information

two-phase flow and employed the statistical characteristic of network to characterize the nonlinear dynamics of gas liquid two-phase flow. Time series are mapped into a network representation (where the connections between nodes capture the series structure according to the mapping criteria) and graph theoretical tools are subsequently employed to characterize the properties of the series. Bridging time series analysis and complex networks can be an appealing approach for experimental data analysis and pattern recognition [25]. Based on experimental measures time series from a two-phase flow, an artificial network can be constructed [26].

Therefore, a method from the complex networks perspective is proposed to investigate vertical upward air water two-phase flow. Optical detection (e.g. process tomography) is one of main strategy in the study of two-phase flow now, which has not impact on the flow pattern stability and observation due to no resistance to two-phase flow. But the resolution and accuracy of optical detection are not satisfactory, and sensitivity distributions of process tomography are susceptible to the dielectric distribution of measured multiphase flow. As compared with optical detection, the signal from pressure detection is not affected by the pipe scale and transmittance. Extensive research [29–34] suggests that the signals from pressure detection are closely related to two-phase flow pattern, which can provide sufficient information to identify flow pattern, such as the different pressure signal. From the above, the different pressure signal is employed as measurement signal. The same criterion with Gao and Jin [24] is employed to determine the threshold. Due to the Euclidean distance that reflect the absolute difference of numerical features between individuals, the Euclidean distance has mostly been used to difference analysis as similarity measure, from the dimensions perspective. The Euclidean distance is employed to describe the state of network connection network. The experiments of air water two-phase flow in a 40 mm ID vertical upward pipe are conducted to record flow patterns and get all the differential pressure fluctuation signals of the flow patterns. 178 two-phase flow pattern complex networks (FPCN) are constructed from experimental data to study the nonlinear dynamics of air water two-phase flow. It is found that the power-law exponent of degree distribution (γ) and network information entropy (NIE) can faithfully represent the distinct dynamical states of air water two-phase flow. The results suggest that γ and NIE of flow pattern complex networks can potentially be a powerful tool for revealing the nonlinear dynamics of gas liquid two-phase flows.

2. Experiment and data acquisition

Experiments were carried out in vertical upward gas–liquid two-phase flow facility which was composed by fluid control, information and image acquisition systems. The experimental test section is a transparent plexiglass pipe with inner diameter is 40 mm and the length is 1.5 m. The experimental mediums are air and tap water. The schematic diagram of experimental system is shown in Fig. 1.

The fluid control system consists of several parts: water tank, centrifugal water pump, air compressor, two-phase mixer and regulator. Water is supplied from the water tank, which flow through a float flowmeter into two-phase mixer. Meanwhile air is supplied from the air compressor which flow through into the regulator and then flow through a float flowmeter into two-phase mixer. The mixture flow through the test section into an air–water cyclone separator where the separated water flow into the water tank for cycling utilization and the air is discharged to the atmosphere.

Information and image acquisition system composed of two differential pressure transducers (SBC-A), data acquisition device, and high speed camera. A long transparent section is installed upstream of transducer so that the flow pattern could be observed and recorded by high speed camera. The spacing between pressure probes is 300 mm. The gas flowrate Q_g is varied in the range of 0–15 m^3/h, the water flowrate Q_l in the range of 0–5 m^3/h.

In the experiment, the gas flowrate is increased gradually and the liquid flowrate is fixed in 0.5 m^3/h, 2.5 m^3/h and 5 m^3/h, respectively. The gas flowrate increasing profile in the flow pattern evolution as shown in Fig. 2. It is found that the growth rate of gas flowrate is affected by the liquid flowrate, the higher liquid flowrate, the slower growth rate of gas flowrate. With increasing of the gas flowrate, different flow patterns begin to appear and the typical flow pattern images are acquired such as bubble flow, slug flow and churn flow. The typical flow pattern images are showed in Fig. 3. Through the DAQ Card the different pressure fluctuating

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