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Research Paper

Complexity evolution quantification of bubble pattern in a gas-liquid mixing system for direct-contact heat transfer

Qingtai Xiao[a,b,c], Kai Yang[a,c], Manman Wu[d], Jianxin Pan[e,*], Jianxin Xu[a,d,*], Hua Wang[a,*]

[a] State Key Laboratory of Complex Nonferrous Metal Resources Clean Utilization, Kunming University of Science and Technology, Kunming 650093, PR China
[b] School of Mathematical and Statistical Sciences, University of Texas Rio Grande Valley, Edinburg, TX 78541, USA
[c] Faculty of Metallurgical and Energy Engineering, Kunming University of Science and Technology, Kunming 650093, PR China
[d] Quality Development Institute, Kunming University of Science and Technology, Kunming 650093, PR China
[e] School of Statistics and Mathematics, Yunnan University of Finance and Economics, Kunming 650221, PR China

HIGHLIGHTS

- The pattern complexity of bubble swarms governs heat transfer performance of heat exchanger.
- A characteristic extraction technique for quantifying the complexity evolution is developed.
- Betti numbers was associated with image entropy, leading to measuring the mixture homogeneity.

ARTICLE INFO

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Direct-contact heat transfer
Homogeneity criterion
Mixing process
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Complexity evolution

ABSTRACT

The pattern complexity (kinetics and uniformity) of bubble swarms governs the heat transfer performance in gas-liquid contact systems such as direct-contact boiling heat transfer process. An image analysis technique is developed for quantifying the complexity evolution of bubble pattern in the gas-liquid contact system based on entropy theory and algebraic topology (more precisely, Betti numbers) using organic Rankine cycle direct-contact heat exchangers. The Betti numbers method is associated with image segmentation using entropy theory, leading to a useful model to characterize the homogeneity of the mixture. Experimental results show such an effectiveness. This novel method may be applied the study of a variety of multiphase flows.

1. Introduction

Mixing is defined as the increase in homogeneity through input of mechanical energy (for instance, gas blowing or mechanical stirring) in single or multiphase systems to gain desired high-quality products [1–3]. A multiphase mixing process (one of the most popular nonlinear systems) can generate complex spatio-temporal patterns [4,5]. To obtain high efficiency, mixing patterns must satisfy not only the needs of mass and heat transfer but also the required uniformity in a stirred vessel in short time [6,7]. Rapid homogeneity of the entire mixing system is essential to ensure reproducible and reliable experimental results [8,9]. Understanding flow patterns and their connections with heat transfer enhancement is one of the most intriguing scientific questions [10,11,7]. Several researchers have reported successful passive techniques used to enhance heat transfer and mixing quality performances [12–14]. Other interestingstudies in multiphase flows are facilitated by a variety of imaging technologies, including Laser Doppler Velocimetry (LDV), Particle Image Velocimetry (PIV), Particle Tracking Velocimetry (PTV) and Direct Color Imaging (DCI) [15,16]. The complexity of imaging data of multiphase mixing and heat transfer processes presents challenge to conventional industrial measuring systems and has received increasing interest in recent years [17,18,7,3,5].

In the literature, characterizing the mixing effect and the complex phase transition for a direct contact heat exchanger (DCHE) is an interesting but challenging problem [19]. Researchers evaluated different types of mixing equipment [20,21,5]. The reproducibility and robustness of using image analysis techniques to describe macro-mixing in different types of stirred tanks have been reported in [1,22,23,9]. Ref. [1] dealt with the blending of two powders in a viscous liquid followed by an image processing technique for obtaining the mixing time [1]. In algebraic topology (in particular homology), the topological invariant has been introduced as a characteristic measure for topological complexity [24–26]. To quantify the mixing performance, homology as a mathematical tool provides basic topological (geometrical) information

* Corresponding authors at: School of Statistics and Mathematics, Yunnan University of Finance and Economics, Kunming 650221, PR China (J. Pan). State Key Laboratory of Complex Nonferrous Metal Resources Clean Utilization, Kunming University of Science and Technology, Kunming 650093, PR China (J. Xu, H. Wang).
E-mail addresses: qingtaixiao2016@kmust.edu.cn (Q. Xiao), jxpan1996@126.com (J. Pan), xujianxina@163.com (J. Xu), wanghua65@163.com (H. Wang).

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Nomenclature

A_{vol}	the average of volumetric heat transfer coefficients
B	pixel value of blue component
C	pixel of gray image
C_1–C_6	six levels of experiment
G	pixel value of green component
G_{con}	the height of heat transfer fluid
h_B	histograms of blue component
h_C	the histogram value of an image
h_G	histograms of green component
$H_i(X)$	the ith homology group
h_R	histograms of red component
h_S	the synthetic histogram
m	the number of elements in χ^+
n	the number of elements in χ^-
R	pixel value of red component
R_{con}	the flow rate of the hot fluid
R_{dis}	the flow rate of the refrigerant
t	arbitrary time point
T	mixing time
X	topological space
$\mathbb{Z}$	the integers
β_0	the zeroth Betti number
β_1	the first Betti number
$\beta_1(t)$	the first Betti number at time t
β_i	the ith Betti number
ϵ	the apparent local gas hold-up
τ	the threshold value
χ^+,χ^-	two defined sets of special time points
ΔT_{ini}	the initial heat transfer temperature difference
Φ	a defined objective function
Ω	a defined set of special $\beta_1(t)$

on multiphase flow structures, such as the number of components (continuous phase) and the number of holes (disperse phase) [10,27]. The topological invariant was introduced as a characteristic measure for the complexity of the microstructure occupied by one of the two material phases [25]. Homology is useful for identifying and distinguishing the evolving flow-structures of multiphase flows [27]. While gray-scale photographs can be converted to binary images by threshold values to separate the objects of interest from their surrounding background. It is necessary to have sufficient contrasts between objects and their surrounding matrix for effective threshold and object-background separation. Simultaneously, the measurement precision is highly influenced by the complicated measurement procedure and data processing [28,29]. In the case of complex flows, the sample signal also contains noise, which, if not dealt appropriately, cause a systematic error [30]. Several researchers are interested in the uncertainties that arise from noise, i.e., from random phenomena [29]. Although progress has been made for direct-contact heat transfer platforms, with the development of imaging techniques and advanced mathematical methods to improve characterization of multiphase flows, publications about fluctuation up/down of Betti numbers time series are limited.

In this article, the effects of image segmentation and Betti numbers fluctuation are considered and a combined framework is formulated. The ordinary techniques destroy the inherent spatial structure of the image with useful information. Inspired and motivated by Refs. [20,10,7,5], an entropy theory based on image analysis is applied to find the optimal algorithm for image segmentation. A new objective function based on Betti numbers is defined for optimization. The paper presents a comparison between the experimental and theoretical results under different experimental conditions. Experiments were done for validation of the results. In the review article, Ref. [31] noted the increasing trends and demands of using mixing images for flow regime recognition and prediction, for characterization of subjective human experience, and for understanding association between flow regions and cognitive outcomes. Furthermore, the contributions of this article are twofold. Firstly, our framework offers a systematic solution to this problem and to address multimodality imaging analysis, de-noising analysis, and flow patterns manipulation, all of which remain as challenges. Secondly, general mathematical measure has been developed for of computational homology applications, i.e., topological structure of multiphase flows.

The rest of the article is organized as follows. Section 2 begins with an experimental set-up with a direct-contact heat exchanger and an imaging device, and then provides image data of gas–liquid mixing. Section 3 presents the existing method and a proposed method. Section 4 provides experimental results and discusses the effect of experimental parameters on two-phase mixing effects. Section 5 gives concluding remarks.

2. Experimental investigations

2.1. Experimental details

In this paper, the mixing quantification of gas-liquid two-phase flows is further investigated using a direct-contact heat transfer platform [10,18,27]. Here, the hot phase is oil (THERMINNOL®66) and the cold phase is organic working fluid (R245fa). The direct contact heat exchanger (DCHE) where heat transfer experiments were carried out is a 5-L non-transparent cylindrical steel vessel with inner diameter of 45 cm and height of 1.8 m. There is a vertical viewing window is symmetrically placed around the tank wall. The three nozzles are located in the height of 0.055 m from the bottom. An imaging technique was applied to the gas-agitated vessel, and the data obtained by a high-speed video camera. Fig. 1 shows the direct contact heat transfer system as experimental set-up.

There are two circulation loops for our experimental system. More narrowly, the first loop is a continuous-phase circulation loop for fluid flow and the second loop is a dispersed-phase circulation loop for working medium flow. Admittedly, the different fluids in the two circulation loops undergo heat transfer inside the DCHE. It should be noted that only the wall near the high-speed video camera was being recorded under normal lighting conditions during experiments. Nevertheless, we were already able to roughly quantify the flow patterns near the wall.

The design is used to verify the feasibility of our method. The system was a fully baffled cylindrical vessel stirred by a liquid phase from bottom. Different levels of experiments (namely, C_1–C_6) are adopted as given in Table 1. The experimental conditions (the height of heat transfer fluid G_{con}, the initial heat transfer temperature difference ΔT_{ini}, the flow rate of the hot fluid R_{con} and the flow rate of the refrigerant R_{dis}) and heat transfer performance details (average of volumetric heat transfer coefficients, A_{vol}) are listed. The stirred tank is filled with heat transfer fluid as the continuous phase. For more details on the DCHE used in this study see our previous work [7,3,5].

2.2. Image acquisition and preprocessing

The mixture of the two phases (continuous and dispersed phases) is examined in DCHE. Visual observation by the high-speed video camera is made to identify the flow pattern in the gas–liquid mixing system. Fig. 1 also shows the data acquisition system. The interesting patterns of complex phase transition were seen by high-speed camera at the speed of 25 frames per second and recorded 8 min in each experiments.