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Extraction and evolution of bubbles attributes in a two-phase direct contact evaporator

Qingtai Xiao [a,b], Qin Gao [c], Jing Zhang [d], Jianxin Xu [a,d,*], Jianxin Pan [e,*], Hua Wang [a,f,*]

[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, The University of Texas Rio Grande Valley, Edinburg, TX 78541, USA
[c] Faculty of Science, Kunming University of Science and Technology, Kunming 650500, PR China
[d] Quality Development Institute, Kunming University of Science and Technology, Kunming 650093, PR China
[e] School of Mathematics, University of Manchester, Manchester M13 9PL, UK
[f] Faulty of Metallurgical and Energy Engineering, Kunming University of Science and Technology, Kunming 650093, PR China

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ABSTRACT

Understanding the bubble regimes is a fundamental step toward conducting heat transfer enhancement. The non-invasive measurement of mixing inside a direct-contact heat transfer process, using a direct video imaging technology, provides powerful opportunities for characterising the visual observations of the phenomena and quantifying the process complexities previously. Experimental bubble shape feature parameters were obtained by means of the photographic recording technique for a direct-contact evaporator. Four design factors with three levels respectively were analysed for the mixing system that involves the exchange of heat between two immiscible fluids (continuous and dispersed phases). Using the Ripley's K function, new results are presented for two-phase flow mixing which can distinguish differences in the mixing behavior of dispersed phase. In all cases considered, quantitative comparisons of the evolution curves representing different experimental conditions were conducted with reported experimental data. Following the local mixing curve, the current results can also be processed to provide the mixing time found to be in good agreement with available data. The relationship between shape feature parameters of bubbles and volumetric heat transfer coefficient was found to be highly independent on experimental design parameters.

1. Introduction

Although boiling is a complex process, it is a very efficient mode of heat transfer in various heat exchange systems [1]. Direct-contact boiling evaporators are widely employed as the chemical reactors in the industrial processes [2,3]. The mixing quality and the critical parameters (such as mixing uniformity of bubbles, droplets, or particles, local bubble size distribution, gas holdup, interfacial area, etc.) in reactor design and control have a great influence on the performance of contactors [4,5]. Direct imaging technology is an effective and convenient method for the estimation of those critical parameters [6,7]. To the best of our knowledge, many researchers have carried out this study thoroughly using numerous techniques including Doppler anemometry techniques [8], tomographic techniques [9], invasive probe techniques, and direct imaging techniques [10]. Additionally, image analysis with advanced mathematical methods, regarded as a normal practice, is gaining importance for object identification [11,12].

On the one hand, mixing uniformity of objects (bubbles, droplets, or particles) has been considered [13,14]. The purpose of mixing is to obtain homogeneous [15]. It has a decisive impact on the overall performance of reaction processes. There is therefore an increased desire for measuring and comparing mixing performance [16,17]. The efficient evaluation of mixing uniformity is also required in the boiling heat transfer process which is one of the most efficient kinds of heat transfer processes widely used in numerous engineering systems. The resulting improvement heat transfer performance is believed on how uniformly the discrete phase is mixed into the continuous phase. The bubble detection problem is not easy to solve because the bubbles are not transparent when imaging inside a same industrial process, which causes the bubble appearance to vary. For granular materials, the nonuniformity of porosity distribution within a specimen was evaluated

* Corresponding authors at: State Key Laboratory of Complex Nonferrous Metal Resources Clean Utilization, Kunming University of Science and Technology, Kunming 650093, PR China (J. Xu, H. Wang) and School of Mathematics, University of Manchester, Manchester M13 9PL, UK (J. Pan).

E-mail addresses: qingtaixiao2016@kmust.edu.cn (Q. Xiao), xujianxina@163.com (J. Xu), jianxin.pan@manchester.ac.uk (J. Pan), wanghua65@163.com (H. Wang).

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using imaging techniques [18]. The literature concerning bubbling is extensive [19]. There is also homogeneous bubbling regimes where the size of the bubbles present little variation in heat transfer process [3]. For the air-water system, a photographic methodology was used to experimentally determine in a direct-contact evaporator under different operating conditions [2]. Moreover, the authors also developed a sparger model for a non-coalescing system and using bubble formation models for isothermal and non-isothermal conditions [20]. Coënt et al. proposed a non-intrusive method to follow the blending of powders and viscous liquid in a classical reactor under different agitation conditions by taking a series of images and analyses them [21].

On the other hand, the shape feature parameters of bubbles are also considered. The bubble size distribution (BSD) of the discrete phases in multiphase systems such as the BSD of bubbles in gas-liquid or gas-liquid-solid systems is significant for the operation of the specific applications. The knowledge of BSD can enhance the understanding of mixing and heat and mass transfer properties for design and scale-up of the operations [10]. The direct imaging technique has been a common technique for BSD measurement in multiphase systems [22,23]. In a direct-contact contactor, Busciglio et al. employed particle image velocity techniques coupled with advanced image processing tools to measure local features of gas-liquid dispersions, such as bubble size, gas hold-up and interfacial area [24,4,5]. Kalbfleisch and Siddiqui (2017) experimentally investigated the influence of a mesh-type bubble breaker in a two-phase vertical co-flow using high-speed imaging [25]. The effect of surfactant addition on void fraction distributions has been investigated by Kleinbart et al. [26]. Statistical theories coupled image processing techniques are receiving an increasing interest for measuring flow quantities and local bubble distribution in multiphase flow mechanically agitated vessels [27,19]. It also provides powerful opportunities for characterising and quantifying the process complexities. Zafari et al. presented a method for segmentation of clustered partially overlapping objects with a shape that can be approximated using an ellipse [28].

Among those studies, several methods can be necessarily used to measure the critical parameters. Currently, a number of commonly used measurement techniques, able to access local information on dispersion properties has been devised over the years, including phase Doppler anemometer [29,30,8,31], capillary suction probe [29,32], digital imaging analysis [29,33,34], etc. The local (probe) results are obviously not representative of the global state of mixing. Recently, statistical image analysis and feature extraction methods are used to quantitatively characterize time-lapse images containing thousands of nascent aggregates [35]. The study of bubble swarm distributions in direct-contact heat exchanger was addressed experimentally [15]. Hence, the knowledge of the shape of the gas region in the gas-liquid two-phase flow is very important to improve the knowledge of the flow structure and flow pattern transition. However, none of the existing studies can provide this information. Aim of this work is that of providing a straightforward procedure able to extract the shape feature parameters of bubbles in a direct-contact evaporator. Also, the details of the hardware configuration and the software and the computations are described in this article. Bubbles images acquisition was carried out as previously referred [14]. These images are then treated, analyzed in the following sections.

Out of the above considerations, the remainder of this article is organized as follows. Section 2 begins with a direct-contact heat transfer platform manufactured previously [14] and the image processing routines to visualize the bubble formation as well as the medium gas bubble behavior within the direct contact heat exchanger (DCHE), and then introduces some region properties of bubble population, including perimeter, area, equivalent diameter and orientation. Section 3 provides the existing methods for quantifying bubble mixing state and some notable advantages of our investigation. Then the results and discussion, such as temporal mixing curves, mixing time estimated by above curves and association between a new index for characterizing the flow pattern and the average volumetric heat transfer coefficient, are presented in Section 4 while the conclusion is briefly summarized in Section 5.

2. Data acquisition and processing

2.1. Experimental study

The methodology proposed in this study is verified with the feature measurement of direct-contact heat transfer processes in a dynamic system. The experimental set-up used for conducting the evaporation experiments is represented in Fig. 1. In all runs, the gauge pressure in the line was kept equal to 1.0×10^5 Pa. Once the flow rate is determined, the cold fluid is taken to the heating system, which consists of an electric heater whose design temperature ranges from −160 °C to 225 °C. Two K-type thermocouples register the operating temperature of the heater. Aiming at minimising the energy loss from the fluid to the surroundings, cotton was coated around this part of the pipeline. The temperature of cold fluid is measured both at the outlet of electric heater and in the chamber on the sparger using K-type thermocouples, whose sensors are located in the middle of the sparger. The evaporator consists of a column 41.3 cm in inner diameter and 200 cm in height, at the bottom of which the nozzle, inlet of cold fluid and outlet of thermal fluid are placed and whose top are connected with outlet of cold fluid and inlet of thermal cold. Four thermometers, 50 cm in length, are placed vertically and isometrically in this column for measuring the mixture temperature.

In this present study, the mixing state of the two-phase flow was analyzed in the DCHE using the fast video recording technique. Bubble spots were filmed with 1280 × 720 pixels and RGB Color levels using a high-speed video camera, whose brand is PRAKTICA from Germany and by whose flash in house the required illumination was provided through adjusting the shutter speed setting. To proceed, all the pictures were extracted from the video and analyzed individually. The mixing and morphology of the bubbles were observed by the photographs taken as bmp files. The following image processing was performed with Matlab using the image processing toolbox and in-house functions (i.e., *imtophat*, *im2bw*, *imfilter*, and *imopen*).

2.2. Bubbles image preprocessing

Images were reduced to a window but avoiding the walls of the vessel and other parts of the mixer or devices which could interfere with the analysis. Typical bubbles images from the real DCHT (direct contact heat transfer) process contain a huge amount of bubbles and have a low image quality because of harsh conditions. Once the images extracted and the correct area selected the digital image processing steps were performed. Fig. 2a shows four bubble images of the heat transfer fluids. Digital image processing techniques have been widely used in many process industries for pattern recognition [36], such as the production line of porous powder metallurgy [37]. In this study, the shape feature parameters of bubbles in a direct-contact evaporator are examined by a computer vision technique. The time-lapse images were processed with Matlab using the Image Processing Toolbox (IPT) and in-house functions. The bubble images are also processed by an image processing tool, for instance, ImageJ or more sophisticated methods recently developed. For this current research, we focused on the properties of transient bubbles in DCHE. The visualization of