International Communications in Heat and Mass Transfer 75 (2016) 162–168

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Accurate estimation of mixing time in a direct contact boiling heat transfer process using statistical methods☆

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A R T I C L E I N F O

Available online 16 April 2016

Keywords:
Direct contact heat transfer
Mixing
Betti number
Three sigma
Simulation

A B S T R A C T

A novel method relying on image analysis and statistics is developed to estimate the mixing time accurately in a direct-contact heat exchanger. The critical point determination of pseudo homogeneous process impact on the accurate estimation of mixing time is investigated by proposed a three-sigma (3σ) method, which satisfies approximately normal distribution and exceeding the range of $\mu - 3\sigma$ occurring twice. Quantitative comparisons of the mixing time are conducted with mean value method, slope method and standard deviation method. Results show that correlation degree and correlation coefficient for the mixing time estimated by 3σ method give good agreement with the volumetric heat transfer coefficient average. Additionally, quasi steady state is quantified by time intervals between inhomogeneous time and mixing time. Experiments and simulations confirmed that neglecting critical point could result in significant errors in mixing time estimation. This method is capable of estimating the mixing time obtained by different mixing curves (e.g., slope p) that vary at the beginning of mixing and rapidly become stabilized after fluctuations, which can be an alternative tool for practical engineering applications with good accuracy.

1. Introduction

Mixing plays a fundamental role in many industrial applications, but due to its complexity, theoretical approaches are very limited. Monitoring or measuring the mixing properly is of great importance from the practical point of view and for the validation of theoretical models as well [1]. The presence of a second phase makes the flow and mixing process of the continuous phase even complicated, especially for a direct contact boiling heat transfer process. However, to obtain high quality products and high efficiency processes, mixing must satisfy not only the needs of mass and heat transport but also the required homogeneity in the vessel in the shortest time. It is thus believed that the information related to macro-mixing is very important to control the performance of reactions occurring in the continuous phase in the presence of immiscible oil drops [2]. The macro-mixing is usually characterized by mixing time, i.e., the time required to achieve certain degree of homogeneity of an inert tracer or object. Mixing time is an important performance indicator for liquid–liquid stirred system. The mixing time in the presence of immiscible oil drops is sensitive to many variables such as agitation speed, impeller clearance, oil volume fraction and oil viscosity, etc. [3].

The accuracy requirements of the mixing time for different scales and processes are not the same. For example, mixing time of metallurgical reaction process can take up to several hours, and error of a few seconds or even minutes has little effect on reaction process. In addition accurate determination of the mixing time is essential in orbitally shaken bioreactors for the optimization of mixing processes and minimization of concentration gradients that can be deleterious to cell cultures [4]. Both mixing speed and phase transition time in the direct contact boiling heat transfer process are fast. Accurate characterization of mixing time is not only essential for the evaluation of mixing effects and optimization of heat transfer process but also can precisely control the reaction time and evolution of mixing homogeneity over time. Also, an accurate mixing time is critical to appropriately evaluate computational fluid dynamics (CFD) models and then enhances equipment understanding and develops scale down models for process characterization and design space definition during late stage process development [5].

Over the past years, many researchers studied mixing time and a lot of measurement methods appeared. There is however no universally accepted method for the measurement of mixing time mainly because each method has its own limitations, such as conductivity [6], pH [5], the dual indicator system method [3], tracer concentration [7,8,9,10], electrical resistance tomography [1], coloration decoloration methods

☆ Communicated by W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.04.012

[11], the box counting with erosions method [12], and Betti numbers with analysis [13]. Some limitations have been reported in details [11]. Of all the above techniques, the Betti numbers is one of the most valuable methods to determine mixing time and acquire more information of mixing process, which can successfully quantify mixing time, development of mixing, degree of homogeneity, and inhomogeneity of mixture. It has been applied to a direct contact boiling heat transfer process for characterizing the evolution of bubbles swarm. However, we found that mixing time determined by Betti numbers method exhibits a similar trend to those obtained by different evaluating indexes, such as the slope p [12], pH, tracer concentration c_t, the percentage of mixed pixels M (%) [11], and the standard deviation (σ_G) [3]. These indexes vary at the beginning of the mixing and rapidly become stabilized after fluctuations. These fluctuations are due to the heterogeneity of the mixture. It is inevitable that the critical point determination of pseudo-homogeneous process impacts on the accurate estimation of mixing time, which has often been neglected. A literature survey shows that mean value of Betti number (mean method) [13], slope p (slope method) [12], and standard deviation (SD method) with a selected threshold [4] are mainly used to determine the critical point of mixing time. Much less work has been published regarding the accurate estimations of mixing time, especially the critical point determination impact. The idea of a three-sigma method is inspired and motivated by statistical process control (SPC). According to Woodall [17], SPC can generally be divided into two phases. The data of phase I are clean gathered under stable operating conditions, whereas the major of phase II is to detect any changes in the proles. The 3σ principle is that if the sample data come from a normal distribution $N(\mu, \sigma^2)$, most of the data (99.73%) will lie within the range $[\mu - 3\sigma, \mu + 3\sigma]$. It is applied to detect outliers for the sample in the field of quality control. If a production process is normal, the product specification will lie within the range $\mu \pm 3\sigma$ of standard value. Otherwise, the production process is regarded as abnormal. Analogously, a modified three-sigma edit test has been successfully used in distributed self fault diagnosis algorithm for large scale wireless sensor networks [18]. Our study confirmed that neglecting critical point response time could result in significant errors in mixing time estimation.

2. Experiments and methodology

Experiments are carried out in a direct-contact heat exchanger (DCHE). The setup and the principle are shown in Fig. 1. The images were captured using a high speed camera. Heat transfer fluid (HTF) is the continuous phase, and the refrigerant R-245fa (1, 1, 1, 3, 3 pentafluoropropane) is the dispersed phase. The settings of the experimental plan affecting the heat transfer performance of the tested DCHE are obtained through the orthogonal array experimental design method. As listed in Huang et al. [13], four different parameters, including the height of the HTF, the initial heat transfer temperature difference, and the low rate of refrigerant and HTF, are selected to investigate the effect of critical point on mixing time estimation. The numbers L_1–L_9 denote different experimental levels, as follows: 1—direct contact evaporator, 2—electric heater, 3—gear oil pump, 4—centrifugal pump, 5—storage vessel, 6—plate condenser, 7—liquid mass flow meter, 8—gas mass flow meter, 9—stop valve, 10—check valve, 11—manual modulation valve, 12—camera.

In algebraic topology, the zeroth Betti number β_0 equals the number of connected components that make up the space and the first Betti number β_1 provides a measure of the number of tunnels in the structure [19]. According to Xu et al. (2011), the Betti numbers can be applied to quantify the efficiency of multiphase mixing. The zeroth Betti number β_0 simply represents the number of pieces in the patterns, and the first Betti number β_1 represents the number of the holes in the domain [20]. According to Huang et al. (2014), the Betti numbers can be applied to characterize the heterogeneous and pseudo-homogeneous bubbling regimes. The zeroth Betti number β_0 represents the number of continuous phases, and the first Betti number β_1 represents the number of bubble swarms [13].

It is true that the fluctuation of signal is very large in our experimental cases. Betti numbers fluctuations is a normal state in the mixing process, it is due to the measurement equipment error or other random noise. However, the fluctuation of signal stays within a rational broad range. Moreover, the top hat transform is used before to suppress the background of the original image and to eliminate noise and enhance the image [13]. In our work, the processing before help us obtain the identifiable image, results show that mixing time can be estimate accuracy in this case. Thus, the reasonable variability does not have a huge influence on the determination method after adequate image processing technology.

2.1. Mixing pattern and selection of mixing criteria

The selection of mixing criteria to estimate the final mixing time is important in order to obtain objective and reliable estimates [4]. In this study [13], image analysis is used to characterize the mixture of bubbles swarm in a direct contact heat transfer process by Betti numbers properties. Indeed, the time profile of the first Betti numbers of an image gives information on the degree of mixing. These digital patterns are analyzed by computational homology method which is employed to perform the Betti numbers analysis of binary images. The bubbles' images obtained were processed with the MATLAB software.

2.2. Three-sigma method (3σ method)

An event is considered to be practically impossible if it lies in the region of values of the normal distribution of a random variable at a distance from its mathematical expectation of more than three times the

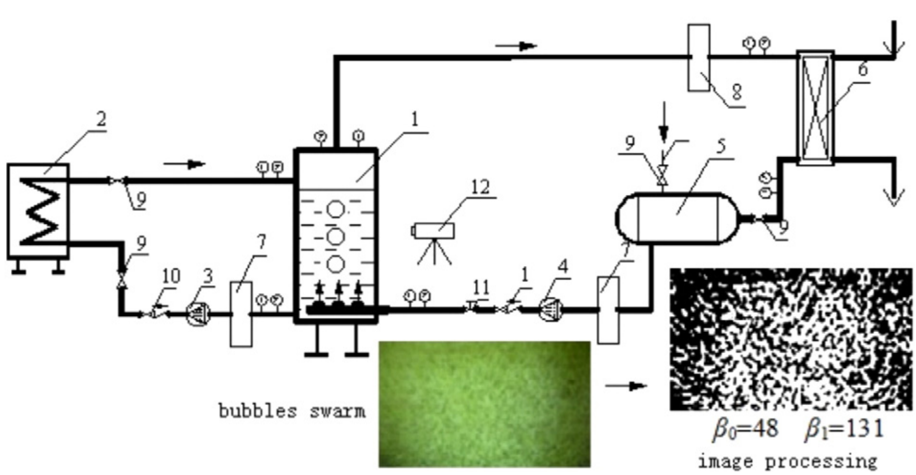

Fig. 1. Scheme of experimental equipment.