Ultrasonics xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Ultrasonics

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

In-line mixing states monitoring of suspensions using ultrasonic reflection technique

Xiaobin Zhan, Yili Yang, Jian Liang, Dajun Zou, Jiaqi Zhang, Luyi Feng, Tielin Shi, Xiwen Li *

State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan 430074, China

ARTICLE INFO

Article history:
Received 23 November 2014
Received in revised form 18 October 2015
Accepted 26 October 2015
Available online xxxx

Keywords:
Ultrasonic
Solid–liquid mixing
Mixing state
Suspensions
Homogeneity

ABSTRACT

Based on the measurement of echo signal changes caused by different concentration distributions in the mixing process, a simple ultrasonic reflection technique is proposed for in-line monitoring of the mixing states of suspensions in an agitated tank in this study. The relation between the echo signals and the concentration of suspensions is studied, and the mixing process of suspensions is tracked by in-line measurement of ultrasonic echo signals using two ultrasonic sensors. Through the analysis of echo signals over time, the mixing states of suspensions are obtained, and the homogeneity of suspensions is quantified. With the proposed technique, the effects of impeller diameter and agitation speed on the mixing process are studied, and the optimal agitation speed and the minimum mixing time to achieve the maximum homogeneity are acquired under different operating conditions and design parameters. The proposed technique is stable and feasible and shows great potential for in-line monitoring of mixing states of suspensions.

1. Introduction

Mixing is a fundamental and important process which has a wide range of applications in the fields like fine chemicals, mineral processing and polymer processing [1]. The mixing states have significant effects on products [2]. For example, the mixing state of solid propellant slurry directly affects its mechanical properties and combustion characteristics [3]. The mixing states of suspensions depend on the operating conditions (e.g. the agitation speed and the mixing time), the design parameters (such as the impeller diameter) and so on [4]. In general, the higher the agitation speed is and the longer the mixing time is, the better the homogeneity of suspensions is. However, once the suspensions reach the maximum achievable homogeneity, it will be useless for the improvement of suspensions performance and even inevitably raise the cost of production to further increase the impeller speed and/or prolong the mixing time. At the same time, it is not easy to judge whether these parameters are appropriate. Therefore, the studies on the mixing states of suspensions will provide the researchers an access to the optimal operating conditions and design parameters.

So far, several methods have been proposed to study the mixing states of suspensions. The investigation of particle suspension characteristics with conductivity probes is accurate but intrusive, and subject to the flow disturbance to a certain extent [5]. Visual methods are commonly used to determine the mixing states of suspensions through observing the particle remaining time [6], the cloud height [7] or the settled bed height [8]. Optical methods can be used to measure the solid concentration profiles through measuring the light intensity attenuation [9] or the multiple light scattering [10]. Despite the advantage that visual methods and optical methods have no disturbance to the flow patterns, it is necessary to fabricate transparent agitated tanks in order to observe the mixing states of suspensions. The fabrication of transparent agitated tanks can be easily realized at the laboratory scale but is impractical for large-scale industrial applications. The pressure gauge method [11] is very suitable to measure the fraction of suspended solids in the industrial application, but this method is likely to be affected by the flow patterns. Recently, the industrial process tomography (IPT) techniques, e.g., electrical resistance tomography (ERT) [12], electrical impedance tomography (EIT) [13] and magnetic resonance imaging (MRI) [14], are developed to study the mixing states of suspensions. Nevertheless, IPT techniques are generally confronted with the problems of high cost and complexity.

Owing to the advantages of stability and cost-effectiveness [15], ultrasonic sensors can provide real-time measurement of the

* Corresponding author at: 1037 Luoyu Road, Wuhan 430074, China. Tel.: +86 27 87542079; fax: +86 27 87559004.
E-mail address: xiwenli@hust.edu.cn (X. Li).

http://dx.doi.org/10.1016/j.ultras.2015.10.024
0041-624X/© 2015 Published by Elsevier B.V.

mixing states of suspensions with high temporal and spatial resolution [16]. The ultrasonic techniques have been extensively applied in the process industry [17,18]. Stelzer et al. [19] adopted the ultrasonic crystallization monitoring technique to quantify the industrial crystallization process. Hunter et al. [20] studied the settling and sedimentation processes in particle dispersion with the ultrasonic velocimetry technique. A wealth of literature is available on the application of ultrasonic methods for the measurement of the suspensions properties (e.g. density [21], concentration [22] and particle size [23]). However, the studies regarding of the mixing process of suspensions are still limited. Bamberger and Greenwood [24] put forward a simple single frequency ultrasonic technique to in-line measure the ultrasonic attenuation and track the slurry mixing process, but ultrasonic sensors were completely immersed in suspensions, which exerted certain effects on the mixing flow field. Yucel and Coupland [25] mounted a single transmitter–receiver pair in the agitated tank to measure the mixing, agglomeration and quiescent sedimentation of sucrose crystals in vegetable oil. This study gave a good indication for the kinetics and extent of the mixing process of suspensions and described the steady mixing state. Nevertheless, the mixing states of suspensions and the relations among the mixing states, mixing time, homogeneity and mixing parameters of suspensions need further studies and the ultrasonic techniques should be further improved to better meet the requirements of monitoring the mixing states of suspensions.

In this study, a simple ultrasonic reflection technique is proposed and the mixing process and states of small particle suspensions (the non-dimensional wave number $kr \ll 1$ [23]) with moderate volume concentration in an agitated tank are monitored using two ultrasonic sensors. The criteria to determine the states of suspensions are presented and the homogeneity of suspensions is quantified. The effects of the impeller diameter and the agitation speed on the mixing process are studied. The optimal agitation speed and the minimum mixing time to achieve the maximum homogeneity under different testing conditions are also discussed. The proposed technique can find facile and inexpensive applications in both laboratories and the industrial field.

2. Materials and methods

2.1. Experimental setup

The experimental setup is shown in Fig. 1(a). The mixing system consisted of a transparent flat-bottomed cylindrical tank, with an inner diameter (T) of 130 mm and a height (h) of 150 mm, respectively. To avoid dead zones as well as vortexes, four standard baffles, with the width (B) of $T/12$, were symmetrically fixed to the inner wall of agitated tank [4]. Both the agitated tank and the baffles were made of polymethyl methacrylate (PMMA). The agitation speed was adjusted with an adjustable-speed motor. The mixing system was agitated using four-bladed 45° pitched blade turbine (PBT-4) impellers and the impeller diameters (D) were 50 mm, 60 mm and 70 mm, respectively. The clearance (C) between the impeller and the bottom of agitated tank was one fourth of the height of suspensions (H).

The ultrasonic system was composed of two Olympus V306-SU ultrasonic immersion sensors (with a center frequency of 2.25 MHz) and two ultrasonic Pulser/Receiver units in the pulse-echo mode. One end of the buffer rod was bonded to the ultrasonic sensor TRA, while the other end was slightly submerged into the suspensions and positioned parallel to the bottom of the agitated tank which acted as a reflector plate. The buffer rod was made of PMMA as well. The ultrasonic sensor TRB was bonded to the bottom of the agitated tank using couplant. The two sensors were mounted close to the wall of agitated tank and separated by the

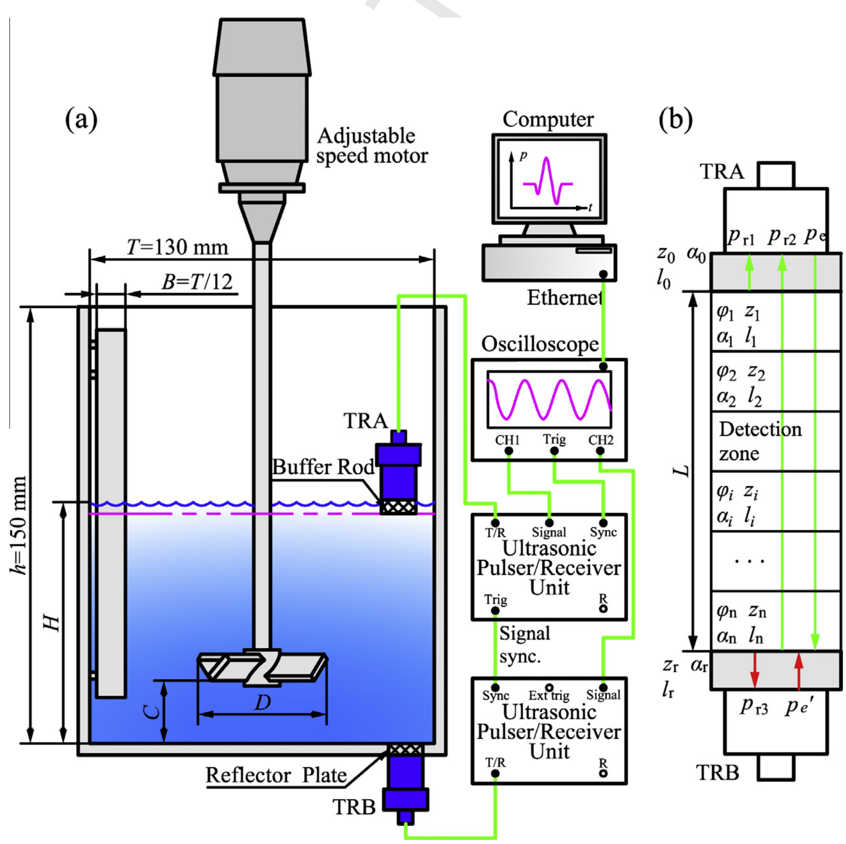

Fig. 1. (a) The experimental setup. (b) The schematic measuring principle.