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Enhancement of liquid–liquid mixing in a mixer-settler by a double rigid-flexible combination impeller

Zuohua Liu [a,b,*], Xiongpan Zheng [a,b], Di Liu [a,b,c], Yundong Wang [c], Changyuan Tao [a,b]

[a] School of Chemistry and Chemical Engineering, Chongqing University, Chongqing 400044, China
[b] Chongqing Key Laboratory of Chemical Process for Clean Energy and Resource Utilization, Chongqing 400044, China
[c] Department of Chemical Engineering, Tsinghua University, Beijing 100084, China

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ABSTRACT

Mixing is crucial in the dispersion of two immiscible fluids. The rational design of an impeller is necessary to form suitable flow conditions and improve fluid mixing efficiency. A double rigid-flexible combination impeller was designed by connecting the upper and lower rigid impeller blades with flexible pieces. Experimental measurements were performed in a laboratory-scale mixer-settler under different impeller types. The largest Lyapunov exponent (LLE) and multi-scale entropy (MSE) were investigated using Matlab. Results showed that the double rigid-flexible combination impeller enhanced liquid–liquid mixing in the mixer-settler through the multiple-body motion behavior triggered by the swings of flexible pieces. At the optimum mixing point of each impeller, the LLEs of the double impeller, double rigid combination impeller, and double rigid-flexible combination impeller were 0.018, 0.055, and 0.057, respectively. At 75 rpm, the MSE of the combination impellers was obviously greater than that of the double impeller, and the rigid-flexible combination impeller had larger MSE than the double rigid combination impeller. The mixing efficiency of the rigid-flexible combination impeller increased with increasing width and quantity of the flexible piece. The quantity of rigid blade slice also influenced the enhancement of mixing ability. The double rigid-flexible combination impeller intensified the chaotic mixing of the two-phase fluid by changing the flow field structure and energy dissipation mode, ultimately achieving an efficient-mixing operation.

1. Introduction

Stirred tanks that involve two immiscible liquids are extensively used in chemical and metallurgical industries, such as suspension/emulsion polymerization, heterogeneous/phase-transfer catalytic chemical reaction, and hydrometallurgical solvent extraction [1]. The purpose of such an operation is to mix two phases and increase the interfacial area by intensifying the dispersion of one liquid into another and to consequently enhance the interphase heat/mass transfer and chemical reaction [2]. Mixing has an important function in these systems; this process controls liquid blending, liquid–liquid mass transfer, and chemical reactions. Mixing significantly affects product quality, yield, and process cost. Insufficient or excessive mixing may lead to wastage of processing time and raw materials and/or the formation of by-products [3,4].

Investigations previously conducted on liquid–liquid dispersion in stirred tanks principally focused on the dispersion characteristics of two phase and breakage and coalescence of droplets [5–10]. Liquid–liquid extraction in a mixer-settler is a typical non-linear, non-equilibrium, irreversible physical and chemical process [11–13]. Thus, liquid–liquid mixing in a mixer-settler is a highly complex chaotic process that exhibits spatiotemporal chaos behavior [14].

Chaotic mixing is an effective method of improving the mixing efficiency in a stirred tank [15]. To date, various methods of chaotic mixing in stirred tanks have been developed. These methods including turbulent flow, time-varying rotation [16], eccentric rotation [17,18], reciprocating stirring [19], and so on. These methods destroy the periodicity of moving fluid particles through dynamic disturbance and induce chaos within the flow field, thereby improving the mixing efficiency. However, these methods are not widely applied in the industry because of their instability and high cost. Therefore, we propose a rigid-flexible combination impeller.

Liu et al. [20,21] developed a rigid-flexible combined impeller that improves manganese leaching rate and thus shortens the ore

* Corresponding author at: Chongqing University, School of Chemistry and Chemical Engineering, Chongqing 400044, China. Tel.: +86 15922926287.
E-mail address: liuzuohua@cqu.edu.cn (Z. Liu).

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Nomenclature

D_T	side length of square mixer (m)
D	diameter of rigid impeller (m)
h	distance between upper and lower layers (m)
h_1	off-bottom clearance (m)
LLE	largest Lyapunov exponent
m	embedding dimension
MSE	multi-scale entropy
N	rotational speed (rpm)
n	time series length
r	threshold
std	standard deviation
τ	scale factor

leaching time. Karray et al. [22] analyzed the flow-solid coupling behavior of a flexible anchor agitator and found that the fluid has an important influence on flexible paddle deformation. Campbell and Paterson [23] studied the flow-solid coupling motion behavior in flexible turbines and observed that the deformation of flexible paddles could induce the coupling movement of flow and impeller paddles. These studies suggest that the rational design of a rigid-flexible combination impeller can enhance fluid mixing efficiency and reduce energy requirement.

Chaotic analyses have been conducted to study the mixing enhancement in steady laminar flows [24] and identify the characteristics of gas–liquid two-phase flow patterns [25]. Using chaotic analyses, Liu et al. [26,27] investigated the chaotic mixing performance of a high-viscosity fluid that is intensified by a flexible impeller and then explored the chaotic mixing in a stirred tank [28] and a mixer-settler [29]. However, few studies have focused on the correlation between the impeller structure and chaotic characteristic of liquid–liquid systems.

The present study aims to conduct experimental measurements of chaotic mixing in a laboratory-scale mixer-settler with a double rigid-flexible combination impeller. The mixing performance in the mixer-settler was investigated for various types of double rigid-flexible combination impeller. Then, the mixing performance was compared by non-linear chaotic analyses, including Lyapunov exponent (LLE) and multi-scale entropy (MSE). The mixed renderings of oil and water were also obtained simultaneously.

2. Materials and methods

2.1. Experimental apparatus

The experiments were performed in a mixer-settler made of transparent poly methyl-methacrylate (PMMA) with a dimension of 0.8 m × 0.2 m × 0.33 m. The mixer was a square vessel with a side length of D_T = 0.2 m, and the diameter of the rigid impeller was D = 0.5D_T with six blades. This novel rigid-flexible combination impeller was made of two Rushton disc turbine (RDT) rigid impellers fixed to the agitator shaft and six flexible connection pieces. The flexible materials were connected to the rigid impeller by bolts (Fig. 1). The distance between the lower edge of the upper impeller and the upper edge of the lower layer h was 0.11 m, and the length of the flexible piece was 1.2 times of that distance. The off-bottom clearance (from the lower edge of the lower impeller to the entrance of mixture phase) of the impeller h_1 was fixed at 0.01 m for all experiments.

In the experiment, PVC and silicone were selected as flexible materials to construct the rigid-flexible combination impeller. The

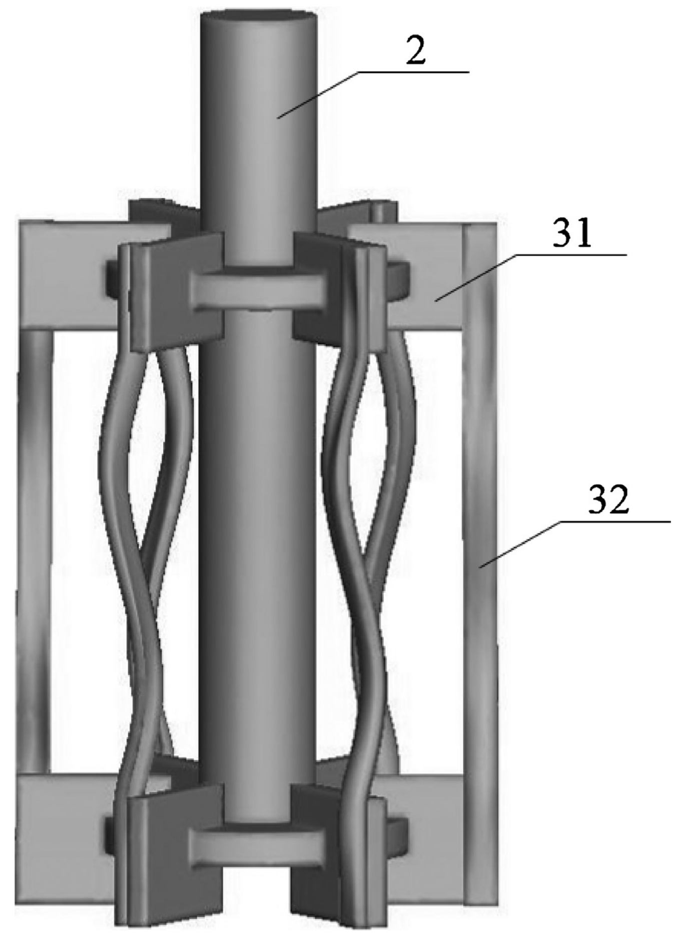

Fig. 1. Structure of double rigid-flexible combination impeller.
2, agitator shaft; 31, rigid blades of impeller; 32, organic flexible connection piece.

geometric characteristics of the impeller and mixer-settler are depicted in Figs. 1 and 2.

2.2. Experimental procedures

In all cases, the experiments were conducted at room temperature (25 ± 2 °C). All experiments were performed under liquid–liquid phase conditions. Tap water and kerosene were used as aqueous and organic phases, respectively, and the oil–water ratio in the feed was 1:5 (in volume). The experiment was continuously operated with kerosene and tap water as working fluids. As the dispersed liquid phase, kerosene was dyed to red using Sudan III to visualize the interface between the organic and aqueous phases. The physical properties of the liquids and flexible materials tested at room temperature are listed in Table 1.

For the mixer, agitation was provided by a 60 W tri-phase induction motor with rotational speed controlled by a variable frequency drive. In both cases, a digital tachometer was used to measure the impeller rotational speed.

The pressure time series was measured by a transducer based on a silica chip and a pressure sensor, which revealed small pressure variations [19]. The transducer was inserted into the mixer by side-wall ports placed above the impeller. The signal from the pressure transducer was amplified, and the time series were recorded and transferred to a personal computer using a data acquisition card (NI USB-6009) controlled by a LabView program. For each experimental run, a time history of 20 min was recorded and a sampling frequency of 600 Hz was adopted, and a time series