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Estimation of the micromixing time in the torus reactor by the application of the incorporation model

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ABSTRACT

On the basis of previous experimental results in a torus reactor, micromixing time is determined using the incorporation model. Obtained results allowed the characterisation of the performances of this new configuration of reactor in comparison to other reactors, such as the stirred tank reactor. In addition, a correlation is proposed for each incorporation law, in order to determine the micromixing time from the experimental micromixedness ratio (α). Finally, in terms of Kolmogorov's turbulence theory, a relationship between micromixing time and the local energy dissipation rate is obtained and compared to those previously published.

1. Introduction

In the context of sustainable development, industries are making efforts to improve their processes in order to reduce wastes and therefore contribute to preserve the environment; and among these efforts, the quest for new configurations of reactors more efficient, economic energetically and environment friendly.

Because of the disadvantages of the conventional reactors, it became necessary to search other configurations, such as the torus reactor which presents a promising alternative relative to the conventional stirred reactors. In this context, several studies were led in order to characterize this new reactor configuration [1–3]; among which the characterization of the micromixing efficiency in a torus reactor that was carried out in our laboratory [4]. In this previous study, the micromixing efficiency in the torus reactor was compared to those obtained in other configurations of the reactors. In addition, on the basis of the local energy dissipation rate (ϵ), the experimental results showed that the performances of the torus reactor were better than those of the stirred reactors. The determination of the characteristic time of micromixing was the object of several studies in different types of mixer by the application of appropriate models, particularly the incorporation model which was the aim of several applications. Yang et al. [5] have determined the micromixing time of viscous media in a micro-channel reactor by the application of the incorporation model and an iodide–iodate test reaction system. They noticed that the micromixing efficiency in a micro-channel reactor is better than in the stirred tank reactor.

When applying the incorporation model and the test reaction system iodide–iodate, Monnier et al. [6] and Fang et al. [7] estimated the micromixing time, respectively, in an ultrasound mixer and a static mixer. Their results showed that for the same energy dissipation, the micromixing times determined in those devices were lower than those obtained in the stirred tank reactors. Under same conditions than the above works, Liu et al. [8] estimated the micromixing time in a Couette flow reactor. They showed that, in a laminar flow regime, the estimated micromixing time remains unreasonably high, but in a turbulent vortex flow regime, the micromixing time decreased and reached values of about 10^{-3}–10^{-4} s.

Schaer et al. [9] have estimated the micromixing time of an impinging jets mixer placed in a stirred tank. Their results showed that the micromixing time decreased with the increase in the feed flow rate of impinging jets to reach values of micromixing time of about 4 ms. Therefore, they have suggested the use of this impinging jets mixer as an appropriate device for the rapid mixing of reactants, allowing to generate a high local energy dissipation capacity for high velocities of jets. On the other hand, it was

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Nomenclature

d_1	impeller diameter (mm)
N	Stirring speed (mn^{-1})
N_P	Power number
P_i	Feed location (i)
Q	Incorporation flow rate ($l\,s^{-1}$)
V	Reaction volume (litres)
X_s	Segregation index
Y	Ratio of sulphuric acid mole number consumed by reaction (2) divided by the total acid mole number injected
Y_{ST}	Value of Y in total segregation case
Z_t	Axial coordinate of feed location in the torus reactor by report the impeller (mm)
α	Micromixedness ratio (/)
$\bar{\epsilon}$	Mean rate of specific energy dissipation (W/kg)
ϵ	Local rate of specific energy dissipation (W/kg)
ν	Fluid kinematic (m^2/s)
ϕ	Proportionality constant

observed that the calculated energy dissipation rates, using computational fluid dynamics, are in good agreement with experimental data. Finally, for different volumes of stirred tank reactors, several studies [10,11] were realised to determine the characteristic time for micromixing on the basis of iodide–iodate test reaction and the incorporation model.

Despite several applications of the incorporation model, it can present like all other models some limits of validity related to some phenomena involved in the micromixing process which are not considered by the model. Therefore, significant differences can be observed between the experimental and theoretical values. Experimental techniques, such as the laser Doppler velocimetry (LDV) [12] and the particle image velocimetry (PIV) [13] can significantly improve the determination of local specific energy dissipation rate (ϵ), and thus the determination of the micromixing time by the use of Kolmogorov's turbulence theory. In addition to the problem related to the choice of a coherent model for the determination of the micromixing time, it was observed that the iodide–iodate method is not yet a quantitative method for the determination of micromixing time. The kinetic model mentioned above gave qualitatively consistent results, but quantitatively the comparison of different models published previously showed a large difference in the iodine yield.

In a previous short communication, Bourne [14] showed that the difference in the results, corresponding to different Kinetics models already published, depends especially on reagent concentrations and ionic strength used in mixing experiments. In the same context, Kölbl [15] raised other problems concerning iodide–iodate reaction method. Among those, the solubility problem and the choice of the mixing device used to study the chemical kinetics of the fast chemical reactions. Finally, Fournier [16] observed also that quantitatively the results depended on the reagent concentration, consequently, she suggested that the kinetic study of iodide–iodate test reaction should continue in perspective to validate it in a wider concentration range.

The aim of this study consists to estimate, based on the obtained results in previous works and the incorporation model, the micromixing time in a new configuration of torus reactor. Obtained results will help assess the local energy dissipation rate (ϵ) in order to compare the torus reactor performances to those of other devices. This comparison will be limited only to the studies having used the same incorporation model and the same iodide–iodate test reaction system.

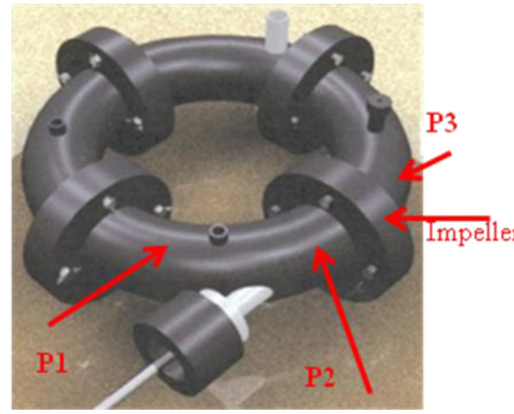

Fig. 1. Schematic of the torus reactor used in this work.

2. Experimental section

2.1. Description of the experimental device

The torus reactor used in this study is similar to that used by Nouri et al. [4]. It is constructed from four poly-vinyl chloride bends of inner diameter (D_t) 55 mm. The mean length of the torus reactor is 884 mm, which corresponds to a volume of 2.1 l (Fig. 1). The mixing and the flow are achieved by a marine screw impeller of diameter *d*, driven by a variable speed motor (Heidolph RZR 2021). The geometrical characteristics of the torus reactor and the feed locations of the injected sulphuric acid, relative to the impeller plane, are given in Table 1.

2.2. Operating conditions

The experimental conditions adopted in this work are the same as those used in previous work [4]. Obtained results show that for an injection time greater than 140 s the segregation index becomes constant, which corresponds to a flow rate of about 1 ml/min. Concerning the experimental procedure of successive injections, it was found that, for four successive injections the segregation index remains practically constant for a given stirring speed.

2.3. Experimental test reaction

The chemical method adopted in this study is the same than that used in previous work [4,10,11,16]. it is based on a competitive parallel reactions system and described by the following scheme.

$$H_2BO_3^- + H^+ \xrightarrow{k_1} H_3BO_3 \quad \text{quasi-instantaneous} \tag{1}$$

$$5I^- + IO_3^- + 6H^+ \xrightarrow{k_2} 3I_2 + 3H_2O \quad \text{very fast} \tag{2}$$

$$I_2 + I^- \underset{k_3}{\overset{k_3}{\rightleftarrows}} I_3^- \tag{3}$$

The first reaction (1) is instantaneous; the rate of the reaction is given by

$$r_1 = k_1[C_{H^+}][C_{H_2BO_3^-}] \tag{4}$$

where k_1 is the rate constant of the reaction (1), equal to $10^{11}\,l\,mol^{-1}\,s^{-1}$ at 25 °C.

The kinetic model of the second reaction iodide–iodate (Dushman reaction) adopted in this work is the same than that determined by Guichardon et al. [17] and applied by Fournier et al. [10]. The rate of this reaction is given by:

$$r_2 = k_2[C_{H^+}]^2[C_{I^-}]^2[C_{IO_3^-}] \tag{5}$$