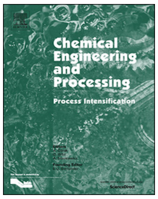
Chemical Engineering & Processing: Process Intensification 130 (2018) 11–18

Contents lists available at ScienceDirect

Chemical Engineering & Processing: Process Intensification

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



Gas to liquid mass transfer in mixing system with application of rotating magnetic field

Rafał Rakoczy[a,*], Maciej Konopacki[a], Joanna Lechowska[a], Monika Bubnowska[a], Anna Hürter[a], Marian Kordas[a], Karol Fijałkowski[b]

[a] West Pomeranian University of Technology, Szczecin, Faculty of Chemical Technology and Engineering, 42 Piastów Avenue, 71-065 Szczecin, Poland
[b] West Pomeranian University of Technology, Szczecin, Faculty of Biotechnology and Animal Husbandry, 45 Piastów Avenue, 70-311 Szczecin, Poland

ARTICLE INFO

Keywords:
Gas-liquid mass transfer
Gas-liquid mass transfer coefficient
Oxygen transfer
Stirrer tank reactor
Rotating magnetic field

ABSTRACT

This study reports a new multiphase device, the mixer equipped with the rotating magnetic field (RMF) generator, which shows high rates of gas-liquid mass transfer in comparison to a convectional mixer with impeller. The volumetric gas-liquid mass transfer coefficient k_La in the tested apparatus with application of the RMF increases with increasing magnetic field and superficial gas velocity. It is shown that the mass transfer process under the RMF action has significantly higher values of the k_La coefficient than the conventional Rushton turbine or the synergistic effect of the rotational Rushton turbine and the RMF generator. The empirical relationships between this coefficient and the operational parameters obtained in this work can provide helpful guidance for design and operation of set-up equipped with the RMF or the mechanical mixer supported by RMF.

1. Introduction

The oxygen transfer rate is often the limiting factor in bioprocessing. Improving mass transfer in the gas-liquid systems may be achieved by changing certain reaction parameters or apparatus. It has been demonstrated that the mass transfer is influenced by several factors such as the flow pattern, bubbles sizes, physical properties of fluids, operational conditions and geometrical parameters of the applied apparatus [1]. The oxygen transfer may be quantitatively defined by means of the volumetric oxygen transfer coefficient, k_La [2]. This coefficient is affected by many factors such as mechanical design, the geometry of mixer and air distributor, operating conditions or hydrodynamics [3,4].

Data from several sourced have identified that the stirred tank technology is more versatile to obtain good mixing conditions in the gas-liquid systems [5,6]. Gas-liquid stirred vessels are widely employed to carry out chemical or biochemical reactions involving a gas and a liquid phase [7]. A stirred tank is a very often used contractor, in which a gas is distributed in a liquid, in the form of bubbles and an agitation system which causes an intense mixing of the liquid phase [8,9]. Another type of reactor widely used in bioprocessing is an airlift bioreactor which consists of a draft tube [10].

Stirred tank bioreactors are used in bioprocessing providing high values of mass transfer rate. One of the most important challenges in the operation of bioreactors is a non-uniform distribution of energy with direct consequences on gas-liquid transport rate. The mass transfer in these systems is influenced by the power input that drives the two-phase flow in the mixers [11]. It has been demonstrated that a high value of the mass transfer coefficient was obtained by a new type of self-inducing turbine [12,13]. Thus far, previous studies have shown that the various types of mixers were used in order to improve the mass transfer process [14,15].

Recently, alternative configurations for mechanical mixers have started to find applications in the gas-liquid mass transfer process. One of the examples are airlift reactors, these are used in operations that do not require mechanical stirring [16]. More recent attention has focused on the application of spinning fluids reactors. This apparatus is based on the centrifugal force field that generates fine bubbles and the high interfacial area [17]. Previous research has established that the multi-impeller agitators are also used in order to increase gas hold-up and mass transfer ratio in gas-liquid systems [18]. Data from several studies suggest that the mass transfer in gas-liquid system may be realized by means of microchannels [19,20]. To date, studies have indicated that the volumetric gas-liquid mass transfer coefficient, k_La, may be increased by using a rotor-stator spinning disc reactor [21]. Previous research has established that a rotating spiral device is applied to enhance mass transfer ratio in the gas-liquid systems [22]. Data from several studies suggest that the k_La coefficient is higher for monolith reactors than for airlift and bubble columns [23]. It has been demonstrated that the rotating packed bed with split packing may be treated as a novel gas-liquid contractor. This type of apparatus intensifies the

---

[*] Corresponding author.
E-mail address: rrakoczy@zut.edu.pl (R. Rakoczy).

https://doi.org/10.1016/j.cep.2018.05.013
Received 26 March 2018; Received in revised form 18 May 2018; Accepted 23 May 2018

Nomenclature

B_{avg}	averaged values of magnetic field induction, T
E	enhancement factor
J	the absorption flux of oxygen in the presence of dispersed phase (e.g. microorganism or solid phase), mol $O_2 \cdot m^{-2} \cdot s$
J_{RMF}	RMF-enhancement factor
J_0	the absorption flux without a dispersed phase, mol $O_2 \cdot m^{-2} \cdot s$
J_{1TR}	enhancement factor for mixing system with single RT
J_{2TR}	enhancement factor for mixing system with double RT
$\left[J\|_{\substack{RMF\\1\,TR}}\right]_1$	enhancement factor for mixing system with RMF action with single RT
$\left[J\|_{\substack{RMF\\2\,TR}}\right]_2$	enhancement factor for mixing system with RMF action with double RT
$k_L a$	volumetric liquid-side mass transfer coefficient, s^{-1}
$k_L a\|_{RMF}$	volumetric oxygen transfer coefficient with the action of RMF, s^{-1}
$k_L a\|_{\substack{RMF=0\\TR=0}}$	volumetric oxygen transfer coefficient for the mixing system without the action of RMF and mechanical mixing, s^{-1}
$k_L a\|_{\substack{RMF\\1\,TR}}$	oxygen transfer coefficient for the mixing system with the action of RMF and mechanical mixing (single RT), s^{-1}
$k_L a\|_{\substack{RMF\\2\,TR}}$	oxygen transfer coefficient for the mixing system with the action of RMF and mechanical mixing (double RTs), s^{-1}
$k_L a\|_{1\,TR}$	volumetric oxygen transfer for mixing system with single RT, s^{-1}
$k_L a\|_{2\,TR}$	volumetric oxygen transfer for mixing system with double RT, s^{-1}
N	impeller speed, rpm
p	constant
w_s	gas superficial velocity, $m \cdot s^{-1}$

Subscripts

1 TR	single Rushton turbine
2 TR	double Rushton turbine
RMF	rotating magnetic field
RT	Rushton turbine

mass transfer process controlled by gas-side resistance [24]. In order to overcome the limitations (e.g. problem related to mixing efficiency), the oscillatory flow reactors have been tested [25]. Detailed examination of the high-throughput microporous tube-in-tube microchannel reactor by Chen et al. [26] showed that this apparatus is used to enhance the mass transfer process. The gas-liquid mass transfer may be also increased by applying a mixing insert [27]. The airlift reactor may be also modified by using helical flow promotes [28].

A novel approach to the mass transfer is focused on the application of the various types of the magnetic field [29]. Up to now, several studies have demonstrated that the increase of magnetic strength enhanced the volumetric mass transfer coefficient in the gas-liquid systems [30–32]. In a study conducted by Rakoczy et al. [33,34]it was shown that the external magnetic field may be successfully applied as the reinforcing factor in the mass transfer process in the gas-liquid system.

From the data available in a literature it is clear that the attention has not been focused on the experimental studies of the gas-liquid transfer process in a mixing system with a rotational impeller and the generator of rotating magnetic field (RMF). Therefore, the main aim of this work is to study the influence of the mixing system with the RMF generator, the mixer with the Rushton turbine (RT) and the hybrid mixing system (the magnetic field-assisted mixer with the application of RT).

2. Experimental details

2.1. Experimental set-up

A schematic sketch of the experimental set-up used in this experimental study is shown in Fig. 1.

This apparatus consisted of the housing (1) and the RMF generator (2). In the case of this experiment, the RMF was generated by using the three-phase stator of the squirrel cage induction motor. The a.c. transistorized inverter (3) was used to adjust the RMF frequency in the range of 10–50 Hz. This inverter was connected to the personal computer (4) equipped with the software to control the RMF generator. The temperature of the working liquid was controlled by the cooling system based on oil circulation in the heat exchanger (5), the pump (6) and water circulation in the internal coil (7). A total of 4 dm^3 of the working liquid (distilled water) was introduced into the vessel (8). The liquid temperature was equal to 20 °C. Nitrogen gas was used for elimination form the liquid. Air was injected into the tested liquid by using the membrane sparger (9). The applied sparger was enabled to obtain fine bubbles with narrow size distribution in the range between 0.5 and 3 mm. The superficial gas velocity was changed in the range between 0.001 – 0.005 $m \cdot s^{-1}$. The solved oxygen concentration in the tested liquid was measured by means of the recorder (10) connected with probes (11).

The mass transfer process in the gas-liquid system (air-distilled water system) was also affected by way of the RT. Fluid mixing was also carried out by conventional positioned singly or doubly on the same shaft. The applied mixing systems are presented in Fig. 2.

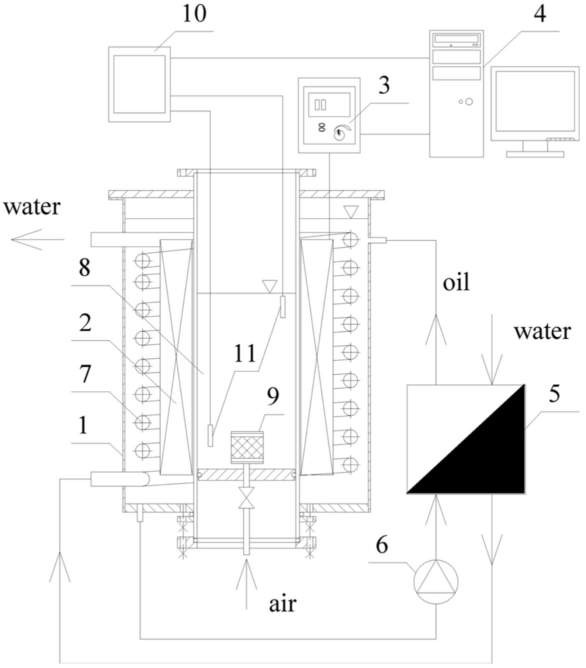


Fig. 1. The sketch of experimental set-up: 1 – housing, 2 – RMF generator; 3 – a.c. transistorized inverter; – personal computer; 5 – heat exchanger; 6 – pump; 7 – internal coil; 8 – vessel; 9 – membrane sparger; 10 – recorder; 11 – probes.