Chemical Engineering Journal 327 (2017) 608–617

Contents lists available at ScienceDirect

Chemical Engineering Journal

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

Effects of a rotating magnetic field on gas-liquid mass transfer coefficient

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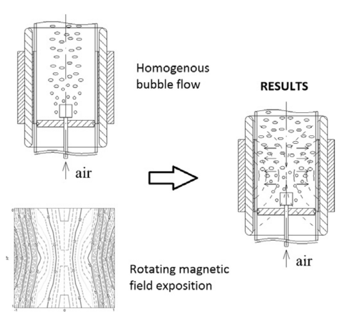
HIGHLIGHTS

- Investigations of the mixing system with a generator of RMF are presented.
- Gas-liquid mass transfer coefficients for the tested systems are obtained.
- Data indicate the enhancement of mass transfer process under the action of RMF.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 16 April 2017
Received in revised form 22 June 2017
Accepted 23 June 2017
Available online 26 June 2017

Keywords:
Gas-liquid mass transfer coefficient
Rotating magnetic field
Magnetic mixer
Mathematical correlation

ABSTRACT

The mass transfer coefficient k_L is a key parameter for an aeration mixing design and optimization. From the practical point of view, the volume-related liquid side mass transfer coefficient (k_La) is commonly applied in the gas-liquid contacting devices. This parameter is affected by several factors such as geometrical and operational characteristics of the vessel, media composition and microorganisms. Moreover, the rate of the mass transfer between two phases depends on the physicochemical properties of the mixed system, the interface surface and the hydrodynamic conditions of the process. The present study aim at: (i) analyzing the influence of the rotating magnetic field (RMF) on the aeration process of various types of liquids and (ii) quantifying the obtained liquid volumetric mass transfer coefficients (k_La) by using the new type of relationships. To quantify the impact of RMF on the hydrodynamic conditions, modelling using various correlations issued from the theoretical considerations was performed. The results shown that the hydrodynamic parameters analyzed depend mainly on the applied RMF magnetic induction and the composition of the liquid subjected to exposure.

1. Introduction

Most microbial processes are aerobic, and are mostly carried out in medium containing inorganic and organic substances. In biotechnological processes, oxygen is an important nutrient that is used by microorganisms for growth, maintenance and metabolite production [35]. The oxygen transfer rate OTR) is the limiting factor in the bioprocess due to the low solubility in the liquid [26]. Mass transfer from gas phase to liquid phase is identified as a rate-limiting step in bioprocesses [40]. Therefore, it is important to ensure an adequate delivery of oxygen from a gas stream to the culture medium [14]. Practically, the gas-liquid mass transfer is described as proportional to the concentration gradient, where the proportionality is defined by means of the volumetric

Abbreviations: BC, bacterial cellulose; HS, Hestrin-Schramm; MF, magnetic field; OTR, oxygen transfer rate; OUR, oxygen uptake by microorganisms; RMF, rotating magnetic field; SMF, , static magnetic field.

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http://dx.doi.org/10.1016/j.cej.2017.06.132
1385-8947/

Nomenclature

a	interfacial area, m^{-1}
B	magnetic field intensity, $kg{\cdot}A^{-1}{\cdot}s^{-2}$
c	instantaneous concentration of dissolved oxygen, $kmol{\cdot}m^{-3}$
c^*	saturation concentration of dissolved oxygen, $kmol{\cdot}m^{-3}$
c_0	initial concentration of dissolved oxygen, $kmol{\cdot}m^{-3}$
E	electrical field, $V{\cdot}m^{-1}$
f	frequency, Hz
F_{em}	electromagnetic force, N
J	the absorption flux of oxygen in the presence of a dispersed phase (e.g. microorganisms), mol $O_2{\cdot}m^{-2}{\cdot}s$
J_0	the absorption flux without a dispersed phase under the same hydrodynamic conditions m, mol $O_2{\cdot}m^{-2}{\cdot}s$
k_L	liquid-side film coefficient, $m{\cdot}s^{-1}$
k_La	volumetric liquid-side mass transfer coefficient, s^{-1}
N	impeller speed, s^{-1}
p	constant, –
P	power input, W
$\dot{Q}$	volumetric flow rate of air, $m^3{\cdot}s^{-1}$
t	time, s
t_0	initial time, s
V	liquid volume, m^3
V_S	gas superficial velocity, $m{\cdot}s^{-1}$
ω_{RMF}	angular velocity of rotating magnetic field, $rad{\cdot}s^{-1}$

liquid-side mass transfer coefficient, k_La. This coefficient is the product of the liquid film coefficient, k_L, and the interfacial area exposed to transfer in a liquid volume, a. Incorporating them into one coefficient, k_La, provides the ability to obtain a measurable value in complex field aeration systems [44]. It may be affected by a lot of factors, such as geometrical and operational characterization of the mixing system.

Thus far, previous studies have shown that the various types of reactors were used in order to improve the gas-liquid mass transfer [3,57,43,27,15,47,33,39,71,37,32,70]. These investigations suggest that the turbulence parameters are among the most important factors for the transport of mass from/to the surrounding liquid. Moreover, the OTR is influenced by several factors such as the flow pattern, shear stress, size of bubbles, physical properties of fluids, operational conditions and the geometrical parameters [20,45]. Generally, a stirred tank is a very often used contractor, in which a gas in the form of bubbles is distributed in a liquid, by using an appropriate distributor and a stirrer which cause a mixing of a liquid phase [16]. Mass transfer predictions in gas-liquid systems using CFD have been reported previously for various mixing systems [58,66,4].

A novel approach to the mixing process focuses on the application of a rotating magnetic field (RMF). This kind of magnetic field (MF) may be used as a non-instructive mixing device in various areas of chemical engineering and it has been discussed in the relevant literature [50,63,48]. RMF induces eddy currents and they create their own magnetic field that in a co-action with the principle one creates small dynamos mixing the liquid at micro-level [22]. Micromixers utilizing magnetic forces represent important class of mixing possibility [67]. These mixers use Lorentz force to agitate fluids and induce secondary complex chaotic flows [36,69,55].

Recent experiments have shown that the increase of magnetic strength enhanced the volumetric mass transfer coefficient k_La [22]. Al-Qodah and Al-Hassan [1] found that this parameter become higher as the gas velocity and the magnetic strength increased. Chen and Leu [7] presented that the k_La was enhanced by the magnetic strength. A recent study by Hajiani and Larachi [18] involved the influence of RMF on the gas-liquid transfer.

From the data available in a literature it is clear that the attention has not been focused on the experimental studies of the mass transfer in a gas-liquid system under the RMF action. Therefore, the main aim of this work is to study the influence of the RMF on the aeration process of various types of liquids and to work out some mathematical correlation for oxygen transfer in the presence of the external magnetic field (MF). The proposed equations may be useful for optimization or scaling-up of aeration efficiency under the action of RMF. The capability of prediction of equations proposed is discussed using the k_La experimental data and empirical correlations obtained in RMF mixer for both water and Hestrin-Schramm (HS) medium [19]. The medium is commonly used for cultivation of bacterial cellulose (BC). BC is biocompatible and is thus becoming a promising material for several applications such as a scaffold for tissue engineering [64], blood vessels [29], as well as for artificial skin [12]. Process production of BC in a bioreactor is complex, mainly because the culture used consists of solid BC and cells, liquid medium and air gas [6]. The dissolved oxygen in the culture medium is an important factor affecting BC production. The oxygen availability is the limiting factor for cell metabolism and production rate is dependent on the oxygen transfer rate [61,30]. Kouda et al. [31] showed that the production rate and yield of BC is dependent on k_La and the oxygen consumption rate. They reported that the Maxblend impeller and a gate with turbine were suitable for BC fermentation because these mixing systems had large value of k_La. Therefore, the predominate motivation for the present work is to investigate the possibility of the mixing system provided with a generator of RMF for the aeration process of a various types of liquids, including water and HS medium (as an example of microbiological medium used in biotechnological process of BC production).

2. Experimental details

2.1. Experimental set-up

A schematic diagram of the experimental set-up used in the presented study is shown in Fig. 1. The experimental apparatus consisted of a housing (1) and the generator of RMF (2). In the case of this work the RMF was generated by the 3-phase stator of the squirrel cage induction motor. The three phase windings of this stator were displaced form each other by 120°. These windings were supplied by a balanced three phase ac supply. The three phase currents flow simultaneously through the windings. A RMF, which emerges from superposition of three, 120° out of phase magnetic fields, has a constant intensity over time while it changes its direction continuously at any point of the domain. The vessel (3) was axially aligned with the RMF generator. The mixing system consisted of a vessel of 145 mm inner diameter and 415 mm height. The a.c. transistorized inverter (4) was used to adjust the frequency of electrical current, f, in the range of 10–50 Hz, and to regulate the maximum voltage in the range of 10–100 V. The inverter was connected to a personal computer (5) equipped with the software to control the RMF generator. Nitrogen gas (6) was used for oxygen elimination in the experimental set-up. A rotameter (8) was applied in order to monitor the flow of nitrogen and the average supply air flow rate (7). Gas was injected into the tested