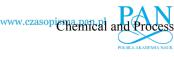# Influence of Rotating Magnetic Field on Gas-Liquid Volumetric Mass Transfer Coefficient

Rafał Rakoczy[*1], Maciej Konopacki[1], Marian Kordas[1], Radosław Drozd[2], Karol Fijałkowski[2]

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The main objective of these experiments was to study the oxygen mass transfer rate through the volumetric mass transfer coefficient (k_La) for an experimental set-up equipped with a rotating magnetic field (RMF) generator and various liquids. The experimental results indicated that k_La increased along the magnetic strength and the superficial gas velocity. Mathematical correlations defining the influence of the considered factors on k_La were proposed.

Keywords: mass transfer; volumetric mass transfer coefficient; rotating magnetic field

1. INTRODUCTION

In many biotechnological processes oxygen supplied to a liquid is insufficient to meet the demand of microorganisms. The oxygen transfer rate is often the limiting factor in bioprocesses due to the low solubility in the medium (Karimi et al., 2013). The oxygen supply into a liquid constitutes one of the decisive factors for microbial growth and can play an important role in optimization of aeration of microbial culture (Galaction et al., 2004a). It should be noticed that the gas-liquid mass transfer is generally the rate-limiting step in many industrial processes (Mills et al., 1999). Therefore, it is important to ensure an adequate delivery of oxygen to the culturing media.

The oxygen mass transfer, described and analyzed by using the volumetric mass transfer coefficient, k_La, is controlled by oxygen solubility into liquids. This parameter may be affected by a lot of factors, such as geometrical and operational characterization of the mixing system. Generally, mechanically agitated gas-liquid contractors are frequently applied in chemical processes or biochemical industries. Mechanical agitation can promote the mass transfer rate because it increases interfacial area between the liquid and gas phases (Garcia-Ochoa et al., 2009; Torab-Mostaedi et al., 2008).

There have been various strategies to improve the oxygen transfer rate in mixers. The novel approach for a mixing process was based on the application of a rotating magnetic field (RMF). As reported by Rakoczy et al. (2011), the RMF can augment the process intensity instead of mechanical mixing. Magnetic fields can be applied to induce *in vivo* and *in vitro* effects in many biological systems (Rakoczy et al., 2016). Recently, increasing attention is directed towards bio-magnetic stimulation of microorganisms using various types of magnetic fields (El-Gaddar et al., 2013; Gorobets et al., 2013;

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Santos et al., 2010). Magnetically assisted bioprocesses are conducted using a non-conventional stimulation of classical bioprocesses by various types of magnetic field (Hristov et al., 2011). It should be noted that RMF can be a versatile option for enhancing molecular transport and diffusion in aqueous culture media (Hajiani et al., 2013b).

Weng et al. (2011) pointed out that the increase of magnetic strength enhanced the volumetric mass transfer coefficient (k_La). Al-Qodah et al. (2000) found that this parameter becomes higher as the gas velocity and the magnetic strength increase. Chen et al. (2001) presented that the k_La was enhanced by the magnetic strength. A recent study by Hajiani et al. (2013a) involved the influence of RMF on the gas-liquid transfer. These results demonstrated that the mass transfer rate was enhanced due to nanoconvective stirring using magnetic nanoparticles.

The main aim of this work was to study the influence of RMF on the aeration process of distilled water and Herstin-Schramm (HS) medium 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.

2. EXPERIMENTAL DETAILS

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

A total of 4 dm^3 of the working liquid was introduced into a vessel (3). The distilled water and Herstin-Schramm (HS) medium composed of glucose (2 w/v%), yeast extract (0.5 w/v%), bacto-pepton (0.5 w/v%), citric acid (0.115 w/v%,) Na$_2$HPO$_4$ (0.27 w/v%), MgSO$_4$·7H$_2$O (0.05 w/v%) and ethanol (1 v/v%) added after sterilization of the base (Ciechańska et al., 1998) were used as experimental liquids. The HS medium is commonly used as the growth medium in the process production of bacterial cellulose (Fijałkowski et al., 2015). The liquid phase height and temperature was equal to 0.3 mm and 20 °C, respectively.
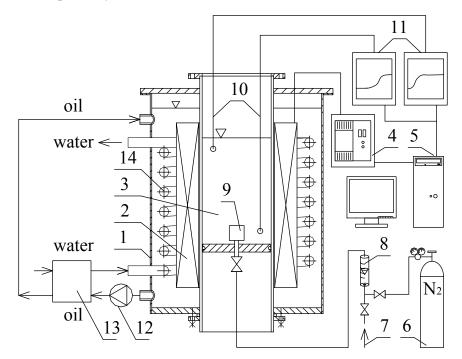

Fig. 1. Schematic diagram of the experimental set-up;
1 – housing, 2 – RMF generator, 3 – vessel, 4 – a.c. transistorized inverter, 5 – personal computer,
6 – nitrogen cylinder, 7 – air supply, 8 – rotameter, 9 – membrane sparger, 10 – oxygen probes,
11 – recorders, 12 – circulating pump, 13 – heat exchanger, 14 – internal coil

Nitrogen gas (6) was used for oxygen elimination from 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 liquids by means of a membrane sparger (9). The membrane enabled to obtain fine bubbles with narrow size distribution (in the range between 0.5 and 3 mm). The gas (air) flow rate was varied between 1 and 5 $dm^3 \cdot min^{-1}$. The superficial gas velocity was changed in the range between 0.001 - 0.005 $m \cdot s^{-1}$.

Oxygen probes (10) and recorders (11) were used to measure changes in dissolved oxygen concentration. The solved oxygen concentration in the working liquids was measured using CX-701 multifunction meters with COG-1 probes (Elmetron, Poland). It was assumed that the response of the oxygen electrode to the change in the oxygen concentration is sufficiently fast and does not affect the determination accuracy (Galaction et al., 2004b; Montes et al., 1999; Ozbek and Gayik, 2001).

The temperature of the working liquid during the exposition to RMF was controlled by an additional cooling system based on oil circulation (in a heat exchanger (13) a pump (12)) and water circulation in an internal coil (14).

The active power for the RMF system was calculated by the following relation (Rakoczy, 2013):

$$P = \sqrt{3}\, U\, I \cos(\varphi) \quad \Rightarrow \quad P = \sqrt{3}\, U\, I\, 0.85 \quad \Rightarrow \quad P = 1.47\, U\, I \tag{1}$$

The values of current intensity and voltage were recorded by means of the inverter software.

According to the proposed relationship (see Eq. (1)), a plot from calculated data is presented in coordinates (P, f and $P/V_L, f$) in Fig. 2.
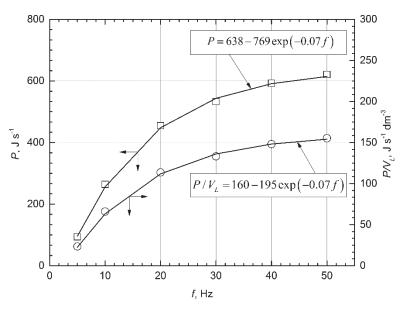

Fig. 2. The graphical presentation of relations between the calculated active power and the specific power input versus the RMF frequency

In the case of the current study, the RMF was identified by means of the magnetic induction *B*. The values of magnetic induction B at different points inside the vessel were measured using the Hall probe connected and controlled by the frequency of the ac excitation current, *f*. A typical example of the magnetic field distribution in the cross-section of the RMF generator is given in Fig. 3a. Based on experimental measurements, the relationships of the maximum and the averaged values of the magnetic induction versus the frequency of the excitation current are shown in Fig. 3b.

The volumetric mass transfer coefficient, k_La, was determined using the well-known dynamic gassing-in method (Chistii, 1989). Two independent measurements were made simultaneously by means of two

oxygen probes (localization is given in Fig. 1). The coefficient k_La was calculated as the averaged value from these measurements. The fluid was deoxygenated with nitrogen until the dissolved oxygen concentration had declined below 2% of air saturation. At that point the nitrogen flow was stopped, the present flow of air established and the dissolved oxygen concentration measured until the liquid became saturated with oxygen to the initial level.
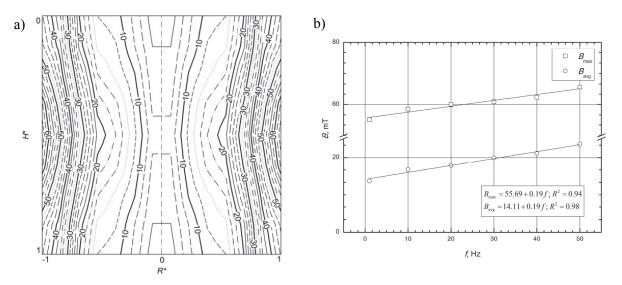

Fig. 3. A typical example of spatial distribution of the magnetic field in the cross-section of the RMF generator for $f = 30$ Hz (a) and the graphical presentation of the relations between the maximal (B_{max}) and the averaged (B_{avg}) values of magnetic induction versus the frequency of the excitation current f (b)

The volumetric mass transfer coefficient, k_La, was determined on the basis of the following expression (Heim et al., 1995):

$$\frac{dc}{dt} = k_L a \left(c^* - c \right) \tag{2}$$

Taking into consideration that the oxygen transfer coefficient was constant throughout the process, the above Eq. (2) was integrated to:

$$k_L a = -\frac{1}{t - t_0} \ln \left(\frac{c^* - c}{c^* - c_0} \right) \tag{3}$$

3. RESULTS AND DISCUSSION

The proposed correlations for the volumetric mass transfer coefficient in mechanically mixers are usually presented in the following form (Galaction et al., 2004b):

$$k_L a = f\left(\frac{P}{V_L}, w_s \right) \quad \Rightarrow \quad k_L a = p_1 \left(\frac{P}{V_L} \right)^{p_2} \left(w_s \right)^{p_3} \tag{4}$$

In the case of these experimental results, the total power input P was equal to the active power PRMF as defined by Eq. (1) (Rakoczy, 2013).

In order to provide a comparison of the mass transfer performance of the tested liquids, the experimental volumetric mass transfer coefficients k_La are plotted in Fig. 4.
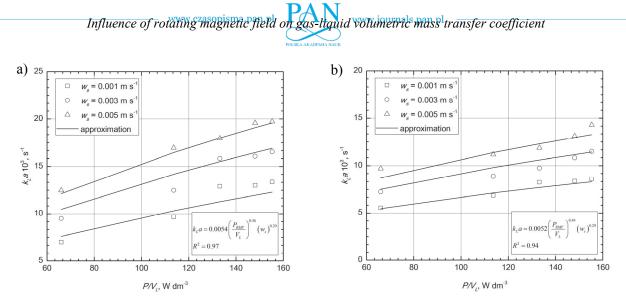
Fig. 4. The volumetric mass transfer coefficient versus the specific power input for distilled water (a) and HS medium (b)

Figure 4 shows that for a particular value of w_s, at equivalent P/V_L, both liquids were characterized by different values of k_La. Figure 4 also shows that the increase of specific power input increased the volumetric mass transfer coefficient for the distilled water (Fig. 4a) and the H-S medium (Fig. 4b). This parameter was enhanced by increasing aeration and specific power. The dependence of the oxygen mass transfer rate on the specific power is more pronounced for the distilled water. As shown in Fig. 4, the increase of the specific power led to the significant intensification of oxygen mass transfer.

The obtained results are compared with available experimental data for the standard mixer (Karimi et al., 2013). Fig. 5 demonstrates that the mixer which produces higher values of k_La is the Rushton type turbine (single and dual impellers) for the tested aeration rates. The mass transfer data obtained for the mixer with a dual Rushton turbine is consequently higher than the data obtained for a single impeller and magnetically assisted aeration process.

In the present work, the gas-liquid mass transfer under the action of RMF may be correlated by the following relationship (Li et al., 2006)

$$k_L a = f\left(B_{avg}, w_s\right) \tag{5}$$

Based on the experimental results, it can be assumed that the volumetric mass transfer coefficient is the function of magnetic induction and the superficial gas velocity.
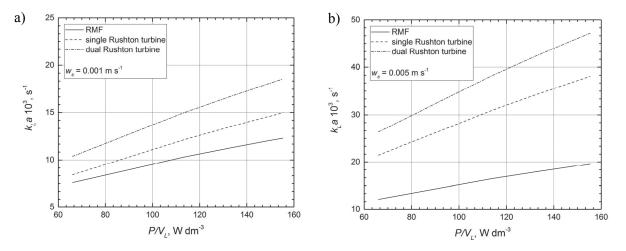

Fig. 5. The performance comparison of the obtained results for distilled water (with RMF application) with literature data from viewpoint of volumetric mass transfer coefficient (two types of impellers – single and dual Rusthon turbines)

The following correlation was developed to estimate k_La for the distilled water and the HS medium, respectively:

$$k_La\big|_{water} = 0.0035\left(B_{avg}\right)^{1.11}\left(w_s\right)^{0.32}$$ (6a)

$$k_La\big|_{H-S\,medium} = 0.0028\left(B_{avg}\right)^{1.03}\left(w_s\right)^{0.31}$$ (6b)

The k_La measurement data are presented as a function of the averaged value of the magnetic induction and the superficial gas velocity in Fig. 6. As can been seen, the volumetric mass transfer coefficient did not react very sensitively on the airflow modulation. In contrast it more sensitively responded to changes in magnetic induction. Fig. 6 also shows that over a wide interval of the averaged magnetic induction, the application of distilled water as the working liquid led to significantly higher k_La values than the HS medium at the same magnetic induction.

The influence of the magnetic field on the volumetric mass transfer coefficient may be described by means of the amplification factor (Galaction et al, 2004b). The effect observed due to the magnetic field can be described using the ratio between the volumetric mass transfer coefficient under the RMF action, $(k_La)_{Bavg=var}$, and for the volumetric mass transfer coefficient without the RMF action, $(k_La)_{Bavg=0}$, obtained for similar experimental conditions.
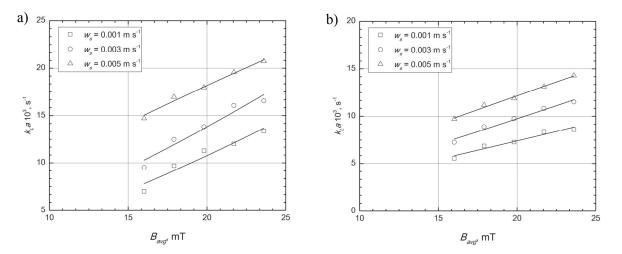

Fig. 6. The volumetric mass transfer coefficient versus the averaged magnetic induction for distilled water (a) and HS medium (b)

The variation in the coefficient k_La depending on the volumetric flow rate of air is presented in Fig. 7.

Fig. 7. The volumetric mass transfer coefficient versus the superficial gas velocity
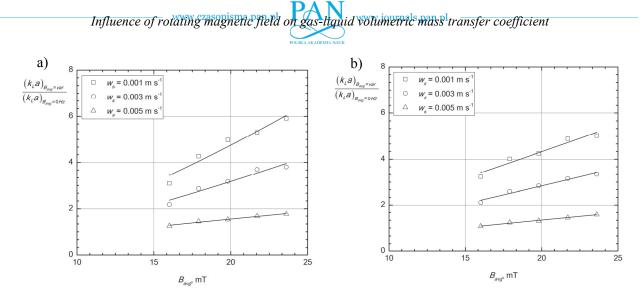
Fig. 8. The effect of the averaged magnetic induction on the amplification factor
of the volumetric mass transfer coefficient

Figure 8 shows the ratio $(k_La)_{Bavg=var}/(k_La)_{Bavg=0}$ obtained with aeration and in the presence of RMF. Figure 8 also shows that RMF caused a significant enhancement of the volumetric mass transfer coefficient as compared to the k_La value for the working liquids without the RMF action.

For a better characterization of the RMF generator according to the oxygen mass transfer, the term of oxygen transfer efficiency, E_{O_2}, may by applied and defined as (Chisti et al., 2002)

$$E_{O_2} = \frac{k_L a}{\left(\dfrac{P}{V_L}\right)} \tag{7}$$

As can be seen form Figures 9a and 9b, plotted for the two considered liquids, the variation of the oxygen transfer efficiency with the specific power input was contrary to that of k_La with the specific power input (see Fig. 4). These results suggest that the oxygen mass transfer rate reaches higher values under the action of RMF, but with considerable energy consumption. As shown in Fig. 9 for the air-distilled water and the air-H-S medium systems, the increase of the aeration rate is connected with the increase of the oxygen transfer efficiency due to the enhancement of turbulence and of the extent of the interfacial area needed for oxygen transfer.
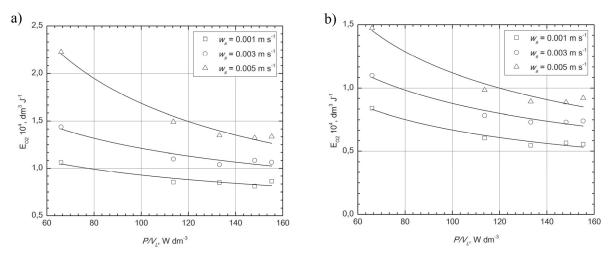

Fig. 9. The influence of specific power input on oxygen transfer efficiency

The obtained results may be explained by the fact that apart from molecular diffusion, fluid vorticity is the only mixing mechanisms of the liquid bulk in gas-liquid contractor (Hajiani et al., 2013a). It should

be noticed that the electrically conductive fluid exposed to alternating MF (including RMF) induce the Lorentz electromagnetic force. This force which is generated perpendicularly to the electric field, acts as the driving force inducing currents inside the liquid and causing liquid rotation (Moffat, 1965; Rakoczy, 2011; Spitzer, 1999; Volz et al., 1999).

The movement of the medium exposed to RMF can be explained on the basis of micro-level dynamo concept (Gaafar, 2008). The RMF associated eddy currents can be induced in the liquid as a consequence of the magnetic field because the liquid contains various charged particles e.g. ions (Anton-Leberre et al., 2010; Hristov 2010). Eddy currents may generate local MFs around ions, which in combination with an externally-applied MF, cause induction of their rotation and thus the movement of the liquid in accordance to the MF vector. As a consequence of this process, rotating ions create "dynamos" which cause the effect of micro-mixing (Anton-Leberre et al., 2010; Mehedintu et al. 1997). This mixing effect of RMF can enhance the mass transfer by reducing the diffusion mass transfer resistance (Hristov, 2010). Hristov (2010) indicated that the hydrodynamic effects on the mass transfer in magnetically assisted bioreactors are of primary importance. It was also suggested that the coefficient $k_L a$ can be effectively controlled by the magnetic field. Iwasaka et al. (2004) showed that the magnetic field gradient in the horizontal direction causes a convectional flow, which increases oxygen concentration in the liquid. It was suggested that the magnetic field can be applied for the motion control of diamagnetic and paramagnetic elements in the liquid phase (Iwasaka et al., 2004). Kitazawa et al. (2001) clearly indicated that the application of magnetic field significantly enhances oxygen concentration in water dissolved from the gas phase. It has turned out that dissolution kinetics can be enhanced several times by the magnetic field. A possible explanation for the enhancement of $k_L a$ factor under the RMF action might be that the increase of $k_L a$ is mainly due to the possibility of keeping bubbles small in size (Al-Qodah et al., 2000). Weng et al. (1992) reported that bubble rise velocity and bubble diameter decrease with the magnetic field strength. It was suggested that the magnetic field retains bubbles in liquid and it might increase the surface tension of bubbles, thereby enhancing the lifetime of bubbles (Fabian, 2002).

4. CONCLUSIONS

Results obtained in the present study indicated that RMF provided higher values of the volumetric mass transfer coefficient $k_L a$ in the analyzed liquids (distilled water and HS medium). This parameter increased along with the magnetic field strength and the superficial gas velocity. The intensification of aeration led to the increase of turbulence inside the analyzed liquids, thus promoting the acceleration of oxygen transfer rate. Therefore, it can be concluded, that modifying the specific power input between 60 - 160 W·dm⁻³ and the superficial air velocity from 0.001 to 0.005 m·s⁻¹, the maximum $k_L a$ can be increased by 6 times in the case of distilled water and by 5 times in the case of the HS medium.

SYMBOLS

B_{avg}	vector magnitude of magnetic field, kg·A⁻¹·s⁻²
c	instantaneous concentration of dissolved oxygen, kmol·m⁻³

c_0	initial concentration of dissolved oxygen, kmol·m^{-3}
c^*	saturation concentration of dissolved oxygen, kmol·m^{-3}
I	current intensity, A
$k_L a$	volumetric mass transfer coefficient, s^{-1}
P	total power input, W
Pa	active power, J·s^{-1}
p_1, p_2 and p_3	constants for a given combination of the fluid and the RMF generator
t	time, s; t_0 – initial time, s
U	voltage, V
V_L	volume of liquid, m^3
w_s	superficial gas velocity, m·s^{-1}

Greek symbols

$\cos(\varphi)$	phase shift angle between voltage and current

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