



Gas-liquid-solid volumetric mass transfer coefficient and impeller power consumptions for industrial vessel design

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ABSTRACT

Waste-water treatment, fermentation, chlorination/de-chlorination and hydrogenation are processes often realized in mechanically agitated vessels. In many cases the gas-liquid mass transfer can be the limiting process in the utilization of mechanically agitated vessels. The parameter describing gas-liquid mass transfer intensity (volumetric mass transfer coefficient $k_L a$) becomes than the key parameter. Because in fermentation processes as well as in hydrogenation ones solid particles are usually also present in gas-liquid system, we aim to study experimentally the effect of solid particles presence on $k_L a$ and power input values using reliable measuring methods. This study broadens the results on transport characteristics published in IJHMT recently (Petříček et al., 2017) [1].

Measurements were conducted in a three phase multiple-impeller fermenter of i.d. 29 cm containing microparticles of the diameter $137 \pm 30 \mu\text{m}$. To cover the effect of impeller type in our results, we gradually used Rushton turbine, Pitched-blade pumping down and Techmix pumping down impellers of the diameter of 1/3 of the vessel diameter. To measure $k_L a$ using dissolved oxygen (DO) polarographic probes the Dynamic pressure method (DPM) has been chosen. We present our results in the form of dependencies of $k_L a$ on process parameters as impeller power, gas superficial velocity, impeller blade speed, etc. We used several mathematical shapes of the dependencies to find which ones will describe the $k_L a$ dependency accurately well, to be used in agitated vessels industrial design, when gas-liquid-solid system should be treated.

Usually, $k_L a$ correlations are based on gassed power input and superficial gas velocity. We tested several correlation types, evaluated their empirical parameters and proposed the correlation shapes suitable for fermenter design, operating and scale-up under the conditions, where solid particles affect the interfacial mass transfer.

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1. Introduction

Several applications, such as fermentation, oxidation, chlorination and hydrogenation, work with aerated stirred reactors where gas-liquid mass transfer takes place. There are many applications where the presence of solid particles takes significant effect, e.g. leaching, fermentation, reactions utilizing a solid catalyst, crystallization, coagulation, and water treatment.

The prediction of parameters such as volumetric mass transfer coefficient, power input and gas hold-up in a three-phase stirred vessel is often essential to design the industrial scale apparatuses. Many aspects need to be taken into account in the design and scale up procedure: reactor's geometric parameters (type and number of impellers, presence of baffles, type of vessel bottom), operational

conditions (temperature, pressure, composition, mixing intensity, gas flow rate), physical and chemical properties of the batch. Since the gas-liquid mass transfer in general (e.g., oxygen transfer rate, OTR, in the case of fermenters) is affected by all these parameters, $k_L a$ has been often chosen as the main criterion for scaling up. Furthermore, the mass transfer rate often controls the overall rate of the process (e.g., because of the small solubility of oxygen in case of fermenters) and consequently, determines the production capacity of the apparatus. In particular, the gas-liquid mass transfer rate is given by the product of the volumetric mass transfer coefficient ($k_L a$) and the driving force of the process. While the latter is easily measurable, the $k_L a$ is really difficult to determine; its derivation by mathematical models is ineffective due to the fact that unknown parameters are involved in each model. Consequently, the empirical prediction of the $k_L a$ is needed. This is the reason why so many authors tried to predict $k_L a$ value in the last decades [1–5]. Unfortunately, to develop a reliable correlation for

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Nomenclature

Ae	dimensionless aeration number ($=Q/\beta D^3$) [-]	P_0	impeller power number ($=P_u/(\beta^3 D^5 \rho)$) [-]
a	gas-liquid interfacial area per unit liquid volume [$m^2 m^{-3}$]	Q	gas flow rate [$m^3 s^{-1}$]
C_i	empirical constants in the correlations of transport characteristics [-]	Re	Reynolds number for mixing ($=\rho_L \beta D^2 / \eta$) [-]
d	particle diameter [μm]	T	vessel diameter [m]
D	impeller diameter [m]	V_L	liquid volume [m^3]
D_i	impeller blade width [m]	v_s	gas superficial velocity [$m s^{-1}$]
D_L	diffusivity of gas in solution [$m^2 s^{-1}$]	v_t	bubble terminal velocity [$m s^{-1}$]
Fr	dimensionless modified Froude number ($=\beta^2 D^4 / (g D_i - V^{2/3})$) [-]	We	dimensionless Weber number ($=\rho_L \beta^2 D^3 / \sigma$) [-]
g	gravitational constant [$m s^{-2}$]	<i>Greek letters</i>	
J	number of experiments [-]	ε	energy dissipation intensity ($=P/\rho$) [$W kg^{-1}$]
K_i^n	empirical constants in the correlations of transport characteristics [-]	μ_L	dynamic viscosity of liquid [Pa s]
k_L	mass transfer coefficient [$m s^{-1}$]	μ_{sl}	dynamic viscosity of solid phase [Pa s]
k_{La}	volumetric mass transfer coefficient [s^{-1}]	ν	kinematic viscosity of liquid [$m^2 s^{-1}$]
l	characteristic scale defined as Batchelor's microscale of turbulence ($=(\nu^3/\varepsilon)^{1/4}$) [m]	ρ	density [$kg m^{-3}$]
M_{bear}	torque on the impeller shaft in an empty vessel [N m]	σ	surface tension [$kg s^{-2}$]
M_{tot}	total torque on the impeller shaft in a full vessel [N m]	ϕ	volume fraction of solid particles in batches [-]
N	impeller frequency [s^{-1}]	<i>Abbreviations</i>	
P_{TOT}	total power input with gas expansion [$W m^{-3}$]	CFD	computational fluid dynamics
P_g	specific power dissipated by impeller under gassed condition [W]	OTR	oxygen transfer rate
P_u	specific power dissipated by impeller under ungassed condition [W]	DO	dissolving oxygen
		SD	standard deviation
		T30	laboratory scale vessel
		T60	pilot-plant scale vessel

all the conditions is really difficult because the k_{La} is sensible to many variables. In case of gas-liquid stirred tank, many k_{La} correlations are based on the theory of isotropic turbulence. One of the most important parameter of this theory is the specific power input; other variables, however, such as gas hold-up, superficial gas velocity and batch characteristics should also be taken into account.

When solid particles are present in the system, the complexity of transport characteristics dependency might increase, making the prediction of mass transfer characteristics more difficult. Literature shows that the effects of settling and floating particles on mass transfer characteristic parameters are mutually different. In this work settling particles are used.

Our aim is to assess the effect of solid particles on the volumetric mass transfer coefficient and to establish the correlations usable for the design and scale-up of agitated vessels, when gas-liquid-solid system treated.

2. Theory

2.1. Correlation for k_{La} prediction

Many literature k_{La} values are described by the standard correlation [6] based on the theory of isotropic turbulence:

$$k_{La} = C_1 (P_g/V)^{C_2} v_s^{C_3} \quad (1)$$

Cooke et al. [7] gathered literature data for three-phase system and summarized them using the following C_1 , C_2 and C_3 values:

$$k_{La} = 0.0059 \cdot (P_g/V)^{0.607} \cdot v_s^{0.36}, \quad (2)$$

Different authors, however, found these empirical parameters significantly different. The wide variability in exponents could be explained by the following reasons. For k_{La} measurements, various

measuring methods are used, which do not give the same results [8–11]. Some of the authors used only one specific impeller type [12,13]. Some of the authors used some variant of dynamic Gassing in or Gassing out method or did not use more apparatus scales, thus the correlation cannot be suggested for scale-up [14]. The most significant problem in k_{La} determination, and later for proposing correlations, can be the use of the combination of certain experimental technique with an unsuitable physical model [15] for experimental data evaluation.

The correlations which commonly describe volumetric mass transfer can be divided into two groups: dimensionless and dimensional ones. In the last three decades, several authors have tried to use the dimensionless equations. These authors did a dimensional analysis of gas-liquid mass transfer in agitated vessels, which resulted in different shapes of the dimensionless equation. Zlokar-nik [16], however, pointed out that there is not enough known about the physics of the coalescence phenomenon, so the resultant set of dimensionless variables in the analysis is unreliable. This could be solved by the separation of the data into the groups, where liquids are coalescent or not. In our previous work [17] a significant difference in k_{La} values was found for coalescent and non-coalescent batches. The k_{La} data in the coalescent batch were more dependent on the power dissipated into the volume of the batch. Contrary to this, the k_{La} s in the electrolyte solution, which was fully non-coalescent, were dependent rather on the impeller tip speed than on gassed power input.

The separate group of correlations could contain the k_{La} data for our three-phase coalescent batch. A broad list of the correlations for coalescent batches was presented by Mills et al. [18]. Several of the literature correlations were tested by Oguz et al. [19]. They identify correlations suitable for coalescent batches. Among the suggested correlations for three-phase batches, the standard correlation (Eq. (1)) for coalescent batches was presented by Cooke et al.

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