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Volumetric mass transfer coefficient in the fermenter agitated by Rushton turbines of various diameters in viscous batch

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ABSTRACT

In cases of aerobic fermentations, the apparatuses for their industrial performance are designed also from the viewpoint of sufficient oxygen supply to avoid oxygen limitation of biomass, i.e. to provide sufficient oxygen gas-liquid transfer rate. For biochemical processes with high respiration rate, the oxygen demand of which is also high, mechanically agitated vessels are usually used. In comparison with airlift reactors and bubble columns, these equipments enable to reach higher oxygen gas-liquid transfer rates, i.e., they reach higher values of volumetric mass transfer coefficient, k_La. Due to the hydrodynamic complexity of mechanically agitated gas-liquid systems, the k_La predictions from first principles are not reliable yet, and, therefore, experimental data are needed for rational design of fermenters. Most fermentation broths are of increased viscosity, for which the lack of reliable k_La data exists due to the limitations of most measurement methods. We recently suggested and verified the methodology to obtain reliable experimental k_La data in viscous batch even for high dissipated energies. We used the dynamic pressure method (DPM), the experimental set-up of which was modified for the measurement in viscous batch. In our previous work, we provided fairly large k_La database to establish suitable correlation shapes to describe k_La dependencies on process conditions in viscous liquids. Now, we focused on the effect of impeller diameter on transport characteristics because in cases of shear stress sensitive biomass this parameter strongly affects the fermentation efficiency. The measurements were conducted in multiple-impeller fermenters, both of laboratory and of pilot-plant scale, using viscous Newtonian batch under a wide range of experimental conditions (impeller frequencies, gas flow-rates, impeller diameters). Rushton turbines of various diameters were used. Based on the experimental data, the correlations were developed to predict k_La in industrial fermenters. Standard correlation $k_La = 0.0024\,(P_{TOT})^{0.86} v_s^{0.49}$ with SD 23%, based on gassed power input P_{TOT} and superficial gas velocity v_s, has low standard deviation. On the other hand, when the term of impeller tip speed (ND) is used instead of P_{TOT}, predicted data have a higher standard deviation $k_La = 0.29\,(ND)^{2.15} v_s^{0.27}$ with SD 37%, but when this correlation is modified taking into account the D/T ratio, the standard deviation decreases significantly. The correlation $k_La = 1.14\,(ND)^{2.23} v_s^{0.27} \left(\frac{D}{T}\right)^{1.3}$ with SD 25% suggested in this work can be used for the fairly accurate design of industrial fermenters. Both the experimental technique and the correlation shape are ready to be used to obtain the design tool for other batches with various viscosities.

1. Introduction

In chemical, food, and biochemical industries, mechanically agitated gas-liquid contactors are frequently used as fermenters and as hydrogenation or chlorination reactors. A wide usage of such apparatuses is, however, limited since, in many cases, their design is not based on chemical engineering data but is still rather empirical. Often, there are the cases of the processes, where gas-liquid mass transfer rate is a controlling step. This situation is typical for bioreactors – fermenters, in which viscous batches are usually used, and for aerobic fermentations, in which the k_La often becomes the key parameter: there is the lack of k_La data due to the complexity of k_La measurement in viscous batch. In addition, the reliability of the correlations presented in literature is questionable as analysed in details by Labík et al. [1]. The problems also arose connected with too strong liquid film effect on oxygen probe reading.

To fill the gap in the experimental data on transport characteristics, various approaches to the k_La determination in gas-liquid systems can be found in literature. One approach is the theoretical prediction of the k_La based on k_La construction from the hydrody-

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Nomenclature

Symbols used

a	gas-liquid interfacial area per unit liquid volume ($m^2\ m^{-3}$)
C_i	empirical constants in the correlations of transport characteristics (–)
D	impeller diameter (m)
D_L	diffusivity of gas in solution ($m^2\ s^{-1}$)
g	gravitational constant ($m\ s^{-2}$)
k_L	mass transfer coefficient ($m\ s^{-1}$)
k_La	volumetric mass transfer coefficient (s^{-1})
l	characteristic scale defined as Batchelor's microscale of turbulence (m)
N	impeller frequency (s^{-1})
P_{TOT}	specific total power input with gas expansion ($W\ m^{-3}$)
P_g	power dissipated by impeller under gassed conditions (W)
P_u	power dissipated by impeller under ungassed conditions (W)
P_0	impeller power number (–)
Q	gas flow rate ($m^3\ s^{-1}$)
T	vessel diameter (m)
V	liquid volume (m^3)
v_s	gas superficial velocity ($m\ s^{-1}$)
v_t	bubble terminal velocity ($m\ s^{-1}$)

Greek letters

ε	energy dissipation intensity ($=P/\rho$) ($W\ kg^{-1}$)
μ	dynamic viscosity of liquid (Pa s)
ν	kinematic viscosity of liquid ($m^2\ s^{-1}$)
ρ	density ($kg\ m^{-3}$)
σ	surface tension ($kg\ s^{-2}$)

Abbreviation

CFD	computational fluid dynamics
DO	dissolving oxygen
SD	standard deviation
T29	laboratory scale vessel
T59	pilot-plant scale vessel

namic description. Several articles [2–11] supporting such construction have been published in the last decades.

Due to the significantly different behavior of various gas-liquid systems, Zlokarnik [12] proposed to divide them into coalescent and non-coalescent categories. This split is also suitable for k_La prediction because the coalescence phenomenon is still not well described, and there is a sharp transition between coalescent and non-coalescent state [4,13]. To that, significantly different behavior was observed [14] for k_La in coalescent and non-coalescent batches. To sum it up, the categorization of k_La predicting correlations to coalescent, non-coalescent and viscous batches is generally accepted. For instance, Takahashi and Nienow [15] mentioned the significance to determine the coalescence rate, which "belongs to parameters from which mass transfer rates can be formulated", and Markopoulos et al. [16] declared that "the common correlation of the k_La involving all 3 batch types would not reach sufficient accuracy of predicted values".

Due to more complex hydrodynamic conditions in mechanically agitated gas-liquid dispersions, the theoretical quantification of k_La based on hydrodynamic principles is less frequent here compared to bubble columns. Recently, comprehensive article on a CFD study of mechanically agitated dispersion was presented by Ranganathan and Sivaraman [17], where an overview of other articles dealing with the topic is also given. These CFD studies, however, need too large computational time and, therefore, some simplifications need to be made. In the case of the work of Ranganathan and Sivaraman [17] the results were obtained using only "two bubble velocity groups to reduce computational cost". As the consequence of the simplification, they could report an agreement with experimental data by Alves [18] for the k_La data up to $0.06\ s^{-1}$ only, while the maximum k_La measured non-coalescent batches are being reported slightly above $1\ s^{-1}$. The survey of the uncertainties and obstacles in the theoretical prediction of k_La data (for instance, a determination of energy dissipation intensity from kinetic energy calculated by CFD) in agitated dispersion has been fairly described by Martin et al. [19].

2. Theory

Many literature k_La values are described by the standard correlation [20] based on the theory of isotropic turbulence:

$$k_La = C_1\ (P_g/V)^{C_2}\, v_s^{C_3} \tag{1}$$

Van't Riet [21] categorized the literature data for water and for electrolyte solutions and summarized them into the equations:

$$k_La = 0.026 \cdot (P_g/V)^{0.4} \cdot v_S^{0.5}, \tag{2}$$

for water and

$$k_La = 0.002 \cdot (P_g/V)^{0.7} \cdot v_S^{0.2} \tag{3}$$

for electrolyte solutions which are generally non-coalescent.

The wide variability in exponents among the authors could be explained by the following reasons. For k_La measurements, various measuring methods are used, which do not give the same results [5,22–24]. Some of the authors used different impeller types [25,26]. 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 [12]. The most significant problem for measuring mass transfer intensities, and later for proposing correlations, can be the use of the unsuitable method or an unsuitable physical model [27] for experimental data evaluation.

The correlations which are commonly describing volumetric mass transfer can be divided into two groups: dimensionless and dimensional correlations. 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. Zlokarnik [28], however, pointed out that there is not enough known about the physics of the coalescence phenomenon, so a 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 [14] 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 it, the k_La's in the electrolyte solution, which was fully non-coalescent, were dependent on the impeller tip speed rather than on gassed power input.

The separate group of correlations could contain the k_La data for viscous batches. A broad list of the correlations for viscous batches was presented by Garcia-Ochoa and Gomez [29]. Several of the literature correlations were tested by Badino et al. [30]. They identify correlations suitable for Newtonian and non-Newtonian batches. Among the suggested correlations for viscous batches,