Chemical Engineering Science 170 (2017) 451–463

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Volumetric mass transfer coefficient in viscous liquid in mechanically agitated fermenters. Measurement and correlation

L. Labík *, T. Moucha, R. Petříček, J.F. Rejl, L. Valenz, J. Haidl

University of Chemistry and Technology, Prague, Chemical Engineering Dep., Technická 5, 166 28 Praha 6, Czech Republic

HIGHLIGHTS

- Experimental k_La data for pilot-plant and laboratory fermenters are presented.
- Experimental k_La data for various impeller types in viscous batch are presented.
- Scaling-up based on k_La is improved, based on impeller power number and tip speed.
- Using various impeller types, the k_La correlations suitable for scaling-up are developed.
- A modification of dynamic pressure method for viscous batches is presented.

GRAPHICAL ABSTRACT

ARTICLE INFO

Article history:
Received 25 July 2016
Received in revised form 7 February 2017
Accepted 4 April 2017
Available online 7 April 2017

Keywords:
Fermenter
Scale-up
Gas-liquid
Viscous
Mass transfer coefficient

ABSTRACT

In the industrial fermentation processes, most liquids are non-coalescent and often exhibit increased viscosity. However, due to the limitations of most measurement methods, there is a lack of reliable data for predicting volumetric mass transfer coefficients (k_La) for viscous batches, especially under high dissipated energies, as the accurate determination of oxygen concentration profile in viscous liquids is not as easy as in low viscosity ones. Our goal is to develop reliable technique for k_La determination in viscous liquids and to establish suitable correlation shapes to describe k_La data. We used the dynamic pressure method (DPM), the experimental set-up of which has been modified for the measurement in viscous liquids. Dissolved oxygen (DO) probes were placed in bypass measuring cells. This set up brings well defined transient characteristics of DO probes, which is crucial for correct k_La evaluation. Measurements were conducted in two phase multiple-impeller fermenters with a non-coalescent viscous Newtonian batch under a wide range of experimental conditions and in the apparatuses of two scales. Using pure oxygen as gas phase, it was confirmed that DPM yields k_La's independent of the driving force of absorption even in viscous batch. The improved set up of DPM enabled to use also optical DO probes as well as polarographic ones. It was confirmed that optical DO probe can be used for k_La values up to 0.4 s^{-1}. Based on the experimental data, correlations were developed to predict k_La in industrial fermenters. Standard correlation $k_La = 2.99 \cdot 10^{-3} \cdot (P_g/V_L)^{0.891} v_s^{0.556}$ with standard deviation, SD, 30%, based on gassed power input P_g and superficial gas velocity v_s, has low standard deviation but it is scale specific. On the other hand, when the term of impeller tip speed (ND) is used instead of P_g, predicted data exhibit neither over- nor under-estimation of k_La for particular apparatus scale; so the effect of the vessel scale is properly described using this term. In addition, the impeller power number P_o was found to be a reliable predictor of k_La in a common correlation for various impeller types, when used together with the impeller tip speed term. The correlation $k_La = 0.295 \cdot (ND)^{2.083} v_s^{0.461} P_o^{0.737}$ with SD 28% suggested in this work can be used for

* Corresponding author.
E-mail addresses: labiklibor@gmail.com (L. Labík), mouchat@vscht.cz (T. Moucha).

http://dx.doi.org/10.1016/j.ces.2017.04.006

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.

Nomenclature

Symbols used

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_M	Probe time constant (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_u	specific power dissipated by impeller under ungassed condition (W)
P_g	specific power dissipated by impeller under gassed condition (W)
P_o	impeller power number ($P_u/\rho N^3 D^5$) (–)
Q	gas flow rate ($m^3\ s^{-1}$)
T	vessel diameter (m)
V_L	liquid volume (m^3)
v_s	gas superficial velocity (m/s)
v_t	bubble terminal velocity (m/s)

Greek letters

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

Abbreviation

DPM	dynamic pressure method
DO	dissolved oxygen
TC	transient characteristic
SD	standard deviation

1. Introduction

Volumetric mass transfer coefficient is one of the most important transport characteristics used in the scale-up, design and performance optimization of mechanically agitated gas-liquid contactors. These apparatuses are frequently used in chemical, food and biochemical industries as fermenters and as hydrogenation or chlorination reactors. However wide the usage of such apparatuses is, their design is not based on chemical engineering data, but is still rather empirical. For the processes where gas-liquid mass transfer rate is the controlling phenomenon, the volumetric mass transfer coefficient (k_La) becomes the key parameter. Many correlations of the k_La have been presented in literature, but their reliability is questionable, especially for viscous batches, where a significant distortion of oxygen probes reading is more probable.

We can find various approaches to the k_La determination in gas-liquid systems. One approach consists in theoretical predictions of the k_La based on its construction from hydrodynamic description of the gas-liquid mixture. Articles (Del Castillo et al., 2011; Kawase and Mooyoung, 1988; Okawa et al., 1999; Prince and Blanch, 1990; Talaia, 2007; Timson and Dunn, 1960) supporting such construction have been presented in the last decades. Another approach could be establishing a neural network over a wide range of experimental values, as was shown by (Garcıa-Ochoa and Castro, 2001; Garcia-Ochoa and Gomez, 2009) and recently by Asgharzadehahmadi et al. (2016). According to these authors, a neural network was able to predict variety of transport characteristics.

Due to the significantly different behavior of various gas-liquid systems, Zlokarnik (2006) proposed the division of 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 (Zahradnik et al., 1999). To sum up, the categorization of k_La predicting correlations to (i) coalescent, (ii) non-coalescent and (iii) viscous batches is generally accepted. For instance, Takahashi and Nienow (1993) mentioned the significance to determine the coalescence rate, which "belongs to parameters from which mass transfer rates can be formulated", and Markopoulos et al. (2007) declared that "the common correlation of the k_La involving all 3 batch types would not reach sufficient accuracy of predicted values".

For gas-liquid dispersions, the theoretical quantification of k_La in mechanically agitated vessels based on hydrodynamic principles is less frequent compared to bubble columns. This is due to more complex hydrodynamic conditions in mechanically agitated dispersions. The survey of the uncertainties and obstacles in the theoretical prediction of k_La in agitated dispersion has been fairly well described by Martin et al. (2009) and Gogate et al. (2000). For the reasons discussed above, for mechanically agitated dispersions the empirical k_La correlations based on experimental data are often presented in literature.

1.1. Correlation for k_La prediction

Many literature k_La data are described by the standard correlation (Cooper et al., 1944) based on the theory of isotropic turbulence:

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

Van't Riet (1979) categorized the literature data for water and for electrolyte solutions and summarized them into the equations:

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

for water and

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

for electrolyte solutions which are generally non-coalescent.

While the C_2 value in Eq. (1) is low for coalescent systems and practically all literature data lie within the interval = 0.6 ± 0.1,