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# Prediction of mean bubble size in pneumatic reactors

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ABSTRACT

In the present work, a new methodology to estimate the mean bubble size ($d_B$) in pneumatic bioreactors is proposed. The semi-theoretical method is based on Higbie's penetration theory and estimates $d_B$. It uses experimental gas hold-up ($\varepsilon$) data and volumetric mass transfer coefficient ($k_La$) obtained in three scales of concentric-tube airlift reactor (ALR) of 2, 5 and 10 dm$^3$ and three different pneumatic bioreactors of 2 dm$^3$, which are concentric-tube airlift reactor (ALR), bubble column reactor (BCR) and split airlift reactor (SAR). The parameter $k_La$ was separated into its components $k_L$ and $a$. Mean bubble size ($d_B$) and convective oxygen transfer coefficient ($k_L$) proved not dependent on the superficial gas velocity in the riser ($U_{GR}$) for ALR and SAR and superficial gas velocity ($U_G$) for BCR reactor in the experimental range studied. The results indicate that $k_La$ is a function only of the gas–liquid interfacial area of the bubbles ($a$) and therefore of the gas hold-up ($\varepsilon$).

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## 1. Introduction

Concentric-tube airlift reactors (ALR), split airlift reactor (SAR), and bubble column reactor (BCR) are classes of pneumatic reactors. They are attractive for chemical and biological reactions due to their inexpensive and simple construction without moving mechanisms and low energy costs when compared to stir tank reactors.

One of the most significant parameters in the design of pneumatic reactors is the volumetric mass transfer coefficient ($k_La$) commonly used to evaluate the capacity of oxygen transfer in bioreactors. This quantity depends on the system geometry and fluid properties, which are related to several other parameters [1]. Most investigations performed on aerobic systems are limited to the determination of the $k_La$. Unfortunately, this parameter is global and insufficient to provide an understanding of the mass transfer mechanisms. Normally, the influence of each parameter, convective oxygen transfer coefficient ($k_L$), and interfacial area of the bubbles ($a$) in the oxygen mass transfer rate are not clear. Therefore, the separation of the parameters $k_L$ should be considered for a better comprehension of gas–liquid mass transfer mechanisms [2]. The interfacial area ($a$) can be determined from the fractional gas hold-up and the mean bubble diameter ($d_B$), which is a very important parameter in gas liquid reactor design and a good criterion for evaluating the efficiency of gas liquid contactor. Small bubbles and a uniform distribution over the cross-section of the equipment are desired to maximize the interfacial area, hence improving transport phenomena.

Many authors have studied the influence of the bubble size on the mass transfer phenomena; most of the bubble size measurements were taken using photographic techniques. Tung et al. [3] compared the bubble size and hydrodynamic behavior in concentric-tube airlift and bubble column reactors. They noticed that the circulation velocity did not have a significant effect on bubble size, however it had a large influence on the bubble frequency. Wongsuchoto et al. [4] investigated the effect of various designs and operating parameters on bubble size distribution in annulus sparged airlift contactors. It was found that the interfacial area, rather than the mass transfer coefficient, played a more significant role in controlling the overall oxygen transfer rate in the system. At high superficial air velocity in the riser ($U_{GR}$), the bubble size was smaller and uniform. In the range of $U_{GR}$ from 0.0059 to 0.0737 m s$^{-1}$, the average bubble diameter was found to be between 3 and 8 mm. Ruen-gnam et al. [1] investigated the effect of salinity on the performance of an ALR. The bubble mean diameter appeared to be smaller in saline water than in fresh water. For fresh water, the average bubble diameter was found to be between 5 and 8 mm in the range of $U_{GR}$ from 0.011 to 0.060 m s$^{-1}$.

Mass transfer by convection involves the transport of material between a boundary surface and a moving fluid or between two relatively immiscible moving fluids. The determination of the mass transfer coefficient is not a simple undertaking. It is related to the physical properties of the fluid, to the dynamic characteristics of the flow such as the slip velocity and turbulence (turbulent kinetic energy), and the geometry of the system. It is the reason for expecting an analytical treatment to estimate $k_L$. At constant tem-

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perature, any improvement in the $k_L$, and therefore $k_La$, may be achieved only by changes in the liquid film thickness (two-film theory), the exposure time (penetration theory) or surface renewal rate (surface renewal theory) depending on the mass transfer hypothesis that is chosen [5]. The oxygen transfer rate depends not only on the gas hold-up and bubble size, but also on the value of $k_L$. According to Higbie's penetration theory, the liquid mass transfer coefficient $k_L$ depends on the diffusivity coefficient and turbulence created in the liquid phase. According to the results of Wongsuchoto et al. [4], the $k_L$ to pure water in an ALR is constant in the range of $U_{GR}$ from 0.0059 to 0.0737 m s$^{-1}$. Ruen-gnam et al. [1] found that this system with water provided a higher level of $k_L$ than saline solutions.

In the literature, there are many works in which the bubble size measurement in pneumatic reactors is conducted by experimental methods, but none of them present a correlation to estimate the bubble size. Therefore, the aim of this work is to propose a new methodology to predict the convective oxygen transfer coefficient ($k_L$) and the mean bubble diameter ($d_B$) from experimental values of volumetric oxygen transfer coefficient ($k_La$) and gas hold-up ($\varepsilon$) in three scales of concentric-tube ALR (2, 5 and 10 dm$^3$) with similar geometric configurations and three types of pneumatic reactors of 2 dm$^3$, concentric-tube airlift reactor (ALR), bubble column reactor (BCR), and split airlift reactor (SAR) using water as the liquid phase. The parameter $k_La$ was separated into its components $k_L$ and $a$, and the results were evaluated for different sizes and types of reactors.

## 2. Materials and methods

### 2.1. Fluids

Distilled water at 28 °C was used as liquid phase and air as gas phase.

### 2.2. Equipment

Concentric-tube airlift reactors (ALR) with 2, 5 and 10 dm$^3$ working volumes were used in this study. The external tube was made of glass of 5 mm thickness. The bottom and top plates, the draft tube (thickness of 1 mm), the gas sparger, the base and the condenser were made of stainless steel. Geometrical characteristics and the relationships between distances are shown in Table 1 for the three different scales of the airlift bioreactor. The holes of the crosspiece type sparger were 0.5 mm diameter and were 5 mm spaced [6]. The ALR is presented in Fig. 1.

**Table 1**
Geometric characteristics of the three scales of concentric-tube internal-loop ALR.

| Liquid volume (dm$^3$) | ALR (2.0) | ALR (5.0) | ALR (10.0) | SAR (2.0) |
|---|---|---|---|---|
| H1 (m) | 0.032 | 0.045 | 0.055 | 0.032 |
| H2 (m) | 0.033 | 0.055 | 0.045 | 0.033 |
| H3 (m) | 0.262 | 0.350 | 0.450 | 0.260 |
| H4 (m) | 0.327 | 0.450 | 0.550 | 0.325 |
| H5 (m) | 0.450 | 0.600 | 0.700 | 0.450 |
| De1 (m) | 0.100 | 0.135 | 0.170 | 0.100 |
| H4/De1 | 3.63 | 3.60 | 3.44 | 3.63 |
| $A_D/A_R$ | 1.68 | 1.78 | 1.84 | 1.31 |
| DI2/De1 | 0.61 | 0.60 | 0.59 | – |
| $L$ | – | – | – | 0.095 |

The bubble column reactor (BCR) of 2 dm$^3$ had the same base and the external tube of the ALR of 2 dm$^3$. The draft tube was withdrawn and the original sparger was replaced by a perforated plate with holes of 0.5 mm diameter, illustrated in Fig. 1b. The geometric characteristics of the BCR were the same as those of the ALR of 2 dm$^3$.

Split airlift reactor (SAR) of 2 dm$^3$ presented the same base and the external tube of the ALR of 2 dm$^3$. The draft tube was substituted by a vertical plate (baffle) of 1 mm thickness and the original sparger was substituted by a specific SAR sparger with holes of 0.5 mm diameter. The split airlift reactor (SAR) is illustrated in Fig. 1c and the geometric characteristics of SAR are presented in Table 1.

### 2.3. Volumetric oxygen transfer coefficient ($k_La$)

The volumetric oxygen transfer coefficient ($k_La$) was determined in triplicate by the dynamic pressure-step method [7]. In this experimental method, the pressure in the vessel is changed abruptly by approximately 15 kPa, and an increase in the dissolved oxygen concentration ($C_e$) in the bubble dispersion occurs regardless of the gas flow pattern. Eq. (1) was fitted to the experimental data ($C_e$ as a function of time) and $k_La$ values were estimated through the

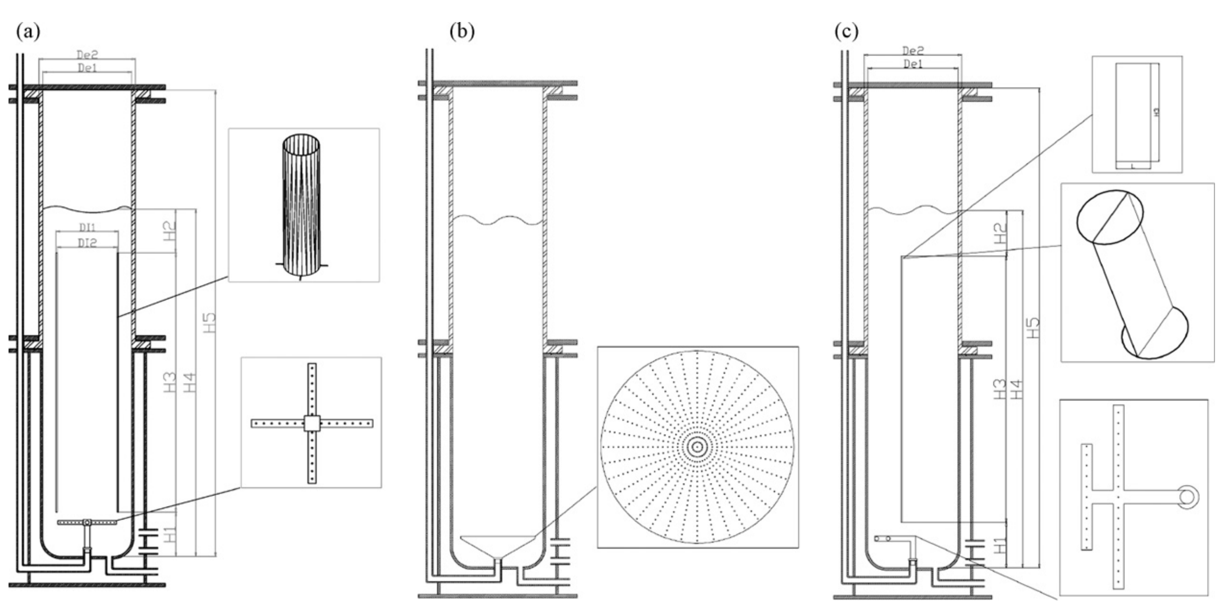


**Fig. 1.** Geometric schemes of the pneumatic reactors: (a) concentric-tube airlift reactor (ALR), (b) bubble column reactor (BCR), and (c) split airlift reactor (SAR).