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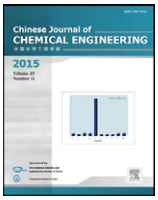

Fluid Dynamics and Transport Phenomena

Gas–liquid hydrodynamics in a vessel stirred by dual dislocated-blade Rushton impellers☆

Fengling Yang *, Shenjie Zhou, Xiaohui An

School of Mechanical Engineering, Shandong University, Jinan 250061, China
Key Laboratory of High Efficiency and Clean Mechanical Manufacture (Shandong University), Ministry of Education, Jinan 250061, China

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ABSTRACT

Towards the objective of improving the gas dispersion performance, the dislocated-blade Rushton impeller was applied to the gas–liquid mixing in a baffled stirred vessel. The flow field, gas hold-up, dissolved oxygen, power consumption before and after gassing were studied using the computational fluid dynamics (CFD) technique. Dispersion of gas in the liquid was modelled using the Eulerian–Eulerian approach along with the dispersed k–ε turbulent model. Rotation of the impeller was simulated with the multiple reference frame method. A modified drag coefficient which includes the effect of turbulence was used to account for the momentum exchange. The predictions were compared with their counterparts of the standard Rushton impeller and were validated with the experimental results. It is concluded that the dislocated-blade Rushton impeller is superior to the standard Rushton impeller in the gas–liquid mixing operation, and the findings obtained here lay the basis of its application in process industries.

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1. Introduction

In the past several decades, there have been considerable efforts to improve the bacteria and cell culture efficiency. These aerobic bio-processes are mostly carried out in aqueous medium with ionic salts where the solubility of oxygen is limited. Under such circumstances, oxygen must be continuously supplied and the rate of oxygen mass transfer is a key task [1]. Therefore, the desire to improve gas dispersion homogeneity has attracted many scientific researchers and engineers.

The most widely used reactor in biochemical industries to carry out the bacteria and cell cultivation operations is the stirred vessel [2,3], within which the fluids are agitated by impellers. For gas–liquid mixing, excellent gas dispersion performance is the essential requirement of the impeller. It is responsible for bubble breakup and dispersion. Many kinds of impeller exist and are continuously being invented to meet various needs. Traditionally, for the operation of gas–liquid dispersion, the standard Rushton impeller has been widely used since 1950s [4]. This impeller has high volumetric gas–liquid mass transfer coefficient [5]. So far, it has served as the measuring yardstick to which other types of impellers are compared [2]. However, in spite of its versatility, the standard Rushton impeller is not perfect and many weaknesses have been identified. For example, the axial pumping capacity is low. It is usually not sufficient to induce the necessary bulk flow to satisfy the oxygen absorption requirements. It can only effectively disperse gas in regions adjacent to the impeller. The uniform dispersion state of gas in the stirred vessel bulk is hard to achieve. Large shear stress could be produced, which is adverse especially for the cultivation of animal cell having no protecting cell wall. Due to the sweeping action of the impeller, there are low-pressure trailing vortices at the rear of the blades. This result in great power drop after gas is introduced and the gas handling capacity is handicapped by flooding [2,6].

For the purpose of improving the gas dispersion uniformity, great efforts have been devoted to the modification of the standard Rushton impeller over the past several decades. To date, many new types of modified Rushton impellers have been developed. Through increasing the blade height and simultaneously adding perforations to the blades, Roman *et al.* [7] designed the perforated Rushton impeller, which has a reduced power consumption and improved oxygen transfer efficiency. Chen and Chen [8] studied the comb blade and the perforated blade disc impellers. The latter was found to have higher volumetric gas–liquid mass transfer coefficient than the standard Rushton impeller at similar power input. Warmoeskerken and Smith [9] proposed the CD-6 impeller which has concaved blade just like cutting from pipe sections. This and subsequent studies [10–12] confirmed that this impeller

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* Corresponding author.
E-mail address: fly@sdu.edu.cn (F. Yang).

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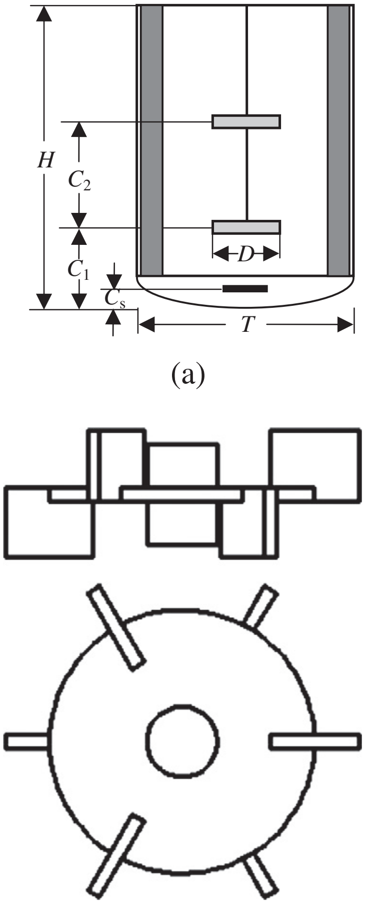
provides better gas–liquid mixing performance than the traditional Rushton impeller. Since then, other impellers with non-flat blades were continuously being developed. For example, the hollow half elliptical blade dispersing turbine (HEDT) was applied to the gas–liquid and gas–liquid–solid mixing in stirred tanks by Chen *et al.* [13]. The void fraction distributions under different operating conditions, including impeller rotational speed, power input, gas flow rate and temperature, were investigated. Vasconcelos *et al.* [14] concluded that the best performance may be expected from retrofitted Rushton impeller with streamlined blades, which lowers the power number, results in less aerated power drop, retards impeller flooding and accordingly, are confirmed more efficient and capable of handling gas. This may attribute to the fact that impellers with streamlined blades could increase the blade curvature and alter the trailing vortices characteristics [15].

Another promising improvement of the standard Rushton impeller is the self-inducing Rushton type impeller. The mixing mechanisms were explored, and the advantages of this impeller in applications of gas–liquid–solid and gas–liquid dispersion were experimentally and numerically validated by several researchers [16–19]. Bakker *et al.* [20–22] invented the Scaba (also named as BT-6) impeller which has vertically asymmetric blades. It was shown that this impeller has a flatter aerated power curve and can disperse more gas before flooding than impellers with symmetric blades. In addition, there are also flexible blade impellers [23–25]. Compared with the rigid blade impeller, the flexible blade impeller is allowed to flex into the desired curved configurations under the action of the fluid. Unfortunately, there is no available information so far for the application of flexible blade impeller in the processes involving microorganisms.

In this work, we investigate the dislocated-blade Rushton impeller in gas–liquid mixing in a baffled stirred vessel using the experimental and CFD methods. This impeller has the same component dimensions as the standard Rushton impeller, except that the blades are mounted above and below the impeller disc alternatively. To be exact, three blades are above the impeller disc, and the bottom edge of each blade is aligned with the bottom surface of the disc. For the other three blades, they are below the disc, and their top edges are parallel to the top surface of the disc. For more details about this impeller, the readers may refer to the literature [26].

2. Stirring System

Fig. 1 depicts the configuration of the stirring system studied in this paper. The impellers are the standard Rushton impeller and the dislocated-blade Rushton impeller (hereafter referred to as SRT and DRT, respectively). The stirred vessel (dia. $T = 0.21$ m) is an elliptical-bottomed cylindrical vessel with four standard baffles. The offset from baffle to the vessel wall is $T/60$. Tap water (density: $\rho_l = 998.2\ \mathrm{kg \cdot m^{-3}}$, dynamic viscosity: $\mu_l = 0.001\ \mathrm{Pa \cdot s}$) was used as the working liquid. For the experimental measurements of dissolved oxygen, the activated sludge effluent was employed, which has the same density and viscosity as the tap water. Air ($\rho_g = 1.225\ \mathrm{kg \cdot m^{-3}}$, $\mu_g = 1.789 \times 10^{-5}\ \mathrm{Pa \cdot s}$) was introduced through a ring sparger located below the lower impeller with the flow rate of $Q = 0.4$ and $0.6\ \mathrm{m^3 \cdot h^{-1}}$. There are 94 upward-facing holes (dia. 0.8 mm) on the sparger pipe with the ring diameter of 0.43 *T*. The other dimensions of the stirring system are given in Table 1, where *B* is the baffle width, C_s and C_1 are the clearances from sparger and the lower impeller respectively to the vessel bottom, C_2 is the spacing between the two impellers. Five impeller rotational speeds, *i.e.*, $N = 300, 400, 500, 600, 700\ \mathrm{r \cdot min^{-1}}$ were selected. The corresponding Reynolds number is in the range of $Re = \rho l N D^2/\mu_l = 3.18\text{–}7.42 \times 10^5$. Power consumptions were measured with the AKC-215 type torque transducer (China Academy of Aerospace Aerodynamics, Beijing, China). Gas dispersion images were captured with a CCD camera (Nikon AF NIKKOR, 1280 × 1024 pixels).



(a)

(b)

Fig. 1. Schematic of the stirring system: (a) stirred tank; (b) DRT impeller.

3. Numerical Simulation

3.1. Gas–liquid mixing modelling

Gas–liquid mixing in the stirred vessel was simulated using the Eulerian–Eulerian multiphase model. Mass conservation equation for each phase is given as follows:

$$\frac{\partial}{\partial t}(\alpha_i \rho_i) + \nabla \cdot (\alpha_i \rho_i \boldsymbol{u}_i) = 0. \tag{1}$$

Liquid phase (*l*) and gas phase (g) are assumed to share space in proportion to their volume such that their volume fractions sums to unity in the cells domain:

$$\alpha_l + \alpha_g = 1. \tag{2}$$

Momentum conservation equation for phase *i* is

$$\frac{\partial}{\partial t}(\alpha_i \rho_i \boldsymbol{u}_i) + \nabla \cdot (\alpha_i \rho_i \boldsymbol{u}_i \boldsymbol{u}_i) = -\alpha_i \nabla p + \nabla \cdot \boldsymbol{\tau}_i + \alpha_i \rho_i \boldsymbol{g} + \boldsymbol{F} \tag{3}$$

Table 1
Dimensions of the stirred vessel

T/m	B/T	C_1/T	C_2/T	C_s/T	D/T	H/T
0.21	0.083	0.33	0.80	0.17	0.38	1.6

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