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Improving oxygen transfer efficiency by developing a novel energy-saving impeller

Zhiyong Zheng[a,*], Dongdong Sun[a], Jing Li[b], Xiaobei Zhan[a], Minjie Gao[a]

[a] Key Laboratory of Industrial Biotechnology, Ministry of Education, School of Biotechnology, Jiangnan University, Wuxi 214122, Jiangsu Province, China
[b] School of Environmental and Biological Engineering, Nanjing University of Science and Technology, Nanjing 210094, Jiangsu Province, China

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ABSTRACT

Radial flow impeller is the energy-intensive and fundamental component in reactors for the gas–liquid transfer process. A newly designed fan-shaped turbine (FT) assembly with annular-sector-shaped concave blades was characterized and compared with the Rushton turbine (RT) and Bakker turbine (BT). A new surface equation was established to design the blade of the FT impeller. Under turbulence conditions, the FT impeller showed a lower power number and higher relative power demand (RPD) compared with RT and BT impellers. The power number of the FT impeller was 1.7, lower by 26% than that of BT impeller. The RPD of the FT impeller was nearly 0.95 at a high impeller speed. The critical dispersion speed, gas holdup, and volumetric oxygen transfer coefficient of the FT impeller were close to those of BT impeller. Moreover, the oxygen transfer efficiency of the FT impeller was remarkably higher by 35%–66% and 23%–34% than that of RT and BT impellers, respectively. The FT impeller showed competence in a broad operation range, strong robustness, energy-saving feature, and efficient mass transfer characteristics.

1. Introduction

Gas dispersion is widely used in aeration, oxidation, chlorination, and hydrogenation processes in industrial applications of aerobic fermentation, environmental engineering, and chemical engineering. Gas dispersion is mostly achieved through agitation, which breaks large bubbles into small bubbles in fluids, thereby promoting gas-to-liquid mass transfer (Bakker et al., 1994). Radial flow impellers are the most commonly used type of impeller, and they are the main energy-consuming component of a gas dispersion unit. To reduce energy consumption during aeration and agitation, engineers often combine gas–liquid dispersion (employed in radial flow impellers) with mixing (employed in axial flow impellers) to construct an efficient gas–liquid reaction system (Gogate et al., 2000). The power input required for a gas dispersion impeller commonly accounts for 40%–70% of the power input of an entire agitation system. Therefore, developing efficient and energy-saving impellers is urgently needed to improve gas dispersion process.

Rushton et al. (1950) designed the first flat-blade impeller (Rushton turbine, RT) in the 1950s. RT became the standard impeller used in gas–liquid dispersion processes for a long time. The impeller is usually assembled with six blades on a disc and thus called RT-6. Although the RT impeller displays a simple structure and good gas dispersion, it requires high power input and brings strong shear force. In the 1970s, Van't Riet and Smith (1975) found that trailing vortexes produced behind the RT-6 impeller blades is the main cause of energy wastage. Cavities are formed when the trailing vortex is filled with gas under gassed condition. The presence of cavities results in unstable power consumption and reduced mass transfer efficiency during gassed agitation. Van't Riet et al. (1976) subsequently developed an impeller assembly consisting of semi-circular tube blades (concave disc turbine, CD), which greatly reduced cavitation and improved the efficiency of gas–liquid mass transfer. Analysis has shown that the formation of flow patterns varies between RT impeller and CD-6 impeller (Devi and Kumar, 2013). Since then, researchers have developed a series

* *Corresponding author.*
E-mail addresses: zhiyong@jiangnan.edu.cn (Z. Zheng), 1115014295@qq.com (D. Sun), lijing2031447@163.com (J. Li), xbzhan@jiangnan.edu.cn (X. Zhan), gaominjie@msn.com (M. Gao).
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Nomenclature

C_L	Dissolved oxygen concentration (g/L)
C_L^*	Saturated dissolved oxygen concentration (g/L)
D	Impeller diameter (m)
d	Disc diameter (m)
E	Oxygen transfer efficiency (m^3/J)
H	Liquid loading height (m)
H_g	Liquid height under gassed condition (m)
h	Upper or lower blade height (m)
h_1	Upper blade height (m)
h_2	Lower blade height (m)
k_{1-6}	Constant
k_La	Mass transfer coefficient (1/s)
L	Blade radial length (m)
m	Torque (N·m)
N	Impeller speed (r/s)
N_L	Critical dispersed speed (r/s)
N_p	Power number
n	Blade number
P_A	Power of aeration (W)
P_g	Power under gassed condition (W)
P_u	Power under ungassed condition (W)
Q_g	Gas flow rate (L/min)
Re	Reynolds number
r	Impeller radius (m)
T	Tank inner diameter (m)
t	Measurement time (s)
V_L	Liquid volume in the tank (m^3)
v_s	Superficial gas velocity (m/s)
W_1	Upper blade width (m)
W_2	Lower blade width (m)

Greek symbols

δ	Blade thickness (m)
ε	Gas holdup (%)
ρ	Liquid density (kg/m^3)
Ψ	Tangential radian of FT blade (rad)

Abbreviations

BT	Bakker turbine
DO	Dissolved oxygen
FT	Fan-shaped turbine
RPD	Relative power demand
RT	Rushton turbine

of impeller assemblies with deeper concaved blades, such as Gasfoil (Hjort and Skanberg, 1988) and Scaba 6SRGT (Galindo and Nienow, 1993; Middleton and Ramshaw, 1993) impellers in the 1980s and 1990s, respectively. Bakker (1998) invented an impeller assembly with asymmetric concave blades (Bakker turbine, BT). The BT impeller presents two advantages: (1) the parabolic-shaped blade has a more curved vertex than the other impeller blades, resulting in weaker cavitation effect; and (2) the upper portion of the blade above the disc hangs over the lower portion to facilitate the capture and dispersion of gas. RT, CD, and BT impellers are widely used in industrial processes, and BT impeller is currently the most efficient radial flow impeller.

We recently designed a new radial flow impeller (Zheng et al., 2017), in which the blade surface employs a new equation (Eq. (1)). The generatrix of the blade in the peripheral direction could be seen as spatial curves of parabola that fit the cylindrical surface. The surface extends the tangential width of the blade without changing the diameter of the impeller. Furthermore, the blade is fan-shaped (annular sector) as projected on the horizontal plane, hence the name fan-shaped turbine (FT). The torque in the outer edge of the blade is high, so the outer side of the blade was designed to have a deeper concave shape, which can possibly reduce power consumption. The extended tangential width and the increased blade area ensure good performance for gas capture and gas dispersion. In the present work, our main purpose is to characterize the agitation and gas dispersion performance of the FT impeller. We carried out an experimental investigation and compared this impeller with the traditional RT and BT impellers.

2. Materials and methods

2.1. Impellers

Three impellers with the same diameter, i.e. BT, RT, and the newly designed FT, were investigated in this work. The surface equation of the FT blade is

$$z = \frac{h}{\Psi^2}\left(\arctan\frac{y}{x}\right)^2$$
$$x \in [r-L, r], \quad y \in [(r-L)\cdot\sin\Psi, r\cdot\sin\Psi] \qquad (1)$$

where h is the upper or lower blade height, Ψ is the tangential radian of the annular sector (the blade projection on the horizontal plane), r is the radius of the impeller, and L is the length of the blade. x, y, and z refer to the three-dimensional coordinates.

The schematic diagram top-view of the three impeller blades in one disc is shown in Fig. 1. The three impellers were plotted using SolidWorks software and printed by a 3D printer (US Stratasys Fortus 250mc) using ABS Plus plastics. The blade was 3 mm thick. The mechanical strength of the blade met the test requirements as revealed in the pre-experiments. Fig. 2 shows the photographs of the three impellers used in the experiments.

Except for the shape of the blades, the impeller diameter, disc diameter, blade length, and blade height of the three impellers were similar. The dimensions of the impellers are presented in Table 1.

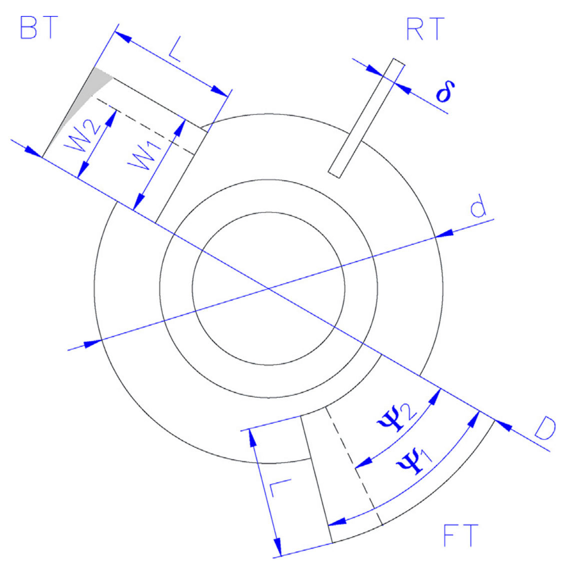

Fig. 1 – Schematic diagram top-view of the three impeller blades in one disc. Gray area in BT blade was speculated to be a low efficiency region for gas dispersion.