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Mass transfer and power characteristics of stirred tank with Rushton and curved blade impeller

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ABSTRACT

Present work compares the mass transfer coefficient (k_La) and power draw capability of stirred tank employed with Rushton and curved blade impeller using computational fluid dynamics (CFD) techniques in single and double impeller cases. Comparative analysis for different boundary conditions and mass transfer model has been done to assess their suitability. The predicted local k_La has been found higher in curved blade impeller than the Rushton impeller, whereas stirred tank with double impeller does not show variation due to low superficial gas velocity. The global k_La predicted has been found higher in curved blade impeller than the Rushton impeller in double and single cases. Curved blade impeller also exhibits higher power draw capability than the Rushton impeller. Overall, stirred tank with curved blade impeller gives higher efficiency in both single and double cases than the Rushton turbine

1. Introduction

Gas-liquid tanks are widely used in several process industries to carry out various gas-liquid reactions [36,14]. The characteristic of fluid dynamics in such tanks is generally understood through the mechanism of interaction between the two phases (gas-liquid) in terms of mass transfer. Studies based on gas-liquid phase in stirred tank were done by several researchers [17,1,30] to predict the mass transfer coefficient in stirred tank. Mass transfer depends on various factors like types and number of impeller, gas superficial velocity and impeller speed. Researchers have used different models to predict mass transfer coefficient such as Higbie Penetration model [13] and surface renewal model [6]. Gimbun et al. [12] used Higbie and Danckwerts model to predict mass transfer on single impeller of Rushton and curved blade impeller. Ranganathan and Sivaraman [30] used two more models apart from above mentioned which are based on slip velocity (difference of gas velocity and liquid velocity).

One of the other significant design parameters for a multiphase stirred tank reactor is the power draw by the agitator which is affected by the physical properties, operating parameters, and geometrical parameters. It is defined as the amount of energy necessary in a period of time, in order to generate the movement of the fluid within a vessel by means of mechanical or pneumatic agitation [32]. Economic selection criteria for an impeller are greatly influenced by the power input for stirred tank application. Researchers [24,23,32] have proposed different correlations to quantify the gassed power input (gas-liquid phase) since the power input is significantly different from gas-liquid phase (gassed condition) and liquid–liquid phase (ungassed condition).

Impeller types and number plays vital role in mass transfer and power consumptions in gas-liquid stirred tanks. Study of Rushton impeller [16,38,21,1] for mass transfer and power input is widely available in literature, however, study forcurved blade impeller is found very less in literarure except few studies done by Myers et al. [27]; Gimbun et al. [12] and Devi and Kumar [7]. In this study, Rushton and curved blade impeller in single and double case is being studied in gas-liquid phase taking constant bubble diameter with Eulerian-Eulerian multiphase model. This study aims in predicting mass transfer and power draw and comparing with published literature.

2. Numerical model

Eulerian-Eulerian multiphase model is used to simulate the hydrodynamics of flow in this study. The continuous and disperse phases are treated as interpenetrating media identified by their local volume fractions. The Reynolds averaged mass and momentum balance equations are solved for each of the phases and are given as follows:

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Nomenclature

a	interfacial area [L^{-1}]
C_μ, $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$, σ_k, σ_ε	constants [–]
C_D	drag coefficient [–]
c	constant [–]
$C_{kL}a$, a, b	constants [–]
d	impeller diameter [L]
d_b	bubble diameter [L]
D_l	liquid diffusion coefficient [$L^2\,T^{-1}$]
$\vec{F}_i$	Coriolis and centrifugal forces [$M L T^{-2}$]
Fl_g	flow number [–]
F_r	Froude number [–]
$\vec{g}$	acceleration due to gravity [$L T^{-2}$]
G_{kl}	rate of production of turbulent kinetic energy [$ML^{-1}\,T^{-2}$]
$\bar{\bar{I}}$	unit tensor [–]
k_i	turbulent kinetic energy of ith phase [$L^2\,T^{-2}$]
K	constant in Eq. 14 [–]
K	exchange coefficient [$ML^{-3}\,T^{-1}$]
k_L	mass transfer coefficient [$L T^{-1}$]
k_La	volumetric mass transfer coefficient [T^{-1}]
$\langle k_La \rangle$	average mass transfer coefficient [T^{-1}]
N	impeller speed [T^{-1}]
N_{p0}	single phase power number [–]
p	pressure [$ML^{-1}\,T^{-2}$]
P_g/P_0	relative power draw [–]
P_g	gassed power input [ML^{-1}]
Q_g	flow rate [$L^3\,T^{-1}$]
$\vec{R}_i$	inter-phase forces [$M L T^{-2}$]
Re	Reynolds number [–]
Re_p	relative Reynolds number [–]
s	surface renewal rate [T^{-1}]
Δt	impeller thickness [L]
t	time [T]
T	tank diameter [L]
t_e	contact time [–]
$\vec{U}_i$	mean velocity of ith phase [$L T^{-1}$]
u_{slip}	slip velocity [$L T^{-1}$]
V	volume of tank [L^3]
v_g	superficial gas velocity [$L T^{-1}$]
v_l	kinematic liquid viscosity [$L^2\,T^{-1}$]
w	width of blade [L]
α_i	volume fraction of ith phase [–]
$\bar{\bar{\tau}}_{eff}$	effective stresses [$ML^{-1}\,T^{-2}$]
$\bar{\bar{\tau}}_{lam}$	laminar stress [$ML^{-1}\,T^{-2}$]
$\bar{\bar{\tau}}_t$	turbulent stress [$ML^{-1}\,T^{-2}$]
ρ_i	density of ith phase [$M L^{-3}$]
ε	dissipation rate [$L^2\,T^{-3}$]
μ_l	liquid viscosity [$ML^{-1}\,T^{-1}$]
π	3.14 [–]
τ	torque [$ML^2\,T^{-2}$]

Continuity equation:

$$\frac{\partial}{\partial t}(\alpha_i\rho_i) + \nabla.(\alpha_i\rho_i\vec{U}_i) = 0 \tag{1}$$

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

where, ρ_i, α_i and $\vec{U}_i$ are density, volume fraction and mean velocity, respectively, of phase i (l or g).

Momentum equation:

$$\frac{\partial}{\partial t}(\alpha_i\rho_i\vec{U}_i) + \nabla\cdot(\alpha_i\rho_i\vec{U}_i\vec{U}_i) = -\alpha_i\nabla p + \nabla\bar{\bar{\tau}}_{\text{effi}} + \vec{R}_i + \vec{F}_i + \alpha_i\rho_i\vec{g} \tag{3}$$

where, p is the pressure shared by the two phases and $\vec{R}_i$ is the inter-phase momentum exchange terms. $\vec{F}_i$, represents the Coriolis and centrifugal forces applies in MRF (multiple reference frame) impeller model which is used in this study as impeller model. The Reynolds stress tensor $\bar{\bar{\tau}}_{\text{effi}}$ is the laminar and turbulent stresses and by Boussinesq hypothesis, it is given as

$$\bar{\bar{\tau}}_{\text{effi}} = \alpha_i(\mu_{\text{lam},i} + \mu_{t,i})(\nabla\vec{U}_i + \nabla\vec{U}_i) - \frac{2}{3}\alpha_i(\rho_i k_i + (\mu_{\text{lam},i} + \mu_{t,i})\nabla.\vec{U}_i\Big)\bar{\bar{I}} \tag{4}$$

$\mu_{\text{lam},i}$ and $\mu_{t,i}$ are laminar and turbulent viscosity. k_i is turbulent kinetic energy and $\bar{\bar{I}}$ is unit tensor.

2.1. Turbulence model

Standard k-ε turbulence model [29] with dispersed k-ε multiphase turbulence model is used in this study to simulate the gas-liquid phase flow as gas is dispersed in continuous liquid. The governing equations of turbulent kinetic energy, k and turbulent dissipation rate, ε, are solved only for liquid phase as:

$$\frac{\partial}{\partial t}(\rho_l\alpha_l k_l) + \nabla.(\rho_l\alpha_l\vec{U}_l k_l) = \nabla\cdot\left(\alpha_l\frac{\mu_{t.l}}{\sigma_k}\nabla k_l\right) + \alpha_l G_{kl} - \rho_l\alpha_l\varepsilon_l + \rho_l\alpha_l\prod_{kl} \tag{5}$$

$$\frac{\partial}{\partial t}(\rho_l\alpha_l\varepsilon_l) + \nabla\cdot\left(\rho_l\alpha_l\vec{U}_l\varepsilon_l\right) = \nabla.(\alpha_l\frac{\mu_{t.l}}{\sigma_\varepsilon}\nabla\varepsilon_l) + \alpha_l\frac{\varepsilon_l}{k_l}(C_{1\varepsilon}G_{kl} - C_{2\varepsilon}\rho_l\varepsilon_l) + \rho_l\alpha_l\prod_{\varepsilon l} \tag{6}$$

Turbulent liquid viscosity is given as:

$$\mu_{t.l} = \rho_l C_\mu\frac{k_l^2}{\varepsilon_l} \tag{7}$$

G_{kl} is the rate of production of turbulent kinetic energy. $\prod_{kl}$ and $\prod_{\varepsilon l}$ represents the influence of the dispersed phase on the continuous phase [8]. C_μ, $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$, σ_k and σ_ε are constants of standard k-ε model. Their values are 0.09, 1.44, 1.92, 1.2, 1.0 and 1.3 respectively.

2.2. Inter-phase momentum exchange

Only drag force is considered in the present work as other forces (lift and virtual) have been neglected because of its less significance in phase interaction [18]. Hence, $\vec{R}_i$ from Eq. (3) reduced only to drag force as:

$$\vec{R}_l = -\vec{R}_g = K(\vec{U}_g - \vec{U}_l) \tag{8}$$

K is the liquid-gas exchange coefficient given as:

$$K = \frac{3}{4}\rho_l\alpha_l\alpha_g\frac{C_D}{d_b}|\vec{U}_g - \overleftarrow{U}_l| \tag{9}$$

d_b is the bubble diameter and C_D is the drag coefficient defined as function of relative Reynolds number, Re_p. The standard formulation of Re_p does not account the effect of turbulence on bubble movement. Hence Re_p has been modified to include the effect of turbulence [17]:

$$Re_p = \frac{\rho_l|\vec{U}_g - \vec{U}_l|d_b}{\mu_l + C\mu_{T,l}} \tag{10}$$