ELSEVIER

Chemical Engineering Journal 115 (2006) 173–193

Chemical Engineering Journal

www.elsevier.com/locate/cej

Effect of impeller design on the flow pattern and mixing in stirred tanks

T. Kumaresan, Jyeshtharaj B. Joshi *

Institute of Chemical Technology, University of Mumbai, Matunga, Mumabi 400019, India

Received 14 April 2005; received in revised form 7 October 2005; accepted 7 October 2005

Abstract

The flow pattern and power number in a vessel depend on the impeller blade angle, number of blades, blade width, blade twist, blade thickness, pumping direction and interaction of flow with the vessel wall. Measurements of the power consumption and flow pattern have been carried out in a stirred vessel of 0.5 m diameter for the range of impellers to study the effect of blade shape on the flow pattern. The comparison of the flow pattern (average velocity, turbulent kinetic energy, maximum energy dissipation rate, average shear rate and turbulent normal stress) has been presented on the basis of equal power consumption to characterize the flow generated by different impeller geometries. Comparisons of LDA measurements and CFD predictions have been presented. The good comparison indicates the validity of the CFD model.

Keywords: Stirred vessel; Impeller design; Impeller types; Mixing; CFD; Sliding mesh; Fluid mechanics

1. Introduction

Stirred vessels are widely used in chemical, pharmaceutical, food and metallurgical process industries as well in municipal and industrial wastewater treatment. In these processes, the requirement of quality of mixing varies over a wide range. These include blending of low viscosity of liquids, high viscosity liquids or high viscosity liquids with low viscosity liquids and vice versa, solid-solid mixing, etc. These also include heat transfer and large number of dispersion applications such as solid–liquid, gas–liquid, liquid–liquid, gas–liquid–solid, gas–liquid–liquid–solid, etc. The quality of mixing mainly depends upon the relative distribution of mean and turbulent kinetic energy. One extreme is the absence of turbulence and the entire energy exists in the form of mean kinetic energy. The other extreme is that the flow is turbulent at all the locations and the mean velocities are zero. Obviously, the real flow is in between the two extremes and depends upon impeller design, diameter and the location of impeller/s, vessel diameter, bottom design and internals such as coils, baffles, draft tube, etc. The desired flow pattern (relative distribution of mean and turbulent kinetic energy) depends upon the application. For instance, blending application prefers all the energy in the form of mean and minimal turbulent kinetic energy (even <5% [1]). On contrast, colloidal mills, homogenizers and emulsifiers need highly turbulent flows. All the other applications can be conveniently classified according to their need of energy distribution.

In stirred vessels, the quality of flow generated by the impeller mainly depends upon the impeller design. Typically, low power number (0.1–0.5) impellers generate mean flow whereas high power number impellers (>3) generate flow having more turbulent kinetic energy. As the flow proceeds from the impeller and circulates within the vessel, the mean kinetic energy is converted into turbulent kinetic energy and as mentioned earlier, the relative distribution at any location depends upon the design of the impeller, vessel and internals. In view of such an immense importance of the knowledge of quality of flow, vigorous research efforts have been made during the last 50 years using various flow measurement techniques and computational fluid dynamics (CFD). A brief review has been presented below for getting a flavour of the existing status of knowledge.

The on going demand for the improved impeller designs usually comes from the users of industrial mixing equipment when the vessels are to be designed for new plants or improvement in the existing design is desired for enhancing quality, capacity, process efficiency and energy efficiency. For meeting these objectives, it is imperative that the relationship between the flow pattern and the design objective is understood. One of the flow characteristics affecting the impeller flow efficiency is the presence of trailing vortices generated at the tip of the

* Corresponding author. Tel.: +91 22 414 5616; fax: +91 22 414 5614.
E-mail address: jbj@udct.org (J.B. Joshi).

1385-8947/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.cej.2005.10.002

Nomenclature

B_C	baffle clearance (m)
B_{tk}	impeller blade thickness (m)
B_T	baffle thickness (m)
B_W	baffle width (m)
c	concentration in the cell (kmol m^{-3})
C	clearance between the impeller to the vessel base (m)
CMC	carboxy methyl cellulose
C_μ, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$	k–ε model constant
D	impeller diameter (m)
D_h	diameter of the impeller hub (m)
H	liquid height (m)
k	local turbulent kinetic energy (m^2 s^{-2})
k_{avg}	average turbulent kinetic energy (m^2 s^{-2})
L	length of the blade from the hub to periphery (m)
LDA	laser Doppler anemometer
N	impeller rotational speed (s^{-1})
N_b	number of baffles
$N_{P,exp}$	experimental power number ($P/\rho N^3 D^5$)
$N_{P,Pred}$	predicted power number, Eq. (4)
N_{QP}	primary flow number, Eq. (1)
N_{QS}	secondary flow number, Eq. (2)
N_{Re}	Reynolds number (ND^2/γ)
P	power consumption (w)
PBTD	pitched blade turbine downflow
PBTU	pitched blade turbine upflow
r	radial coordinate (m)
R	vessel radius (m)
RPS	revolutions per second
R_I	radial location till impeller periphery (m)
R_R	radial location till reversal axial flow (m)
S_Φ	source term for generalized flow variable Φ
T	tank diameter (m)
v_r, v_z, v_θ	mean velocity in the radial, axial and tangential direction respectively (m s^{-1})
v'_r, v'_z, v'_θ	fluctuating velocity in the radial, axial and tangential direction respectively (m s^{-1})
V	operating volume (m^3)
U_{tip}	impeller tip velocity (m s^{-1})
w_g	weight exerted (kg)
W	impeller blade width (m)
W_h	impeller blade width near the hub (m)
W_t	impeller blade width at the blade tip (m)
z	axial coordinate (m)

Superscript

S	small impeller diameter (D/T = 0.2)

Greek symbols

γ	kinematic viscosity (m^2 s^{-1})
γ_{avg}	average shear rate (s^{-1})
γ_{zr}, $\gamma_{r\theta}$, $\gamma_{\theta z}$	shear components in z–r, r–θ and θ–z direction (s^{-1})
Γ	effective diffusivity consisting of molecular plus turbulent diffusivity (m^2 s^{-1})
ε	energy dissipated per unit mass (m^2 s^{-3})
$\bar{\varepsilon}$	average energy dissipated per unit mass (m^2 s^{-3})
ε_{max}	maximum energy dissipated below the impeller (m^2 s^{-3})
θ	tangential coordinate
θ_{CFD}	predicted mixing time (s)
θ_{exp}	experimental mixing time (s)
ν_t	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
$\bar{\tau}_N$	average turbulent normal stress (N m^{-2})
τ_0	torque (kg m^2 s^{-2})
σ_ε, σ_k	k–ε model constant
Φ	generalized flow variable

impeller blades. Firoz et al. [2] studied the strength of the trailing vortex structures close to the four-bladed 45° pitched blade turbine using vorticity maps. It is possible to minimize the vortex size and improve the axial flow efficiency of such impellers by proper designing of the blade tip shape. However, more details of trailing vortices structures for four bladed pitched blade turbine are given by Schafer et al. [3]. Fasano et al. [4] indicated that the large trailing vortex in four-bladed 45° pitched blade turbine (mixed flow impeller) accounts for its lower efficiency compared to that of three-bladed Chemineer HE-3 impeller. Further, they found that the three-bladed HE-3 impeller provides a more stable heat transfer profile at the vessel wall than that of the four-bladed PBTD impeller. The overall heat transfer coefficient in the stirred vessel with HE-3 impeller was found to be 10% higher than that of mixed flow impeller.

Ranade and Joshi [5] investigated the effect of impeller blade pitch (30°, 45° and 60°) on the flow pattern and established that an impeller blade angle in pitched blade turbine significantly affects the flow characteristics. However, the blade width was found important for radial flow disc turbines especially in the gas–liquid dispersion operation. We-Ming et al. [6] investigated the role of blade width on the generated vortex structure at impeller blade tip using a single disc turbine at equal power input. They observed that the impeller with larger blade (W/D = 0.19) produces a fully developed vortex flow and the smaller blade impeller (W/D = 0.07) produces a stronger shear stress due to the mergence of the two symmetric vortices. Rutherford et al. [7] and Bujalski et al. [8] observed the importance of blade thickness for disc turbine where the maximum mean velocity in the impeller discharge region was reduced approximately to $0.18U_{tip}$ when B_{tk}/D was increased from 0.0082 to 0.0337. Medek and Fort [9]. Fentiman et al. [10] made a slight blade twist in the three bladed hydrofoil impeller and found that mixing efficiency increased with the change in blade twist. However, more number of hydrofoil impellers must be investigated to find the effect of mixing efficiency on the bladed twist.

Jaworski et al. [11] compared the superiority of commercial hydrofoils (Chemineer HE-3 and Prochem Maxflo T) in