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Effect of number of branches on the performance of fractal impeller in a stirred tank: Mixing and hydrodynamics

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ABSTRACT

Number of blades of an impeller, impeller design and its positioning in a stirred tank is known to affect the mixing in a stirred tank reactor. The extent of non-uniformity in mixing from conventional impellers can be reduced significantly using a space-filling impeller like a fractal impeller. In this work, we report the effect of number of branches (and hence the number of blades) of fractal impeller on power consumption, mixing and hydrodynamics. Velocity measurements were carried out using ultrasonic velocity profiler (UVP). Measurements showed that the performance of fractal impeller with different configuration is equivalent, however, better than standard impellers in terms of mixing achieved per unit power consumption. No significant difference was observed in radial and axial mean velocity profiles for three different configurations. However, the tangential velocity was found higher for four branches than two and three branches FI. Two distinct circulation loops were observed in upper as well as lower half of the vessel in *r*–*z* plane. Strong tangential flow throughout the baffled vessel helps to achieve good mixing even at low rotational speeds.

1. Introduction

Stirred tank is among one of the widely used process equipment in the chemical and allied industry. In general, impeller selection is done on the basis of process requirement. For example, axial flow impellers (PBTD, HE3) are mostly preferred for solid suspensions, on the other hand, radial flow impellers are recommended for the gas dispersion in liquids (Kasat and Pandit, 2005; Paul et al., 2004). Paul et al. (2004) have reported that when PBTU is used for gas dispersion, the relative power demand is more than 70% of the un-gassed power draw on gassing. Usually, the design of a stirred tank reactor is optimized on the basis of power consumption, heat transfer, and mass transfer and mixing. Mixing in the stirred tank mainly depends on the bulk flow induced by the impeller (Nere et al., 2003; Nienow, 1997; Patwardhan and Joshi, 1999) as well as the turbulent fluctuations. Depending upon the application, in addition to the type of impeller, various other factors such as vessel type, clearance from bottom, impeller diameter etc. also affect the mixing efficiency (Houcine et al., 2000; Kumaresan et al., 2005). It is known that the most of the energy provided by impeller to the fluid is dissipated around the impeller region which is only 5–10% of the total volume of the reactor (Kresta, 1998; Kresta and Wood, 1993; Ng and Yianneskis, 2000). In order to make the entire reactor hydrodynamically active with very small variation in the nature of energy dissipation, Kulkarni et al. (2011) proposed and demonstrated a Fractal Impeller for mixing and dispersion. These authors have reported that although volume wise a FI occupies almost the same volume as a standard impeller, however it is spread over

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Nomenclature

A_1, A_2	*proportionality constant*
c	speed of sound, m/s
C	clearance of the impeller, m
C_0	conductivity measured before addition of tracer, μS/cm
C_∞	final stable value of conductivity after the test is complete, μS/cm
C_i	conductivity probe output values, μS/cm
C_i'	normalized conductivity output values
d_{NB}	diameter neutrally buoyant particles, μm
D_{FI}	impeller diameter, m
f_D	Doppler shift frequency, Hz
f_0	Doppler frequency, Hz
H	liquid height in the tank, m
k_m	mean kinetic energy, m^2/s^2
l	length of blades from the center, m
N	rotational speed in seconds, 1/s
N_{BL}	number of blades
N_P	power number = $P_0/\rho N^3 D^5$
N_Q	flow number = Q_{FI}/ND^3
P_0	power, W
P_{Max}	maximum penetration depth, m
P_W	power per unit mass, m^2/s^3
Q_{FI}	discharge flow rate, m^3/s
r, z	coordinates in radial and axial direction, m
rpm	rotational speed in minutes, 1/min
R	radius of the tank, m
Re	Reynolds number = $D^2 N\rho/\mu$
t_{turf}	time period of pulse, s
t	time delay, s
T	diameter of the tank, m
u, v, w	mean radial, axial and tangential velocity components, m/s
U_{Max}	maximum velocity in the stirred tank, m/s
U_x, U_y	instantaneous velocities at x and y directions, m/s
V	velocity measured by UVP, m/s
W	baffle width, m
x, y	coordinates in x-axis and in y-axis, m
X	distance measured by UVP, m
ρ	density of the fluid, kg/m^3
ρ_s	density of the solid particles, kg/m^3
θ_{mix}	mixing time, s

Subscripts

FI	fractal impeller
Max	maximum
RMS	root mean square
NB	neutrally buoyant

the entire tank and covers almost 95% of the total volume of the tank. It was reported that the performance of the FI in terms of mixing time per unit power consumed, solid handling and dispersion of gas in liquid was much better than that of standard impellers. In continuation, more recently, Mule and Kulkarni (2015) reported the work on flow characteristics of FI and the interaction of different velocity components in different regions of a stirred tank. The observations on the flow patterns indicated that the contribution of tangential velocity component was significantly higher compared to radial and axial velocity components.

The encouraging performance of fractal impeller in terms of mixing, solid suspension, gas dispersion and hydrodynamics has now motivated us to study its various design aspects, which include: fractal structure, number of branches, blade configuration, dimensions of blades, orientation of blades etc. This study explores the effect of number of branches on the performance of FI. The performance is measured in terms of power consumption, mixing time and flow pattern so as to choose the right configuration for further studies.

In view of the above discussion, this manuscript is organized as follows: after Section 1, we have given the details in Section 2, on tank geometry, impeller configurations and the experimental procedure. The flow characteristics of FI were studied using ultrasonic velocity profiler (UVP) and details on UVP are given in Section 2. Section 3 gives the results and discussions in detail and finally we summarize the findings.

2. Experimental

2.1. *Tank geometry*

Experiments were carried out in an acrylic tank of diameter (*T*) 0.3 m having four baffles (baffle width $W = T/12$). The tank has a dish shaped bottom with a bottom outlet for removing liquid. The liquid height (*H*) was maintained at 0.31 m as to minimize the air entrainment at higher rotational speeds.

2.2. *Fractal impeller*

Fractal impeller has self-similar geometrical features at different scales. It has multiple blades placed at different axial and radial locations, of which half of the blades are vertically oriented and the remaining are horizontal. These blades are attached to the sub-branches (B_{IK}) that are attached to main branch (B_I), which are attached to the impeller shaft. The details on the design are as follows;

1) Each sub-branch (B_{IK}) has square shaped four blades (30 mm × 30 mm × 1 mm), two are horizontal and two are vertical (see Fig. 1).
2) Three sub-branches of the above design are attached to a main branch (B_I). The sub-branches are attached in such a manner than one is co-axial to the main branch while the other two (B_{I1} and B_{I3}) are parallel to the shaft and perpendicular to the main branch. These sub-branches are arranged in such a way that the B_{I1} and B_{I3} branches are placed equidistance from perpendicular branch (B_{I2}).
3) The main branch (B_I) having three sub-branches is attached to the impeller shaft at a fixed plane for creating local advection through rotational movement. The number of main branches that are attached to the shaft can be changed using a small hub.
4) An additional sub-branch (B_S) with four blades (two vertical and two horizontal) was attached to the impeller shaft to create sufficient flow at the bottom of the tank.

With this concept, different configurations of fractal impeller were assembled. It is necessary to mention that with the specific dimensions of blades and branches, FI with five branches was not found feasible as blades of two different branches were found overlapping in the same plane. Hence