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Short communication

Effect of scale on entrainment in stirred tanks

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ABSTRACT

In the present work, surface turbulence characteristics at the onset of entrainment in air water system have been investigated. For the present study, shear type entrainment in stirred tanks has been considered. Experiments have been performed in stirred tanks with different scales for different types and sizes of impellers. The results of the work reveal that radial RMS, axial RMS velocities and turbulent kinetic energy showed similar magnitudes at onset even at different scales. The RMS velocities as well as TKE magnitudes did not vary with type or size of impellers. Local energy dissipation rates have been estimated from autocorrelation function of fluctuating velocity. Very low magnitudes of local energy dissipation rates at onset have been observed.

Keywords: Shear type entrainment; Surface turbulence; Stirred tanks; UVP; Autocorrelation; Turbulent kinetic energy

1. Introduction

Entrainment of gas in liquids has generated momentous interest over the years predominantly because it is commonly observed in various engineering applications. It is important to characterize the underlying fluid mechanics causing entrainment. Based upon nature of flow, entrainment mechanisms have been classified as shear type, vortex type and liquid fall type. When surface velocities are large, shearing action makes the interface unstable, producing surface waves which lead to entrainment of gas near the free surface.

Several researchers have attempted to correlate the onset of gas entrainment with operating parameters, geometry of the system (Baum and Cook, 1975; Bin, 1988; Madarame and Chiba, 1990; Bhattacharya et al., 2007; Mali and Patwardhan, 2009; etc.). Present study focuses on interfacial turbulence characteristics associated with shear type entrainment observed in stirred tanks. A brief review of the literature on similar studies has been presented in the following section.

Initial studies on gas entrainment in baffled stirred vessels focused on mass transfer and effect of parameters such as impeller type, submergence on aeration rates. Later studies concentrated on effect of fluid properties and tank geometry on onset of entrainment. Clark and Vermeulen (1964) reported visual observations of the liquid surface under the conditions of surface aeration in baffled stirred tanks. As per their observations, region of high shear occurred on the liquid surface due to the combination of flows in opposing directions. First, the impeller discharge flow and second the flow rebounded off the baffles. The liquid surface appeared oscillatory. These oscillations formed small waves on the surface, trapping small quantities of gas, which were subsequently carried into bulk of the liquid. Sverak and Hruby (1981) proposed a semi empirical correlation for critical impeller speed for surface aeration. They compared the bubble formation at the surface with formation of a non rotational vortex when fluid is sucked into a thin vertical tube placed just below the liquid surface. Greaves and Kobbaccy (1981) investigated the mechanism of air entrainment in stirred tanks. They correlated the critical impeller speed for the onset of gas entrainment with the impeller type, impeller location, impeller size and geometry of the tank. They observed that formation of surface vortices was largely governed by interfacial turbulence. These vortices entrapped the gas bubbles. Entrainment of gas into liquid occurred when downward velocity of liquid increased above the terminal rise velocity of gas bubbles. Bhattacharya et al. (2007) conducted experiments on stirred tanks with up pumping and down pumping pitched blade turbines to

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Nomenclature

D	Impeller diameter (m)
DT	Disc turbine
H	Height of liquid in tank (m)
g	Acceleration due to gravity (m/s^2)
k	Turbulent kinetic energy (m^2/s^2)
N_{CSA}	Impeller speed at the onset of entrainment (rpm)
PBTD	Pitched blade turbine down flow
PBTU	Pitched blade turbine up flow
r	Radial location from center of tank
R	Radius of tank (m)
R_b	Radius of bubble (mm)
RMS	Root mean square velocity (m/s)
S	Submergence of impeller below the liquid surface (m)
T	Tank diameter (m)
u''	Velocity scale (m/s)
u	Axial RMS velocity (m/s)
U	Axial Average velocity (m/s)
U_C	Convection velocity (m/s)
$u'(t)$	Fluctuating velocity component (m/s)
V_Z	Axial mean velocity (m/s)
V_r	Radial mean velocity (m/s)
V_θ	Tangential mean velocity (m/s)
v_z	Axial RMS velocity (m/s)
v_r	Radial RMS velocity (m/s)
v_θ	Tangential RMS velocity (m/s)
W	Baffle width (m)

Greek symbols

ρ (τ)	Normalized autocorrelation function
ζ	Integral time scale (s)
ε	Dissipation rate (m^2/s^3)
τ	Time profile (s)
σ	Surface tension (N/m)
μ	Dynamic viscosity (Ns/m^2)
ρ	Liquid density (Kg/m^3)

determine effect of impeller submergence, impeller diameter, baffle geometry and physical properties of fluid on onset of entrainment. They proposed a mechanistic model to predict the onset. They concluded that the key predicting variable at the onset of entrainment was the ratio of RMS velocity at the surface to the mean downward velocity and that this ratio just balanced the physical properties of fluid at onset. Mali and Patwardhan (2009) carried out experiments in stirred tank with different impeller geometries and impeller sizes for gas–liquid and liquid–liquid systems. They reported almost constant values of turbulent kinetic energy for various types of impellers, submergences and impeller sizes. They concluded that axial RMS contributed significantly to turbulent kinetic energy as compared to radial and tangential RMS.

In the present work, effect of scale on the turbulence characteristics at the surface has been investigated for a wide variety of impeller types and sizes.

2. Experimental

Experiments were performed in fully baffled acrylic tanks of three different sizes (diameters – 0.15 m, 0.3 m and 1 m) and baffle width (W = 0.1 T). Three types of impellers (pitched blade up flow – PBTU/down flow – PBTD and disc turbine – DT) were used for the experiments. All the experiments were performed at room temperature (25–30 °C) with water as the test fluid. A constant H/T ratio of 1 was maintained in all cases.

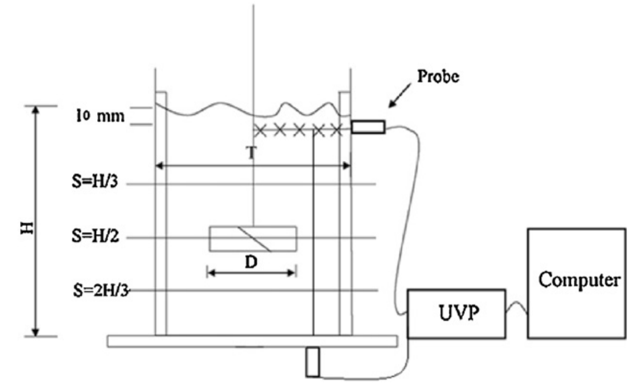

Fig. 1 – Experimental setup for study of shear type entrainment in stirred tanks.

In 1 m diameter tank, measurements were carried out with PBTD (D/T = 0.33) for two submergences (H/2 and H/3). In 0.15 m diameter tank, measurements were made for three types of impellers (PBTD, PBTU and disc turbine) with D/T of 0.36 and for submergences (2H/3, H/2 and H/3). In 0.3 m diameter tank, two sizes of impellers (D/T = 0.18 and D/T = 0.36) were used for all the measurements. A schematic of the experimental setup is shown in Fig. 1.

The onset condition was pre determined by visual observations: Only a few (2–5) bubbles were formed consistently at the air water interface. A low concentration of bubbles was deliberately maintained so as to avoid the interference of air bubbles during velocity measurements. It was ensured that an identical onset was maintained for every single measurement by closely monitoring the speed of the impeller motor. The tank was allowed to equilibrate at onset condition for 3–5 min before starting the velocity measurements. The accuracy of the RPM measurement was within ±5%. Velocity measurements were made 10 mm below air water interface with Ultrasonic velocity profiler (UVP). Both radial and axial velocity components were measured with 1 MHz and 4 MHz UVP probes. The working principle of UVP has been explained elsewhere (Mali and Patwardhan, 2009).

2.1. *Autocorrelation function and dissipation rate*

Autocorrelation coefficient is given as follows:

$$\rho(\tau) = \frac{\overline{u'(t)u'(t-\tau)}}{\overline{u'^2}} \tag{1}$$

Integral time scale (ζ, s) of the autocorrelation function is given as follows:

$$\zeta = \int_{t=0}^{t=\infty} \rho(t)dt \tag{2}$$

The interval up to first zero crossing in the autocorrelation plot is the first time interval over which the flow is related to itself and is likely to be characteristic of the associated