AIR ENTRAINMENT IN BAFFLED STIRRED TANKS

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Abstract: The impeller speed at which air is first entrained from the surface of a stirred tank (N_E) is an operational limit. Where air entrainment is desirable, it is a lower limit, but where air entrainment is detrimental it is an upper limit. This study (1) determines parameters which affect N_E and (2) develops a mechanistic model of air entrainment. Experiments were conducted to determine the effect of impeller submergence, impeller diameter, baffle geometry, and the physical properties of the fluid on N_E for an up-pumping (PBTU), and a down-pumping pitched blade turbine (PBTD). Mean and RMS velocity profiles were measured for selected cases using laser Doppler velocimetry (LDV). Using this data, air entrainment in stirred tanks and at other free surfaces is compared and is found to depend on the balance between gravity, surface tension and surface turbulence. There must be sufficient turbulence at the surface to overcome surface tension and form bubbles. The entrained bubble size is determined by the mean flow below the surface, which acts to pull the bubbles into the tank. It is shown that impeller variables, such as the power number, impeller speed and diameter, cannot predict the point of air entrainment at the surface. The key predicting variable is the ratio of *u*, the RMS velocity at the surface, to the mean downward velocity *U*. At the point of air entrainment, this velocity ratio just balances the physical properties of the fluid.

Keywords: stirred tanks; surface aeration; air entrainment; up-pumping pitched blade turbine.

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INTRODUCTION

Since its advent in the early 1980s the up-pumping axial impeller has been employed in numerous applications ranging from gas dispersion and ingestion of floating solids to the rapid mixing of feed at the surface of stirred tank reactors (Nienow and Bujalski, 2004; Bhattacharya and Kresta, 2004). At high impeller speeds the PBTU starts ingesting air bubbles from the open surface of the vessel. While entrainment of gases from the head-space is beneficial for some processes it can lead to serious problems in others. Additional gas phase mass transfer is beneficial in processes such as wastewater treatment, reactions with significant heat effects and those requiring large amounts of recycle. On the other hand, in processes such as suspension polymerization, entrained bubbles can adhere to droplets and give rise to poor polymer beads (Tanaka *et al.*, 1986; Tanaka and Izumi, 1987). The impeller speed N_E at which the entrainment of air bubbles commences is therefore an important operational limit.

Initial studies on air entrainment into baffled vessels (Calderbank, 1958; Nienow *et al.*, 1979; Chapman *et al.*, 1980; Albal *et al.*, 1983; Veljković *et al.*, 1991) focused on mass transfer and how the impeller type, speed and submergence affect aeration rates. Later studies investigated the power consumption with surface aeration (Sverak and Hrubý, 1981), and the effects of fluid properties, operating parameters and tank geometry on the onset of entrainment (Greaves and Kobbacy, 1981; Tanaka *et al.*, 1986; Tanaka and Izumi, 1987; Veljković *et al.*, 1991). Numerous empirical relations were developed to relate the impeller speed required for surface aeration to parameters such as D/T, S, H and fluid properties. Selected correlations from these investigations are reproduced in Table 1. These correlations give poor results outside the range of the initial experiments (Bhattacharya, 2005) due to the strong dependence of the flow field on geometry. There is a requirement for more rigorous modelling of surface aeration but only a few such studies are available. Sverak and Hrubý (1981) modelled bubble formation at the surface by comparing it to the formation of a non-rotational vortex when fluid is sucked into a thin, vertical tube placed a short distance below the surface and developed a semi-empirical relation for N_E. Greaves and Kobbacy (1981) proposed a model of surface aeration wherein bubbles were formed near the liquid surface and then drawn down into the tank by liquid

Table 1. Minimum impeller speeds for the onset of surface aeration.

Reference	T(m)	D(m)	D/T	C/T	H/T	Fluids used	Impeller type	Correlation
Sverak and Hrubý (1981)	0.014 to 0.18	—	0.33	—	0.111	Distilled water, glycerine solution, carbon tetrachloride, ethyliodide, aq. tenside solutions	RT	$N_E = 4.8\,D^{-0.614}(V^*)^{0.228}\left(\frac{1000}{\rho}\right)^{0.317}\left(\frac{1}{V_{Tank}}\right)^{0.094}$
Joshi *et al.* (1982)				Data from literature			RT	$\frac{N_E D^{1.98}}{T^{1.1}} = \frac{1.65}{N_P^{0.125}}\left(\frac{\sigma g}{\rho}\right)^{0.19}\left(\frac{\mu}{\mu_g}\right)^{0.031}\left(\frac{d_w}{D}\right)^{0.625}$
Heywood *et al.* (1985)	—	0.128 to 0.54	0.22 to 0.938	0.25 to 0.5	0.56 to 1.29	Distilled water, potassium sulphate solution and Isopropanol analar	RT	$n_{SA1} = 1.04T^{0.616}D^{-0.97}C^{-0.23}H^{0.59}$ (for water)
							PBTD	$n_{SA1} = 0.139T^{-0.545}D^{-2.05}C^{-0.25}H^{1.64}$ (for water)
Tanaka *et al.* (1986)	0.1 0.15 0.2	0.05 0.075 0.1	0.25 to 1	0 to 0.9	0.66 to 1.33	Aqueous polyvinyl alcohol solutions		$N_E = 126\left(\frac{\mu}{\sigma}\right)^{0.94}\left(\frac{D}{T}\right)^{-2.3}\left(\frac{H}{T}\right)^{0.44}\left(1-\frac{C}{H}\right)^{0.3}$
Tanaka and Izumi (1987)	0.12 0.15 0.2	0.05	0.32 to 0.50	S/T (0.2 to 0.75)	0.67 to 1.42	Aqueous dodecylether solution	RT	$\left[Fr_l = \frac{N_E^2 D}{g}\right] = 0.023\left(\frac{\sigma}{\sigma_o}\right)^{3.6}\left(\frac{D}{T}\right)^{-3.6}\left(\frac{H}{T}\right)^{0.88}\left(1-\frac{C}{H}\right)^{0.6}$
							PBTD	$\left[Fr_l = \frac{N_E^2 D}{g}\right] = 0.084\left(\frac{\sigma}{\sigma_o}\right)^{3.6}\left(\frac{D}{T}\right)^{-3.6}\left(\frac{H}{T}\right)^{1.44}\left(1-\frac{C}{H}\right)^{1.06}$
							PBTU	$\left[Fr_l = \frac{N_E^2 D}{g}\right] = 0.080\left(\frac{\sigma}{\sigma_o}\right)^{3.6}\left(\frac{D}{T}\right)^{-3.6}\left(\frac{H}{T}\right)^{1.72}\left(1-\frac{C}{H}\right)^{1.24}$
Veljković *et al.* (1991)	0.2 to 0.675	—	1/3	~1/3	1	Distilled water	RT	$N_E D = 0.732$