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Variability of Energy Dissipation and Shear Rate with Geometry in Unbaffled Surface Aerator

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Abstract

The dissipation rate of turbulent kinetic energy (ε) and shear rate (γ) are the key process parameters for mixing in surface aerators. At constant dynamic variables (rotational speed), both ε and γ are greatly affected by the geometric parameters (impeller diameter, cross-sectional area of the tank, liquid height, rotor blade length and immersion height). By doing numerical computation by VISIMIX ®, present work analyzes the effect of non-dimensional (which is non-dimensionalized through rotor diameter) geometric parameters on e and g. With an increase in liquid height, there is an increase in the case of energy dissipation and shear rate values. In the case of tank area and blade length, it is vice versa. Energy dissipation and shear rate are not affected by the variation in immersion height of the impeller. © 2009 BCREC. All rights reserved.

Keywords: Energy dissipation; mixing; shear rate; surface aerator

1. Introduction

Entrainment of gas from a gas-liquid surface is known as surface aeration. Stirred reactors designed for this type of gas-liquid contact are called surface aerators. The main functions of surface aerators are to enhance the oxygen transfer rate, liquid phase mixing to ensure oxygen availability in all parts of the contactor, and suspension of microorganisms [1-3]. Generally unbaffled tanks are employed for surface aerators, because unbaffled tanks give rise to higher fluid-particle mass transfer rates for a given power consumption [4], which is the paramount importance in designing aeration system. Baffled tanks are also giving rise to dead zones, actually worsening the mixing performance of an aeration system [5]. It has been also recognized that the local value of the mass transfer rates would probably vary from one region to another in baffled tanks [6]. There are regions in the tanks where the surface renewal rate is high and the other parts where the liquid is relatively stationary [6]. This non-uniformity of local value of mass transfer rates is the fundamental disadvantage of the use of baffled tank in mass transfer process.

In surface aerator, mechanical energy is transferred from the impeller to the fluid causing fluid motion and then the energy dissipates in the fluid. The quantification of the dissipation rate of the

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turbulence kinetic energy (ε) is of paramount importance for the optimization of fluid mixing processes in such vessels [7-10]. Shear rate of the flow in a mixing tank is also an important parameter controlling processes characteristics. High shear fields resulting from the fluid physical properties and the hydrodynamics may cause damage to fragile microorganisms and bio-films formation [11-12] or mechanical instability to immobilized biocatalysts [13-14]. However, a certain degree of shearing is required to attain sufficient heat and mass–transfer rates, and to achieve a homogeneous distribution of transferred components into the bulk fluid. Process characteristics of surface aeration depend on the geometrical parameters. In fact, the geometry is so important that processes can be considered "geometry specific". In the present work, it is aimed to find the effect of geometric parameter on these two important process variables (kinetic energy dissipation rate and shear rate).

2. Theory

Figure 1 shows the schematic drawing of a surface aeration tank used in the present study. The geometric variables include cross-sectional area A (m^2) of the tank, depth H (m) of water in the tank, diameter D (m) of the rotor, length l (m) of the blades, distance h (m) between the top of the blades and the horizontal floor of the tank and the number of blades (n) as shown in Figure 1. Rushton type aerator with six flat blades has been used in the analysis. In the present study, the ratio of l/b has been maintained constant (=1.25). The geometric parameters have been non-dimensionalized by dividing through the rotor diameter (D). Cross-sectional area of tank used in the analysis is 1 m^2. Energy dissipation rate (ε in W/kg) and shear rate (γ in 1/s) on different geometric parameters have been calculated by using visimix® software at different impeller rotational speed.

2.1. Dissipation Rate of Turbulent Kinetic Energy, ε

A characteristic feature of turbulent flow is the presence of a wide range of eddy sizes, ranging from the flow domain, i.e. integral scale eddies, to smaller sizes, i.e. Kolmogorov scale eddies [15].

The large eddies are unstable, interact with each other and with the boundaries of the flow and break down into multiple smaller eddies transferring their energy to them. First, this transfer is efficient and very little kinetic energy is lost [15]. When the eddies become small enough, in the order of Kolmogorov scale in size, that the eddy motion is stable, viscosity takes over and the energy is damped out and converted into heat. This process is usually described as a turbulence cascade, where energy continually flows from larger to smaller eddy and at the smallest eddy scale, there is an ultimate sink of energy by viscous dissipation. This conversion of energy can be quantified using the kinetic turbulent energy dissipation rate ε. The direct measurement of ε is very difficult, since it needs to capture precisely the smallest turbulent structures [16]. There have been many attempts to model the rate of energy dissipation because of the difficulties involved in measuring and quantitatively determining it directly. In the past, several methods were developed to estimate the dissipation rate of turbulent kinetic energy:

- Kinetic energy balance term averaged over a control volume [17-19]
- Integration of dissipation spectrum [20-21]
- Dimensional analysis [22]

In the present work, ε of surface aeration systems has been calculated by using commercial software Visimix®. The Visimix® program can be helpful in analyzing the mixing parameters in stirred tanks [10, 23-24]. The calculation procesure (which is kinetic energy balance term averaged over a control volume) are described as follows:

The mean value of the kinetic energy of turbulence, E at the radius r is defined as:

$$E = 3\overline{v'}^2 / 2 \quad (1)$$

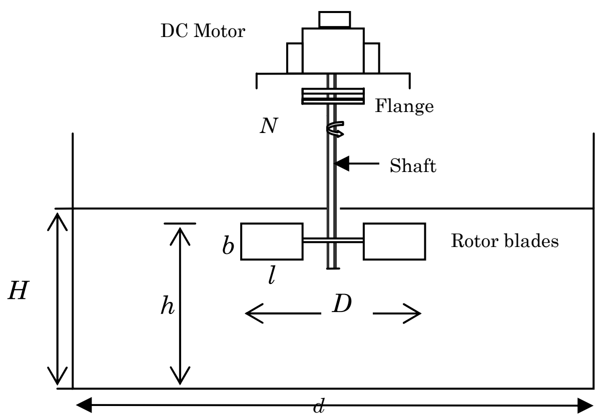

Figure 1: Schematic diagram of a Surface Aeration Tank

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where $\bar{v}'$ is the mean square root velocity of turbulent pulsations corresponding to the largest local linear scale of turbulence. Steady-state transport of the turbulent component of kinetic energy can be described as:

$$q\left(\frac{dE}{dr}\right)-\frac{d}{dr}\left[2\pi rhj\,v_e\left(\frac{dE}{dr}\right)\right]+2\pi rhj\varepsilon=0 \qquad (2)$$

where q is the circulation flow rate through the rotor (1/s), ν_e is the eddy viscosity and h_j is the local linear scale of turbulence which is approximately equal to 1.5b. The dissipation rate of energy around the impeller at single speed is shown in the Figure 2.

As it can be seen from the Figure 2 that dissipation rate is very high in the impeller region. Kresta and Wood [25] investigated turbulence quantities in a stirred vessel with emphasis on energy dissipation. It is assumed that the bulk of the energy is contained in the largest eddies, the flow is at local equilibrium and the flux of energy towards smaller scales is constant. Zhou and Kresta [22] used a dimensional argument and found that most of the total energy is dissipated in the near vicinity of the impeller discharge. Equation (2) is solved for $\bar{v}' = 0$ at $r = \infty$. The value of $\bar{v}'$ on the other boundary ($r = d/2$) is calculated using an estimated value of the maximum dissipation rate in the flow past the blades:

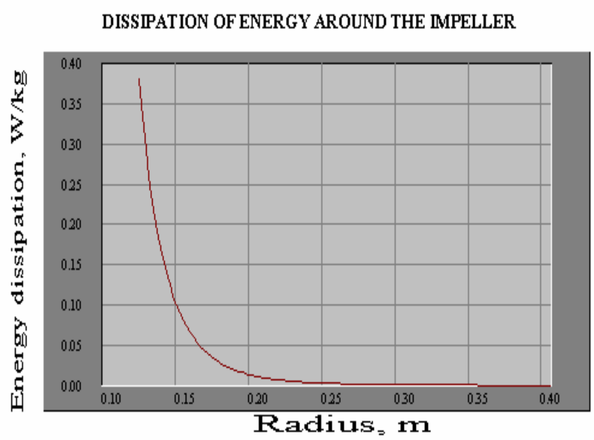

Figure 2: Energy dissipation rate around the impeller

$$\varepsilon_m=\left[(2\pi rN-v_o)Sin\,\alpha\right]^3/l \qquad (3)$$

where v_o is the axial velocity of the rotor (m/s). The dimensions of the *em* zone (length, height and width) are l, b and b/2, respectively. The mean value of dissipation is estimated as:

$$\varepsilon=\varepsilon_m Nb/6\pi r \qquad (4)$$

The unit of turbulent dissipation rate, ε is W/kg. Equation (4) is solved numerically to get the value of ε at different rotational speed.

2.2. Shear Rate

Shear rate is an important parameter in surface aerators, but it is not easy to be characterized. Knowledge of the shear rate is essential for the design and operation of surface aerators. The specific energy dissipation rate in a stirred tank is well known to depend on the shear rate γ and the shear stress τ [5], as follows [26]:

$$\gamma=\sqrt{\frac{1}{\mu}\frac{P}{V}} \qquad (5)$$

where P is the power input (watt), μ is dynamic viscosity of the fluid (NS/m^2) and V is the volume of the fluid in the tank (m^3). Equation (5) applies to laminar, turbulent and transitional flows. In laminar ranges, γ is linearly related to the rotational speed of the rotor (N) [27]. In turbulent flow, it is nonlinearly related to N [27]. One of the simpler ways to calculate shear rate is agitator tip speed over the distance between the tip and the vessel wall:

$$\gamma= N\,D\,/\,(d-D) \qquad (6)$$

where d is the tank diameter. Visimix® however, defines shear rate as the ratio of turbulent fluctuation velocity, v_0, to the Kolmogorov turbulence scale, L_0 as follows:

$$\gamma= v_0\,/\,L_0 \qquad (7)$$

L_0 is called the Kolmogorov length and depends primarily upon the power input per unit mass and the kinematic viscosity. Values of shear rate are calculated at different geometric parameters at different rotational speeds

3. Results and Discussion

Energy dissipation and shear rate are basically correlated with the power consumption and rotational speed of the rotor, which is in turn related with the oxygen transfer capacity of the surface aerator. Based on the analysis of Rao [28], it can be said that at constant rotational speed and for particular sized tank, ε and γ are affected by the geometric parameters such as H/D, h/D, l/D and $A^{0.5}/D$. The purpose of the present work is to find the effect of geometric parameters on ε and γ.

3.1. Effect Due to Variation in *H/D*

As discussed earlier water depth has been non-dimensionalized by the rotor diameter, the value of H/D has been varied from 0.84 to 1.1 to ascertain the energy dissipating trend in the vicinity of the impeller. The results have been shown in the Figure 3. As shown in the Figure 3, both ε and γ show an increasing trend. It clearly indicates that the increase of rotational speed will increase the liquid pumping capacity of the impeller, thus the mixing quality will be improved and consequently energy dissipation and shear rate.

3.2. Effect Due to Variation in *h/D*

The effect due to variation in h/D, which signifies the impeller submergence, has found to be having no effect on the ε and γ as shown in the Figure 4. The reason for such behavior may be probably attributed to the fact that by definition of the surface aeration systems, impeller should be placed as near as water surface. Preserving the definition of surface aerator, there is no significant variations in h/D. The given variations are not able to effect the energy dissipation and shear rate significantly.

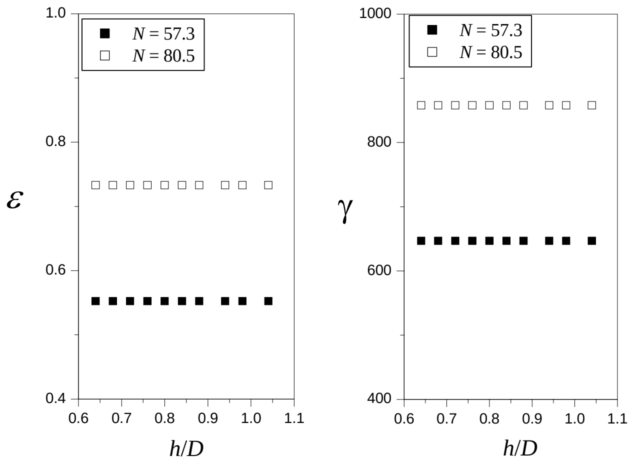

Figure 4: Effect on ε and γ due to variations in h/D

3.3. Effect Due to Variation in *l/D*

The rotor blade is the most critical part of the surface aeration system since it determines the type of flow pattern, pumping and circulation flow rates. In the present case, l/D has been varied from 0.24 to 0.34. Results have been shown in the Figure 5.

It can be seen from the Figure 5 that an increases in blade width have been seen to result in corresponding decrease in ε and γ.

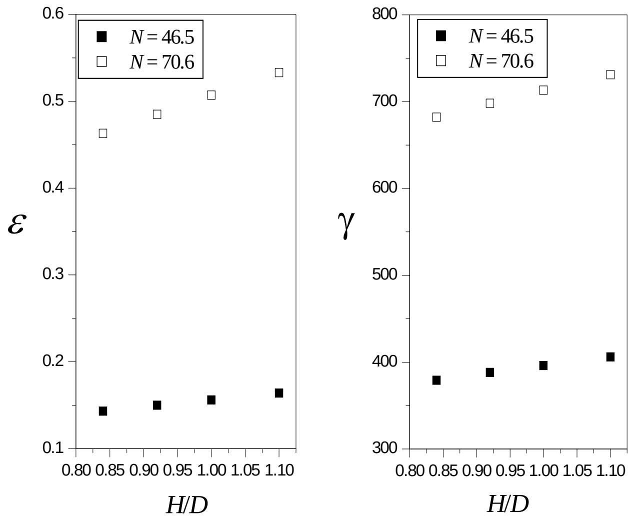

Figure 3: Effect on ε and γ due to variations in H/D

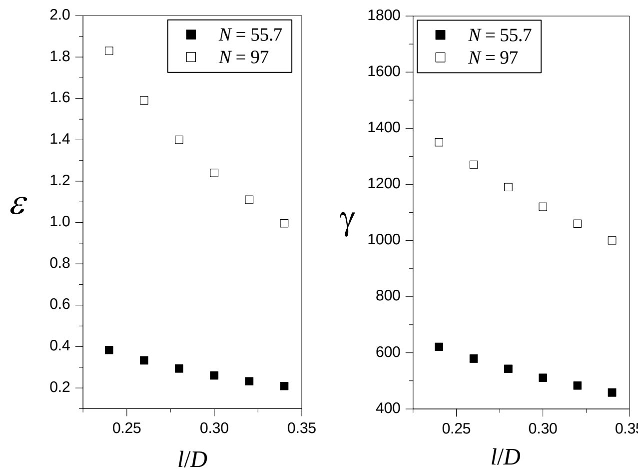

Figure 5: Effect on ε and γ due to variations in

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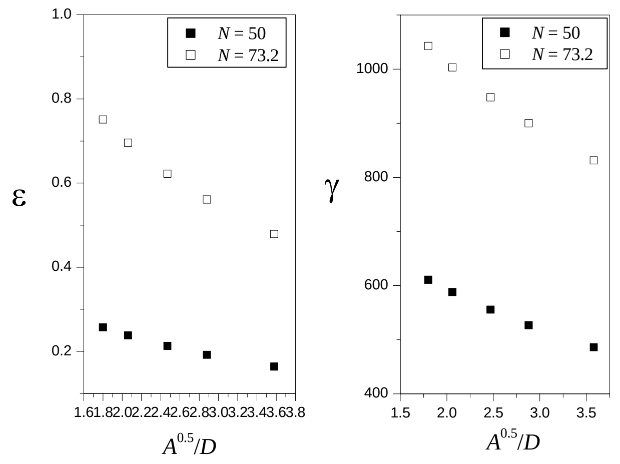

Figure 6: Effect on ε and γ due to variations in $A^{0.5}/D$

3.4. Effect Due to Variation in √*A/D*

Results due to variation in $\sqrt{A}/D$ have been shown in the Figure 6. The trend shows a decreasing with increasing $\sqrt{A}/D$. It can be due to that a lower value of $\sqrt{A}/D$ intensifies the turbulence, which results in high energy dissipation and shear rate.

4. Conclusions

The knowledge of the variation of the rate of dissipation of the turbulence energy (ε) and shear rate (γ) with geometric parameters in surface aeration systems is of paramount importance for the design and operation. Present work shows qualitatively how the variations in geometric parameters affect the ε and γ. It is found that with an increase in *H*/*D*, ε and γ increases whereas it is vice versa in case of *l*/*D* and $\sqrt{A}/D$. It is also found that the variation in *h*/*D* do not affect the ε and γ.

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