ORIGINAL ARTICLES

Interfacial Area Density in Flotation Cell

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ABSTRACT

In this work, a simulation of froth flotation cell has been carried out to study interfacial area density in flotation cell. The phenomena of interfacial area density for gas and liquid phase have been analyzed based on the particle model. The interfacial area density decreases with axial position from impeller tip to mixture height of the cell. The variations of specific power and the interfacial area from the present work have been presented. From the present work it is seen that the interfacial area increases with increase in specific power input. A correlation has also been made to represent the interfacial area density in terms of specific power requirement and axial position.

Key word: Two-phase flow, froth flotation, interfacial area density, CFD, particle model.

Introduction

Flotation cells are very popular in industry for gas-liquid-solid contacting operations involved in mineral processing (Deng et al., 1996). There are various types of flotation cell like Wemco, Denver, Knapp, Bates, etc. are popular in industry for specific applications. Among various types of flotation cell the Wemco type of flotation cell provides higher values of the rate of gas induction (by 50 - 500%) and effective interfacial area (by 50 - 70%) than those provided by pipe and flattened cylindrical impellers at the same power consumption (Sawant. et al., 1981).

One important development area of the recent decade has been Computational Fluid Dynamics. This powerful tool can help to get quick estimation of new designs, cell hydrodynamics optimisation and process optimization by determining optimum setups for each process (Bourke, 2007). There have been lots of investigations on CFD model for flotation cells, and the key for reliable modelling method is the validation work in laboratory and industrial test (Song et al., 2009) There have been some investigations on CFD models for flotation cells and stirred tanks which use the hexahedral elements that give good results in predicting the gas volume fraction in lab (Lane et al., 2005; Koh and Schwarz, 2007). Other different studies by simulations are: modeling hydrodynamics of mechanically agitated flotation cells were mainly based on steady-state analyses (Ranade, 1995); studies on impeller type, impeller speed and air flow rate in an industrial scale flotation cell (Gorain et al. (1996)); flow characteristic (Mavros et al. (2001)); bubble particle collision rates and efficiencies in a flotation cell (Koh et al., 2003). turbulent fluid flow combining fine grids with higher–order discretization schemes (Delgon and Meyer (2006)). Some studies has also been made on multiple turbine on a single shaft such as CFD simulation of mixing in tall gas-liquid flow generated in stirred vessel by three down-pumping pitched blade turbines (Khopakar et al., 2006). Flow patterns, phase fraction and kinetic energy distribution in flotation cell (Khopakar et al., 2006). From the literature it is found that most of the studies have been focused on analyzing the flow field, phase fraction, particle collision and turbulent kinetic energy profile but there is no sufficient quantitative analysis has been done on interfacial area profile in the flotation cell.

However, there are practically no analyses available in the literature regarding the interfacial area characteristics of the flotation cells. The present work, therefore, is concerned with the investigation of the interfacial area density of the flotation cells.

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System Considered in the Present Study:

A cylindrical vessel of diameter of 2.5 m and a height of 3.05 m with semispherical bottom was considered as a flotation tank in this study. A four-bladed Pitched blade impeller pumping down (PBTD) with blades at an angle of 45° from the horizontal plane was considered as a provision to make intense mixing of phases in the tank. The volume of the tank is 15.0 m³. The diameter of the impeller was \( D_a = T/2 \). The width and clearance of bottom were considered as 1 mm and \( C = T/3 \). Four baffles of \( T/10 \) in diameter were considered to equally place around the tank. The working material was water as liquid phase and air as gaseous phase. The rotation speed of the impeller was varied while keeping gas velocity constant and on the other hand gas velocity was varied while keeping rotation velocity of the impeller constant. The schematic diagram of the flotation tank is shown Figure 1.

![Schematic diagram of a flotation cell.](image)

Gas is entering from bottom side of the tank. Due to the symmetry of the geometry, only one-fourth of the flotation cell is considered as the computational domain. The very first step in any CFD simulation is the discretization of the computational domain. In this study the geometry discretization is done using block structured grids which allows finer grids in regions where higher spatial resolutions are required. The computational grid used of its 1/4th section which has been used in this simulation work. The system properties which are considered in the present work are shown in Table 1.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Gas</th>
<th>Liquid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal expansivity</td>
<td>0.003356 K⁻¹</td>
<td>2.57×10⁻⁴ K⁻¹</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>1.831×10⁻⁹ kg/m.s</td>
<td>8.899×10⁻⁴ kg/m.s</td>
</tr>
<tr>
<td>Density</td>
<td>1.185 kg/m³</td>
<td>997.0 kg/m³</td>
</tr>
<tr>
<td>Molar mass</td>
<td>28.96 g/mol</td>
<td>18.02 kg/mol</td>
</tr>
<tr>
<td>Reference pressure</td>
<td>1 atm</td>
<td>1 atm</td>
</tr>
<tr>
<td>Reference temperature</td>
<td>25°C</td>
<td>25°C</td>
</tr>
<tr>
<td>Reference specific enthalpy</td>
<td>0.0 J/kg</td>
<td>0.0 J/kg</td>
</tr>
<tr>
<td>Reference specific entropy</td>
<td>0.0 J/kg/K</td>
<td>0.0 J/kg/K</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>1.0044×10³ J/kg K</td>
<td>4181.7 J/kg K</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>2.61×10⁻² W/m</td>
<td>0.6069 W/m K</td>
</tr>
</tbody>
</table>

Theoretical Background:

Two distinct multiphase flow models are available. These are Eulerian–Eulerian multiphase model and a Lagrangian particle tracking multiphase model. Two different sub-models are available for Eulerian-Eulerian multiphase flow; these are homogeneous model and inter-fluid transfer (inhomogeneous) model. Out of which we have used inhomogeneous model in this simulation work. There are two models available. These are particle model and mixture model. However we have discussed both the models in the following section but in this work particle model has been used. Interfacial transfer of momentum, heat and mass is directly dependent on the contact surface area between the two phases. This is characterized by the interfacial area per unit volume between phase \( a \) and phase \( \beta \), known as the interfacial area density, \( A_{\alpha\beta} \). Interfacial transfer can be modeled using either the particle or mixture models. These essentially provide different algebraic prescriptions for the interfacial area density. The Particle model for interfacial transfer between two phases assumes that one of the phases is continuous (phase \( a \)) and the other is dispersed (phase \( \beta \)).
The surface area per unit volume is then calculated by assuming that phase $\beta$ is present as spherical particles of mean diameter, $d_\beta$. Using this model, the inter-phase contact area or interfacial area is:

$$ A_{\alpha\beta} = \frac{6\gamma_\beta}{d_\beta} $$

(1)

Where different phases of fluids are denoted using lowercase Greek letters $\alpha$, $\beta$, etc. In general, a quantity subscripted with $\alpha$, $\beta$, etc., refers to the value of the quantity for that particular phase. For example, the volume fraction of $\alpha$ is denoted $\gamma_\alpha$. Thus, the volume $V_\alpha$ occupied by phase $\alpha$ in a small volume $V$ around a point of volume fraction $\gamma_\alpha$ is given by:

$$ V_\alpha = V \gamma_\alpha $$

(2)

Non-dimensional inter-phase transfer coefficients may be correlated in terms of the particle Reynolds number and the fluid Prandtl number. These are defined using the particle mean diameter, and the continuous phase properties, as follows:

$$ Re_{\alpha\beta} = \frac{\rho_\alpha |U_\beta - U_\alpha| d_\beta}{\mu_\alpha} $$

(3)

$$ Pr_{\alpha\beta} = \frac{\mu_\alpha C_p\alpha}{\lambda_\alpha} $$

(4)

Where $\rho_\alpha$, $C_p\alpha$ and $\lambda_\alpha$ are the viscosity, specific heat capacity and thermal conductivity of the continuous phase $\alpha$. Mixture model treats both phases $\alpha$, $\beta$ symmetrically. The surface area per unit volume is calculated as:

$$ A_{\alpha\beta} = \frac{\gamma_\alpha \gamma_\beta}{d_{\alpha\beta}} $$

(5)

where $d_{\alpha\beta}$ is an interfacial length scale, to be specified. In this case interfacial area density is expressed by:

$$ A_{\alpha\beta} = \frac{6\gamma_\alpha \gamma_\beta}{\gamma_\alpha d_\beta + \gamma_\beta d_\alpha} $$

(6)

Non-dimensional interphase transfer coefficients may be correlated in terms of the mixture Reynolds number and Prandtl number defined as follows:

$$ Re_{\alpha\beta} = \frac{\rho_{\alpha\beta} |U_\beta - U_\alpha| d_{\alpha\beta}}{\mu_{\alpha\beta}} $$

(7)

$$ Pr_{\alpha\beta} = \frac{\mu C_{p\alpha\beta}}{\lambda_{\alpha\beta}} $$

(8)

Where $\rho_{\alpha\beta}$, $C_{p\alpha\beta}$ and $\lambda_{\alpha\beta}$ are the density, viscosity, specific heat capacity and thermal conductivity of the mixture respectively, defined by:

$$ \rho_{\alpha\beta} = \gamma_\alpha \rho_\alpha + \gamma_\beta \rho_\beta $$

(9)

$$ \mu_{\alpha\beta} = \gamma_\alpha \mu_\alpha + \gamma_\beta \mu_\beta $$

(10)

Bubble size used in the CFD simulation is validated by calculating the bubble size based on the reported correlations in literature (Calderbank and Moo-Young, 1961) according to the following correlation:
Simulation Procedure:

The commercial code of Ansys CFX software is used for the simulation. A uniform velocity profile is assumed in the bottom side inlet. A control volume finite method is employed to solve the governing equations. k-ε model is used for capturing the turbulence of liquid for the given situation. Zero equation models have been employed for capturing the turbulence of gas phase for the given situation for more details. As said in the theory k-ε is two parameter based model sufficient enough for the situation. Steady state simulations are performed for PBTD impeller, different rotational speeds, and gas velocity.

Boundary Conditions:

(i) an inlet through which air enters the mixer. Inlet: Speed = 5 m/s; Static Temperature = 25°C (ii) A degassing outlet, so that only the gas phase can leave the domain. Boundary type = outlet; Location = upper liquid surface, Boundary details = Degassing condition. (iii) Thin surfaces for the baffle and impeller blade. Boundary Type = Wall; Location = Wall Baffles. For air at 25°C, wall influence on flow is taken as free slip. For water, wall influence on flow is taken as no slip. (iv) A wall for the hub and shaft in the rotating domain. Boundary Type = Wall; Location = Wall Shaft, Wall Shaft center. For air at 25°C, wall influence on flow is taken as no slip. Shaft velocity = 100 rev min⁻¹. Axis of rotation was taken in X-direction. (v) A wall for the shaft in the stationary domain. This will be rotating relative to the stationary domain. Boundary Type = Wall; Location = Blade, Hub, Shaft. For air at 25°C, wall influence on flow is taken as free slip. For water, wall influence on flow is taken as no slip. (vi) Periodic domain interfaces for the periodic faces of the tank and impeller.

Initial Values:

The initialization for volume fraction is 0 for air. Therefore, the initial volume fraction for water will be set to 1 so that the sum of the two fluid volume fractions is 1. Initial water velocity is taken as 0 m/s. Turbulent eddy dissipation is incorporated in the simulation. Blend factor of 0.75 is employed as our advection scheme in the solver. Timescale Control = 1s. Max Number of Iterations = 3000. Residual Type = RMS. Residual Target = 10⁻¹⁰.

Results and discussion

Interfacial transfer of heat, momentum, and mass is directly dependent on the contact area between the two phases. This is characterized by the interfacial area per unit volume between phases, known as interfacial area density. In this simulation work Particle model has been considered. Here, the profile of interfacial area density has been shown contour plot in the Figure 2.

From the contour plot (Figure 2), it is clear that interfacial area density is higher in the vicinity of blade region of impeller. Keeping gas inlet velocity constant, rotational speed of the impeller is varied and as the rotation speed increases interfacial area below the impeller increases which demonstrate the importance of these regions to the gas–liquid mass transfer. In the air–water system (Figures 2(a)-(d)), gas–liquid interfacial area increases rapidly with the increasing stirring speed below the impeller. Because of the downward flowing liquid there is a balance between the buoyant and drag force and therefore, bubbles become trapped into these regions. Barigou and Greaves (1996) have made a similar observation. Also the coalescence and break-up events influence the development of the interfacial area concentration that decreases with coalescence and increases with the break-up of large bubbles. Higher turbulence is generated below the impeller which enhances the break-up events of the gas bubbles. Initially up to, Nₚ= 1.67 rps, interfacial area density is varying with less slope but beyond this rotation speed it starts increasing with impeller speed sharply as shown in Figure 3. The same trends of interfacial area changing with impeller speed were observed by Mehta and Sharma (1971), Joshi et al., 1981, Sawant et al. 1981. They stated that at a certain impeller speed, a starts increasing with N and at relatively high impeller speeds a varies linearly with N.

An extrapolation of the linear part of the plot gives the value of N₀, the critical impeller speed, Westerterp et al. (1979) and Mehta and Sharma (1971) have shown that, above the value of N₀, a is practically
independent of the superficial gas velocity (Joshi et al., 1981).

The value of critical impeller speed from this simulation is 10.02 rpm. However, there is no such experimental data is available to validate this result and especially for same geometry of the tank. A comparison of interfacial area obtained by present work with that obtained by correlation developed by Sawant et al., 1981 is also shown in Figure 3.

Fig. 2: Contour plot of interfacial area density at $v_g = 5$ m/s.

Fig. 3: Effect of impeller speed on Interfacial area density.

From the figure it is seen that the error from the present analysis is in the acceptable range (below 15%). The interfacial area decreases axially from the impeller location to the top of the tank. This is due to the axial variation of kinetic energy distribution. The variation of the interfacial area density with the axial position at radial position of 0.625 m from the tip of the impeller blade is shown in Figure 4. At different Reynolds number, the variations of specific power and the interfacial area from the present work is shown in Table 2. From the present work it is seen that the interfacial area increases with increase in specific power input. A correlation has been made to represent the same which can be expressed as:
The correlation (Eqn. 12) predicts the interfacial area density well with 9% error and correlation coefficient ($R^2$) of 0.999.

\[ a = 68.59 \left( \frac{P}{V} \right)^{0.4995} \]  

(12)

A correlation has also been made to predict the interfacial area density as a function of axial length at the mean radial position between impeller diameter and the tank diameter and the impeller speed which can be represented as:

\[ a = A \left( \frac{x}{H} \right)^3 + B \left( \frac{x}{H} \right)^2 + C \frac{x}{H} + D \]  

(13)

\[ A = -2.32 \times 10^3 N^2 + 2.31 \times 10^4 N - 3.24 \times 10^4 \]  

(14)

\[ B = -4.73 \times 10^3 N^2 + 4.76 \times 10^4 N - 6.65 \times 10^4 \]  

(15)

\[ C = -3.13 \times 10^3 N^2 + 3.19 \times 10^4 N - 4.39 \times 10^4 \]  

(16)

\[ D = -0.70 \times 10^3 N^2 + 0.71 \times 10^4 N - 0.96 \times 10^4 \]  

(18)

The correlation (Eqns. 13-18 is found to satisfactorily predict the interfacial area density. The parity plot of simulation vs developed correlation (Eqn. 13) for impeller speed of 3.33 rps is shown in Figure 5.

**Fig. 4:** Variation of interfacial area density with axial length position at radial position 0.625 m from the impeller at radial.

**Fig. 5:** Parity of simulation vs developed correlation (Eqn. 13) for impeller speed of 3.33 rps.
Table 2: Variations of interfacial area inside the tank with Reynolds number, specific power.

<table>
<thead>
<tr>
<th>Re ×10^{-5} (-)</th>
<th>N_p (-)</th>
<th>N_p = P / ρ N^3 D_a^2</th>
<th>N (s)</th>
<th>P (W)</th>
<th>P/V (W/m³)</th>
<th>a (m²/m³)</th>
<th>a (m²/m³) (by eqn. 12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.09</td>
<td>0.03987</td>
<td></td>
<td>0.167</td>
<td>0.57</td>
<td>0.04</td>
<td>15.06</td>
<td>13.81</td>
</tr>
<tr>
<td>58.35</td>
<td>0.036136</td>
<td></td>
<td>1.67</td>
<td>513.61</td>
<td>34.24</td>
<td>409.85</td>
<td>414.31</td>
</tr>
<tr>
<td>116.70</td>
<td>0.041856</td>
<td></td>
<td>2.50</td>
<td>1995.85</td>
<td>133.06</td>
<td>761.68</td>
<td>816.17</td>
</tr>
<tr>
<td>204.23</td>
<td>0.039693</td>
<td></td>
<td>3.33</td>
<td>4472.97</td>
<td>298.20</td>
<td>1146.91</td>
<td>1221.34</td>
</tr>
<tr>
<td>229.03</td>
<td>0.033282</td>
<td></td>
<td>6.67</td>
<td>30139.97</td>
<td>2934.09</td>
<td>3167.37</td>
<td></td>
</tr>
</tbody>
</table>

Conclusions:

From the present work, it can be concluded as:

- Interfacial area density is higher in the vicinity of blade region of impeller.
- The coalescence and break-up events influence the development of the interfacial area concentration that decreases with coalescence and increases with the break-up of large bubbles. Higher turbulence is generated below the impeller which enhances the break-up events of the gas bubbles.
- Effective interfacial area density varies with impeller speed. Initially up to, N=510 rpm, effective interfacial area density is almost constant but beyond this rotation speed starts increasing with impeller speed.
- The value of critical impeller speed from this simulation is 31 rpm.
- Knowledge of interfacial area density is very useful for industrial applications. It may also helpful in optimizing the power drawn for running impeller for a required mass transfer in a particular application.

List of Symbols:

- \( a \) Interfacial area density (1/m)
- \( d_{ab} \) Interfacial length scale (m)
- \( C_{pa} \) Specific heat capacity of the continuous phase \( \alpha \) (J/kg K)
- \( C_{pab} \) Specific heat capacity of the mixture of phase \( \alpha \) and \( \beta \) (J/kg K).
- \( D_a \) Impeller diameter (m)
- \( H \) Tank height (m)
- \( N \) Rotation speed of impeller (rpm)
- \( N_0 \) Critical impeller speed, (rps)
- \( N_p \) Power number, (-)
- \( P \) Power required by the impeller (W)
- \( Re_{ab} \) Reynolds number for phases \( \alpha \) and \( \beta \)
- \( T \) Tank diameter (m)
- \( U \) Velocity vector (m/s)
- \( V_{\alpha} \) Volume occupied by \( \alpha \) phase (m³)
- \( v_g \) Gas inlet flow rate (m/s)
- \( \varepsilon \) Turbulent dissipation rate (m²/S³)
- \( \mu \) Viscosity (kg/m s)
- \( \alpha \), \( \beta \) Phases (-)
- \( \mu_\alpha \) Viscosity of the continuous phase \( \alpha \) (Kg/ms)
- \( \mu_{\alpha\beta} \) Viscosity of the mixture of phase \( \alpha \) and \( \beta \) (Kg/ms)
- \( \lambda_\alpha \) Thermal conductivity of the continuous phase \( \alpha \) (W/m K)
- \( \lambda_{\alpha\beta} \) Thermal conductivity of the mixture of phase \( \alpha \) and \( \beta \) (W/m K)
- \( \gamma_\alpha \) Volume fraction of \( \alpha \) phase (-)
- \( \rho_{\alpha\beta} \) Density of the mixture of phase \( \alpha \) and \( \beta \) (kg/m³)

References


