CFD SIMULATION OF FLUID FLOW IN AN AGITATED SYSTEM WITH A PITCHED BLADE WORN IMPELLER

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Abstract. This paper presents an analysis of the velocity field in an agitated fully baffled cylindrical vessel with a down pumping four blade worn or unworn pitched blade impeller (α = 45°) under a turbulent flow regime. CFD simulations were used to describe of the ensemble-average mean velocity field with worn and unworn impellers and their pumping capacity. It follows from the simulation results that the wear rate of the impeller blade has a significantly negative effect on the velocity distribution in an agitated liquid. The higher the destruction of the worn blade, the higher is the deformation of the velocity field around the rotating impeller with a simultaneous decrease in impeller pumping capacity.

Keywords: Pitched blade impeller; Erosion wear; Ensemble-average mean velocity; Impeller pumping capacity; CFD simulation

1. INTRODUCTION

In all areas of particulate technology where solid particles are handled, structures that come into contact with the particles exhibit wear. In some applications this wear may be so severe as to limit the life of a component or plant [1], while in others it may be negligible [2].

The erosion wear of the impeller blades while mixing a solid-liquid suspension usually has a negative effect on the technological operation. The erosion process of a pitched blade impeller caused by particles of higher hardness can be described by means of the change in the shape in the worn blade leading edge according to the relation [3]

\[ Y(R) = 1 - C \exp[k(1 - R)] \]  

where \( Y \) is a dimensionless transversal coordinate along the width of the blade, and \( R \) is a dimensionless longitudinal (radial) coordinate along the radius of the blade,

\[ Y = y(r)/h \]  
\[ R = 2r/D \]

when \( y \) and \( r \) are the dimensional coordinates of the worn blade edge presented in Fig.1 (\( h \) is blade height and \( D \) is impeller diameter).

The values of the parameters of Eq. (1), the wear rate constant \( k \), and the geometric parameter of the worn blade \( C \) depend on the impeller pitch angle \( \alpha \), on the physico-chemical properties of the solid-liquid suspension, and on time \( t \). These parameters should be calculated from the experimentally determined profile of the worn blade under given conditions in an agitated charge [3].
2. MATERIALS AND METHODS

Measurements of the wear rate of an impeller were presented in [1, 3]. A pilot plant was made from stainless steel with water as the working liquid and with corundum particles. The wear rate was observed after a specified process time, see Table 1, and is described by Eq. (1).

This paper deals with a CFD simulation of the velocity field in agitated liquid water in a fully baffled cylindrical system, see Fig.2, with a down pumping four blade pitched blade impeller, see Fig.3, under a turbulent flow regime. The geometry of the stirred tank was generated by CAD/CAM software according to the experimental apparatus. The leading worn edge of the impeller blade was modified for the appropriate erosion time using relation (1). Four worn blades and an initially unworn blade were modeled by the CAD/CAM system and included in a geometric model of a stirred tank.

The Gambit 2.4 preprocessor was applied to assemble the mesh. Special care was paid to selecting the density of the computational grid (a combination of tetrahedral and hexahedral...
cells) in the vicinity of the curved leading edge of the pitched blade. The tetrahedral elements surrounded only the impeller, while the rest of the model volume was filled by hexahedral cells. The dependency of the convergence sensitivity on the grid size was analyzed. The optimal model mesh size due to convergence and computation time was found. The number of cells was estimated to be $5.10^5$. The cell quality was also examined. The element equiangle and equisize skew parameters were no greater than 0.5 for fewer than 5% of the elements. The Reynolds stress simulation for the steady – state Multiple Reference Frame (MRF) approach was used with the standard wall function in the pilot plant mixing vessel (diameter $D = 300\text{mm}$) [4].

The recommended ratios for the dimensions of the rotating reference frame for an agitated vessel correspond to the impeller blade height and to the diameters of the vessel and the impeller. The height of the MRF is about 2.5 times the blade height [5], and the MRF diameter is equal to the median diameter between the blade tip and the baffle inner edge [6]. The first order upwind, the second order upwind and the high order QUICK scheme were applied to discrete the convective terms. The numerical solution of the flow equation was achieved by a finite – volume method in the realm of the FLUENT 6.3 general purpose CFD code [7].

The ensemble-averaged mean time flow field was calculated both for unworn and worn impellers, where the parameters of Eq. (1) were taken from the experimental data [1, 3], see Table 1.

Table 1. Main characteristics of CFD computations in the investigated system ($k = -2.90 \pm 0.11$).

<table>
<thead>
<tr>
<th>$t$ [h]</th>
<th>$C$</th>
<th>$N_{Qp, exp}$</th>
<th>$N_{Qp, comp}$</th>
<th>$R_{max, z}$</th>
<th>$R_{max, t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.850</td>
<td>0.820</td>
<td>0.227</td>
<td>0.307</td>
</tr>
<tr>
<td>40</td>
<td>0.116</td>
<td>0.816</td>
<td>0.790</td>
<td>0.240</td>
<td>0.307</td>
</tr>
<tr>
<td>60</td>
<td>0.174</td>
<td>0.798</td>
<td>0.782</td>
<td>0.233</td>
<td>0.300</td>
</tr>
<tr>
<td>80</td>
<td>0.232</td>
<td>0.781</td>
<td>0.759</td>
<td>0.253</td>
<td>0.313</td>
</tr>
<tr>
<td>100</td>
<td>0.290</td>
<td>0.763</td>
<td>0.754</td>
<td>0.247</td>
<td>0.313</td>
</tr>
</tbody>
</table>

3. RESULTS AND DISCUSSION

The CFD program computation result is the velocity field in a stirred tank with an unworn or worn impeller. The change in the velocity profiles due to the rate of blade wear was investigated.

A comparison of the velocity fields presented in a vertical cross section for an unworn impeller (left side of the figure) and for a maximally worn impeller for our case (100 hours of abrasive particles action on blades, right side of the figure) is presented in Fig. 4. Only the lower part of the vessel is shown in this figure. The white area in the middle represents the shaft, hub and blades of the impeller. The upper half of the worn blade edge is seen on the right side of the figure. The effect of the wear on the velocity field is obvious. The velocity of the fluid passing through the impeller decreases as the edge wear increases. A stagnation region occurs between the impeller and the vessel wall and it enlarges its volume with increasing level of the worn process. The reattachment point in the impeller discharge stream at the bottom of the vessel was shifted towards the axis of symmetry of the stirred tank.

The flow rate through the rotating impeller was determined by integrating the velocity field on the surface generated below the impeller (1 mm in distance from the cylinder circumscribed to the rotating impeller). Then the impeller pumping capacity was calculated from equation (5). A comparison between the impeller flow rate number determined by CFD simulation $N_{Qp, comp}$ and determined experimentally $N_{Qp, exp}$ [1] is presented in Table 1. It follows from the table that the impeller pumping capacity decreases with a change in the impeller blade due to the erosion process. At the same time, the resulting CFD simulation values $N_{Qp, comp}$ correspond to the experimental data $N_{Qp, exp}$. 

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Figure 4. Comparison of the mean velocity fields in the system with an unworn and a maximally worn down pumping pitched blade impeller (100h), \( n = 300 \text{ min}^{-1} \), velocities in m.s\(^{-1}\).

Figure 5. Axial component of the ensemble-averaged mean velocity at the cross section above the impeller.

The impeller flow rate number is expressed for pitched blade impeller rotation by

\[
N_{Q_p} = \frac{Q_p}{nD^3},
\]

where impeller pumping capacity \( Q_p \) is determined by integrating the axial component of the ensemble-averaged mean velocity \( \bar{w}_z \) in the impeller discharge stream

\[
Q_p = 2\pi \int_0^{D/2} \bar{w}_z(r)rdr
\]

when axial symmetry of this system is considered.
The ensemble-average mean velocity profiles in dependence on the dimensionless radius $R$ were investigated in the regions above and below the impeller. The dimensionless velocity was defined for its axial and tangential components

\begin{align}
W_z &= \frac{\overline{w}_z}{\pi D n}, \\
W_t &= \frac{\overline{w}_t}{\pi D n}
\end{align}

where $\overline{w}_z$ and $\overline{w}_t$ are the ensemble-average mean values of the axial and tangential velocity components, respectively, for a given radius in a stirred tank $r$, $n$ is impeller speed, and $D$ is impeller diameter. The ensemble-average mean velocity was always calculated as an average value of the velocity over the appropriate circle radius.

**Figure 6.** Axial component of the ensemble-averaged mean velocity at the cross section below the impeller.

**Figure 7.** Tangential component of the ensemble-averaged mean velocity at the cross section below the impeller.
The radial profiles of the axial ensemble-average mean velocity above and below the impeller and the tangential ensemble-average mean velocity below the impeller are presented, see Figs. 5, 6 and 7. The velocity field deformation is obvious from the figures. The maximum velocity decreases with increasing blade wear, and the profiles become flat.

The maximum velocity radii \( R_{\text{max},z} \) and \( R_{\text{max},t} \) in the cross section below the impeller were determined from computed data presented in Figs. 6 and 7 for various wear rates. The values of both these radii are reported in Table 1. The slight shift of the maximum velocity position from the impeller rotation axis of symmetry is observed for both velocity components. The radial profiles of the axial ensemble-average mean velocity above and below the impeller exhibit the upstream flow at the vicinity of stirred tank wall, which is well known from experimental results [8].

4. CONCLUSIONS

It follows from the results of CFD simulation that the wear rate of an impeller blade has a significantly negative effect on the mean velocity field in an agitated liquid. The greater the destruction of the worn blade, the higher the deformation of the velocity field below the rotating impeller, with a simultaneous decrease in the ensemble-averaged mean velocity in the impeller discharge stream.

The deformation of the velocity field was proved experimentally in previous work and confirmed by CFD simulations. The measured impeller pumping capacity agrees well with the pumping capacity predicted by a finite volume model. Moreover, the radii corresponding to the maximal axial and tangential velocity components in the impeller discharge stream shift from the impeller rotation symmetry axis to the wall of the stirred tank due to the rate of blade wear observed from the models of the predicted mean velocity field.

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5. REFERENCES