

SLIDING MESH SIMULATION OF LAMINAR FLOW IN STIRRED REACTORS

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The flow pattern created by a pitched blade turbine was calculated using a sliding mesh method for various Reynolds numbers, mostly in the laminar regime. This method allows flow pattern calculations without the use of any experimental boundary conditions. The results compared favourably with experimental data obtained by laser-Doppler velocimetry. At low Reynolds number, the impeller creates a radial flow pattern rather than axial and the pumping number decreases with decreasing Reynolds number. It is concluded that the sliding mesh method is suitable for the prediction of flow patterns in stirred tanks.

Keywords: stirred tank; sliding mesh; impeller; mixing; laminar flow

INTRODUCTION

Computational fluid dynamics models are now regularly used to calculate the flow patterns in stirred reactors. To model the impeller, it is common to prescribe experimentally obtained velocity data in the outflow of the impeller, see e.g. Bakker and Van den Akker¹. This has the disadvantage that it is often necessary to extrapolate the data to situations for which no experiments were or can be performed. Only recently have methods become available to explicitly calculate the flow pattern around the impeller blades without prescribing any experimental data. The presence of baffles complicates such calculations, as they remain stationary while the impeller rotates. The sliding mesh method is a novel way of dealing with the impeller-baffle interaction. The main advantage of the sliding mesh method is that no experimentally obtained boundary conditions are needed, as the flow around the impeller blades is being calculated in detail. This allows modelling of impeller systems and reactors for which experimental data is difficult or impossible to obtain. The purpose of this paper is to report on initial studies to the suitability of this novel method for the prediction of the flow pattern in stirred tanks. The background of the sliding mesh method is discussed first, followed by a presentation of computational results and a comparison with experimental data.

SLIDING MESH METHOD

With the sliding mesh method, the tank is divided in two regions that are treated separately: the impeller region and the tank region that includes the bulk of the liquid, the tank wall, the tank bottom and the baffles, see Figure 1. The grid in the impeller region rotates with the impeller while the grid in the tank remains stationary. The two grids slide past each other at a cylindrical

interface. Here only a 90° section of the tank is modelled, using a cyclic boundary condition at the sides.

In the tank region, the standard conservation equations for mass and momentum are solved. In the rotating impeller region a modified set of balance equations is solved:

$$\frac{\partial}{\partial x_j}(u_j - v_j) = 0 \quad (1)$$
$$\frac{\partial}{\partial t}\rho u_i + \frac{\partial}{\partial x_j}\rho(u_j - v_j)u_i = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}$$

Here u_j is the liquid velocity in a stationary reference frame and v_j is the velocity component arising from mesh motion. Further, p is the pressure and τ_{ij} is the stress tensor. The first equation is the modified continuity equation and the second equation is the modified momentum balance.

At the sliding interface a conservative interpolation is used for both mass and momentum, using a set of fictitious control volumes. No-slip boundary conditions are used at the impeller blades, the shaft, the baffles and the tank walls. No experimental data is prescribed in the outflow of the impeller and all fluid motion strictly arises from the rotation of the impeller blades. The grid was generated with a proprietary program named AgFlow from Chemineer, Inc. and the total number of grid nodes was approximately 49000. All simulations were performed using FluentTM from Fluent, Inc. More details of the numerical methods can be found in Murthy *et al.*² and in the user guide³.

SIMULATION

Time dependent simulations were performed for the flow created by a pitched blade turbine in a tank with a diameter of $T = 0.3$ m. The impeller diameter was

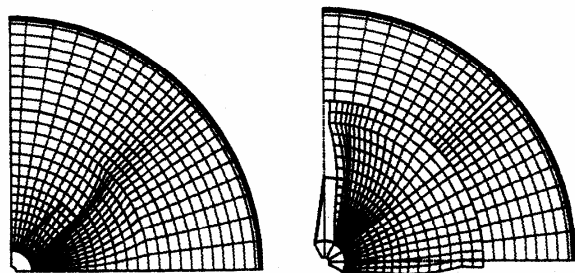


Figure 1. Grid used in the sliding mesh method. The grid is shown at two different time steps. The grid in the impeller region moves with the impeller and slides past the stationary grid for the rest of the tank.

$D = T/3$ and the impeller to bottom clearance was $C = T/3$. The blade width was $W = 0.2D$ and the blades were set at a 45° angle with the horizontal. The tank was equipped with four baffles, $T/12$ wide and $T/72$ offset from the tank wall. The impeller rotational speed was $N = 3.75 \text{ s}^{-1}$ and the viscosity was varied to obtain impeller Reynolds numbers ($Re = \rho ND^2/\mu$) ranging from $Re = 17$ to $Re = 1200$. In this range the flow was laminar and, in addition one simulation was performed for a Reynolds number of 10000 where the flow was turbulent, mainly to obtain an impeller pumping number for comparative purposes. In that case the $k-\epsilon$ RNG turbulence model was used³.

In the simulations a time step of 0.01 s was used and up to 1000 time steps were performed, resulting in 37.5 revolutions. Local and average velocities were tracked as a function of time to determine when periodic steady state was reached. The local velocities close to the impeller converged the fastest, while the average tangential velocity in liquid bulk converged the slowest. The number of revolutions to achieve periodic steady state increased from about 15 for $Re = 40$ to about 35 for $Re = 1200$. Calculation time is approximately 15 minutes per impeller revolution on a Cray C-90 computer. The experimental velocity data of Wang *et al.*⁴, acquired via laser-Doppler velocimetry, was used for validation of the computational results.

RESULTS

Figure 2 shows the velocity field for a Reynolds number of 40. The flow pattern is shown by means of velocity vectors. The vectors point in the direction of the liquid velocity at the point where they originate. The length of the vectors is proportional to the magnitude of the liquid velocity and the experimentally measured velocities are shown on the left while the sliding mesh results are shown on the right. At this Reynolds number the impeller creates a mainly radial flow pattern and two circulation loops form, both above and below the impeller. The flow is very weak away from the impeller. The model results can be seen to compare quite well with the experimental data.

At low Reynolds numbers, the flow was predominantly radial as shown here. However, for Reynolds numbers larger than 400 the jet coming from the impeller hit the tank bottom rather than the wall and the flow was more axial.

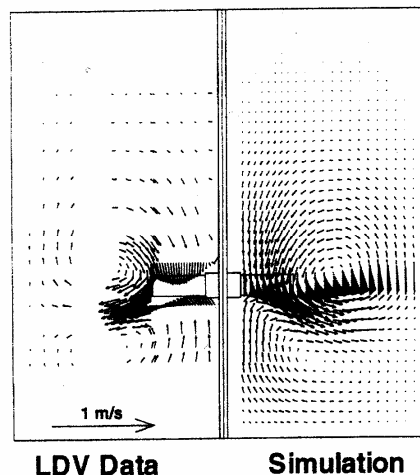


Figure 2. Comparison between experimental data (left) and sliding mesh results (right). The impeller Reynolds number is 40.

Figure 3 shows the local velocity magnitude in a plane just below the impeller for $Re = 40$. Light coloured regions denote high velocities, while dark coloured regions denote low velocities. The highest velocities are found near the impeller blade tip while the lowest velocities are near the baffle. This figure also shows the grid at the impeller blade and under the laminar flow conditions studied here, this grid density seems to be sufficient. However, it is anticipated that under turbulent flow conditions a finer grid will be necessary to resolve the effects of possible turbulent tip vortices.

For a more quantitative validation, the impeller pumping number $N_q = Q_1/N \cdot D^3$ was calculated, both from the experimental data from Wang *et al.*⁴ and from the sliding mesh data. The pumping rate Q_1 includes both

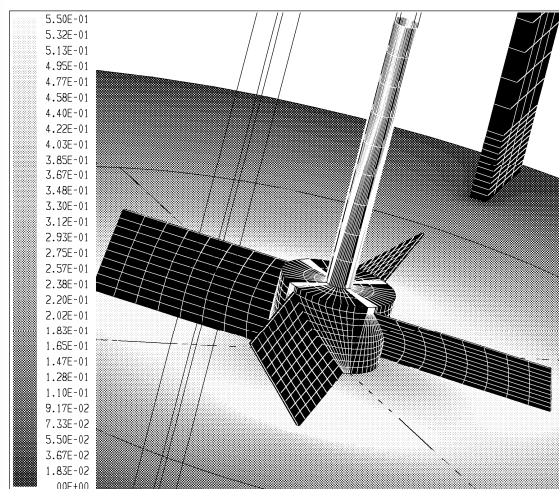


Figure 3. Local velocity magnitude in a plane just below the impeller for $Re = 40$. The grid at the impeller blade and at the baffle is also shown.

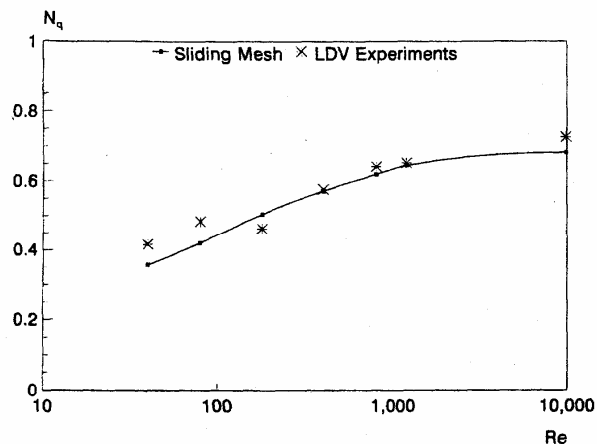


Figure 4. Comparison between experimental data and sliding mesh results for the impeller pumping number as a function of impeller Reynolds number.

the radial flow at the side of the impeller, as well as the axial flow coming from the bottom of the impeller. Figure 4 shows the impeller pumping number as a function of Reynolds number. There is good quantitative comparison between the sliding mesh results and the experimental data. As expected, the pumping number decreases significantly with decreasing Reynolds number.

DISCUSSION

Sliding mesh methods can be used to accurately predict the time dependent laminar flow pattern in stirred reactors, without the need for experimental data as impeller boundary conditions. A drawback is the long calculation time which is about an order of magnitude longer than with steady state calculations based on experimental impeller data.

Further testing and validation of these models for turbulent flow conditions is necessary. Furthermore, grid dependency studies will have to be performed to determine the minimum grid resolution necessary to resolve turbulent tip vortices.

An important application for the sliding mesh method

might be the development of new, optimized impeller designs for specific industrial applications. Other applications are the prediction of flow patterns with impellers for which no experimental data are available, the prediction of flow patterns in multiple impeller systems where there is significant interaction between the impellers and to predict time dependent flow patterns in systems where steady state assumptions are not justified.

NOMENCLATURE

D	impeller diameter, m
N	impeller rotational speed, s^{-1}
N_q	impeller pumping number, -
Q_i	flow rate, $m^3 s^{-1}$
p	pressure, $N m^{-2}$
Re	impeller Reynolds number, -
T	tank diameter, m
u_j	liquid velocity in direction j , $m s^{-1}$
v_j	mesh velocity in direction j , $m s^{-1}$
W	impeller blade width, m
τ_{ij}	molecular shear stress, $kg m^{-1} s^{-2}$
ρ	liquid density, $kg m^{-3}$
μ	viscosity, Pa s

REFERENCES

1. Bakker, A. and Van den Akker, H. E. A., 1994, Single-phase flow in stirred reactors, *Chem Eng Res Des, Trans IChemE*, 72, (A4): 583-593.
2. Murthy, J. Y., Mathur, S. R. and Choudhury, D., 1994, CFD simulation of flows in stirred tank reactors using a sliding mesh technique, *Mixing 8, Proc Eighth Europ Conf on Mixing, IChemE Symp Series No. 136*: 341-348.
3. *Fluent User's Guide*, 1995 (Fluent, Inc.).
4. Wang, M. H., Calabrese, R. V. and Bakker, A., 1995, Effect of Reynolds number on the flow generated by a pitched blade turbine, *Presented at the 45th CShE Conference, Québec City, October 15-18*.

ADDRESS

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The manuscript was received 30 October 1995 and accepted for publication after revision 16 April 1996.