

PIV MEASUREMENTS AND CFD SIMULATION OF VISCOUS FLUID FLOW IN A STIRRED TANK AGITATED BY A RUSHTON TURBINE

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ABSTRACT

Mixing, achieved mostly by mechanically stirring, is one of the most important unit operation processes in chemical and allied industries. The problem of designing and scaling-up stirred tanks has been tackled mainly by means of semi-empirical methods. Measurement and numerical simulation of viscous fluid in a stirred tank is still insufficient and further development is needed. In this paper, computational fluid dynamics (CFD) simulation and digital particle image velocimetry (PIV) measurement have been carried out to study the flow field of viscous fluid in a stirred tank agitated by a four-blade Rushton turbine. The working medium is the mixtures of water and glycerine with various concentrations. The results show mean velocity, turbulent energy, vorticity and pumping capacity of the fluids as well as the flow patterns change with the fluid viscosity. The commercial code of CFX4.4 with sliding grids was used to simulate the flow field. The CFD simulations were compared with the experimental PIV data. The result shows that the CFD simulations reflect the flow of the viscous fluid in a stirred tank.

Keywords stirred tank, PIV, CFD, viscous fluid

NOTATION

a	blade width, m
b	blade height, m
c	glycerine concentration, %(v/v)
C	clearance, m
D	impeller diameter, m
H	liquid height in reactor, m
k	turbulent energy, $m^2 \cdot s^{-2}$
N	impeller rotational speed, $r \cdot s^{-1}$
Q	pumping capacity, $m^3 \cdot s^{-1}$
Re	impeller Reynolds number, dimensionless
T	reactor diameter, m
U	mean velocity in the radial direction, $m \cdot s^{-1}$
V	mean velocity in the axial direction, $m \cdot s^{-1}$
W	mean velocity in the tangent direction, $m \cdot s^{-1}$
U'	instantaneous velocity in the radial direction, $m \cdot s^{-1}$
V'	instantaneous velocity in the axial direction, $m \cdot s^{-1}$
W'	instantaneous velocity in the tangent direction, $m \cdot s^{-1}$
U_{tip}	impeller tip speed, $m \cdot s^{-1}$

x	distance for radial direction, m
y	distance for axial direction, m
μ	viscosity, $mPa \cdot s$
ω	Vorticity vector, s^{-1}

INTRODUCTION

Stirred-tank reactors, mechanically agitated by one or more impellers, are among the most widely used reactors in chemical and allied industries. The rotation of impellers generates extremely complex flow within the stirred vessel. Therefore, understanding fluid dynamic characteristics of the impeller discharge flow is essential for reliable design and scale-up of stirred reactors. But the flow of viscous fluid often occurs in the process of chemical engineering especially in polymerisation process (Feng et al. 2001). So the research on that domain is important.

In the past, the main techniques available for measuring fluid flow has been laser Doppler velocimetry (LDV) (or laser Doppler anemometer, LDA) (Ranade and Joshi, 1990a; Ng et al. 1998). Most studies, including those mentioned here, have focused on a tank stirred by a Rushton turbine. A number of investigations have concentrated on the impeller region and/or on the impeller stream. Yianneskis et al. (1987) synchronized LDV measurements with a pre-designated shaft angle and showed that the trailing vortices maintained their identity for up to 20° displacement from the blade edges. A similar conditional sampling technique was used by Calabrese and Stoots (1989). They reported the results in the form of velocity vector plots, azimuthal profiles of the three mean velocity components at different radial locations, and maps of deformation rate, turbulence energy, and estimated dissipation rate in the impeller mid-plane. Dyster et al. (1993) used LDV in fluids of different viscosity and reported detailed mean and rms velocity profiles in the impeller stream. Lusseyran et al. (1994) began to use two-component LDV and to measure not only mean and fluctuating velocities, but also the Reynolds stresses. In other studies, emphasis has been given to the overall flow field, possibly at the cost of a less accurate investigation of the impeller region. Hockey et al. (1990) conducted LDV measurements for two tank volumes. Wu and Patterson (1989) presented one of the most complete studies and reported in the form of axial profiles of

mean velocity components and rms velocity fluctuations at various radial locations. Ranade and Joshi(1990b) used LDV and reported detailed radial profiles of mean and fluctuating velocities at various locations in the bulk flow. Geisler et al.(1994) presented LDV results for the mean and fluctuating velocities in standard tanks stirred by a variety of impellers. But that technique has its limitation in that LDV is a single point technique to measure the flow characteristics. So it is defective to study transient fluid flow. PIV(Digital Particle Image Velocimetry) is able to record all velocity points of the flow field at a time. That makes it feasible to study transient fluid flow. Myers et al.(1997) used PIV and reported flow field instabilities of axial-flow impellers. Jian et al.(1998) used PIV and reported mean velocity field, turbulent kinetic energy, turbulence dissipation rate and Reynolds stresses. Ranade et al.(2001) used PIV and reported trailing vortices of Rushton turbine.

Since the 2D computational simulation of flow field of stirred tank by Harvey and Greaves(1982a; 1982b), the number of the articles on the flow field in stirred tank via CFD (Computational Fluid Dynamics) has increased quickly. Researchers can not only save much money via CFD but also get data which can not be obtained from experiments. Earlier computations usually used 'black box' model(Ranade and Joshi, 1990b; Hou et al. 2000; Brucato et al. 2000), which sets the velocity distribution and turbulent parameters near blade via experiments. That method was deficient because the researchers can not get particular information of the flow field near blade. Researchers(Ng et al. 1998; Brucato et al. 1998; Ma et al. 2003; Lee et al. 1996) studied the flow field in the stirred tank via sliding mesh method. Via that method researchers can get the flow field without experiments. Perng and Murthy(1993) used a moving-deforming mesh technique for the time-dependent simulation of the flow in mixing tanks. Murthy et al.(1993) used an alternative sliding-mesh technique. This paper investigates fluid flow in a stirred tank by PIV measurements and CFD simulation with the change of fluid Newtonian viscosity.

EXPERIMENTAL

The PIV apparatus used in this study is FlowMap 1500 system from Dantec Measurement Technology. The flow was seeded with polyamid seeding particles of 20 μ m diameter and of 1030 kg·m⁻³ density. An up to 20Hz pulsed Nd:Yag laser with a beam expanding lens was used to create a light sheet of 10mm thickness to illuminate the measurement area. A Nikon Hisence CCD camera was placed at the right angle to the light sheet to record images with resolution of 1280 × 1024 pixels. The recorded images were divided into interrogation area of 64 × 64 pixels with a 50% overlap, resulting approximately 660 vectors for the entire vessel.

The PIV experiments were carried out in a cylindrical Perspex vessel. The configuration of the reactor is shown in Fig.1. The reactor diameter is $T=0.285$ m, and it is equipped with four baffles (width $W=T/10$, 90° apart) and filled with water of a height up to $H=T$. The fluid is stirred by a four-blade Rushton turbine (diameter $D=T/2$, blade height $b=D/5$, blade width $a=D/4$). The impeller clearance, C , is fixed at $T/2$. To minimize the effect of vessel curvature on the intersecting beams and thus on the optical distortion, the whole reactor was submerged into a square glass tank, which was filled with the same working fluids. The measurement area was vertical mid-plane between adjacent baffles. The fluids for measurement are glycerine/water with various glycerine concentrations. Their viscosities are measured by capillary viscometer. Table 1 listed Reynolds number of the measuring glycerine/water liquid at different rotor speeds.

c% (v/v)	μ , mPa·s	N , r·s ⁻¹		
		0.5	1.0	2.0
0	1.0	71250	142500	285000
20	2.0	37478	74956	149912
40	4.8	16388	32776	65552
60	12.2	6751	13502	27004
70	22.9	3678	7356	14712
80	62.5	1377	2754	5508
90	200.0	440	880	1760
100	873.0	103	206	412

Table 1 Re of glycerine/water liquid

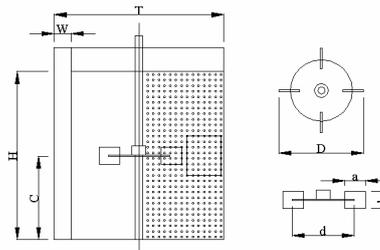


Figure 1: Stirred vessel configuration

The fluid flow is influenced not only by turbulent motion but also periodicity effect of impeller. The measured data are changed with various sampling times because the flow field via PIV is instantaneous. So PIV measure the flow field when impeller rotate 363° at the same location 1024 times and get the average result.

FLOW FIELD MEASUREMENT

Velocity Field

The measured mean velocity vectors in the mid-baffle plane by PIV (40% glycerine/water) with the rotation speed of $0.5 \text{ r}\cdot\text{s}^{-1}$, $1.0 \text{ r}\cdot\text{s}^{-1}$ and $2.0 \text{ r}\cdot\text{s}^{-1}$ are illustrated in Fig.2(a-c). The flow in the stirred tank with four-blade impellers shows an axial-radial flow pattern. An apparent symmetric double loop flow pattern can be observed. The jet flow coming off the impeller blades streams towards the wall and divides into two flows under the influence of the reactor wall: one downward along the wall, to the bottom of the reactor, then back to the impeller region; the other rise along the wall, to the

top of the reactor and back to the impeller region, forming an symmetric double loop. The range and intensity of the swirl increase with rotating speed increasing. Under the same conditions, the measured mean velocity vectors in the baffle plane are shown in Fig.2(d-f). In this circumstance, the tangential flow near wall is restrained because of the existence of baffles. So the fluid is forced to flow toward center of the tank and the swirls are formed above and below the impeller. The swirls are larger, stronger and nearer to the wall than those in Fig. 2(d-f) because the existence of baffles restrains the tangent flow and facilitate fluid mixing.

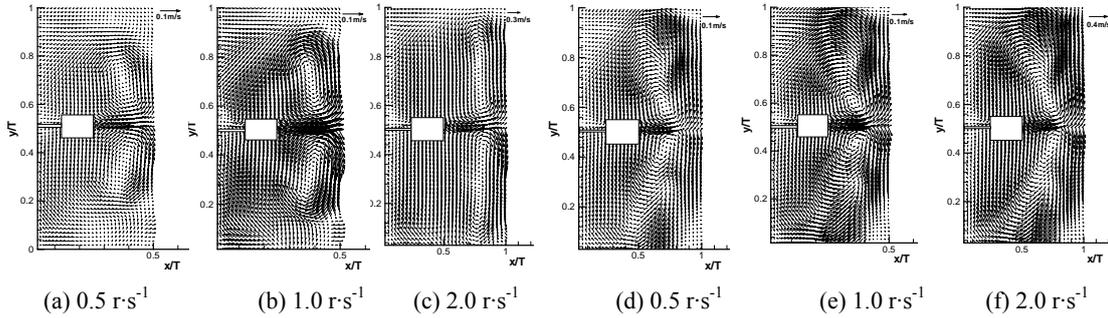


Figure 2: Measured mean velocity vector by PIV (40% glycerine/water, $\mu=4.8\text{mPa}\cdot\text{s}$) in the mid-baffle plane(a-c) and in the baffle plane(d-f)

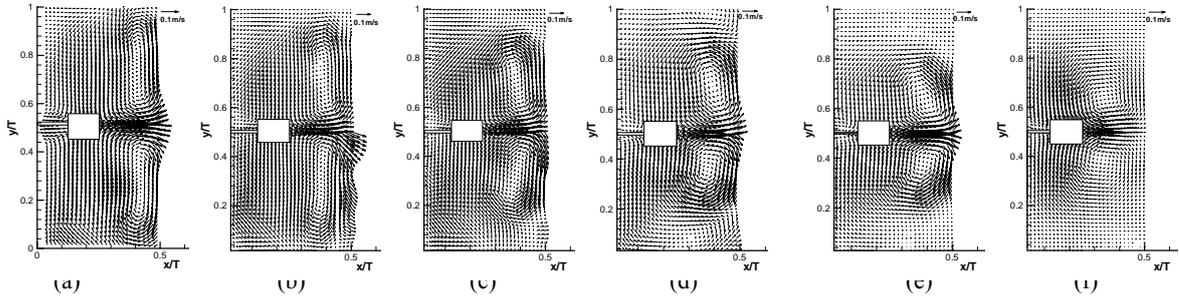


Figure 3: Measured mean velocity vector in R-Z plane by PIV at the stirring speed of $1.0 \text{ r}\cdot\text{s}^{-1}$ with various glycerine concentrations: (a) water($\mu=1.0\text{mPa}\cdot\text{s}$); (b) 20% glycerine/water($\mu=2.0\text{mPa}\cdot\text{s}$); (c) 40% glycerine/water($\mu=4.8\text{mPa}\cdot\text{s}$); (d) 60% glycerine/water($\mu=12.2\text{mPa}\cdot\text{s}$); (e) 80% glycerine/water($\mu=62.5\text{mPa}\cdot\text{s}$); (f) 100% glycerine($\mu=873\text{mPa}\cdot\text{s}$)

The measured mean velocity vectors of various glycerine concentrations in the mid-baffle plane by PIV with the rotation speed of $60 \text{ r}\cdot\text{min}^{-1}$ are shown in Fig.3. The swirls become smaller and weaker with viscosity increasing. So the swirls cannot reach the top and the bottom of the tank and secondary flow appears there and forms two small swirls. The size of those swirls becomes smaller with the increase of the fluid viscosity and disappears finally.

SIMULATION

Based on tank symmetry, a quarter of the tank is taken as the simulation region. The commercial code CFX4.4 is used for simulation. The approach for the modeling of the impeller is the sliding-grid method. The flow domain is

divided into two cylindrical, non-overlapping sub-domains, each gridded as a separate block: the outer one is fixed in the laboratory reference frame, while the inner one rotates with the impeller. The two regions are implicitly coupled at the inter-face separating the two blocks via a sliding-grid algorithm, which takes into account the relative motion between the two sub-domains and performs the required interpolations. Because instantaneous results are obtained with sliding grids, they must be converted into average data for comparison with experimental data. When impeller Reynolds number is larger than 1000, the flow in the tank is turbulent flow and the $k-\epsilon$ model is used. When impeller Reynolds number is below 1000, a flow laminar flow is used (Shi et al. 1996).

Velocity Field

The simulation mean velocity vectors of 40% glycerine/water in the mid-baffle plane with various rotation speed are illustrated in Fig.4(a-c) and the simulation mean velocity vectors of 40% glycerine/water in the baffle plane with various

rotation speed are illustrated in Fig.4(d-f). The flow in the stirred tank with four-blade impellers shows the expected axial-radial flow pattern. There are two primary circulation loops in the upper and lower parts of the vessel.

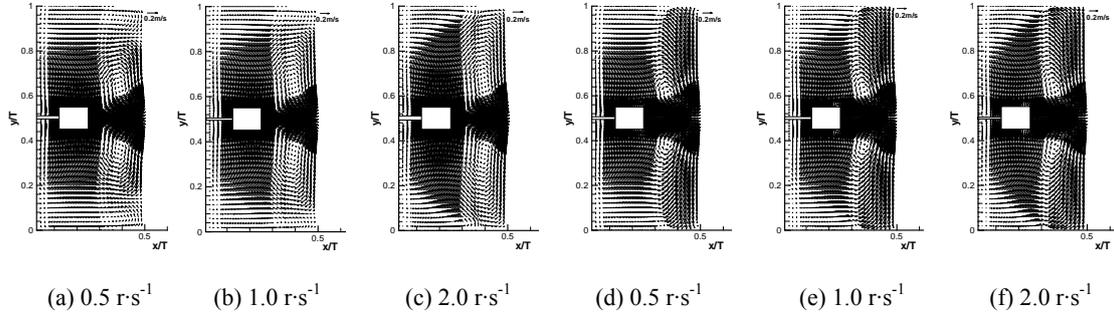


Figure 4: Simulated velocity vectors of 40% glycerine/water in the mid-baffle plane(a-c) and in the baffle plane(d-f)

The simulation mean velocity vectors of various glycerine concentrations in the mid-baffle plane with the rotation speed of $1.0 \text{ r}\cdot\text{s}^{-1}$ are shown in Fig.5(a-f). The fluid in the impeller area comes into high velocity radial flow toward the tank wall by the rotation of impellers. It becomes two flows after it impacts the tank wall. Part of the flow goes upward along the wall, while part of the flow goes downwards towards the bottom of the tank.

Then the fluid returns impeller area by the pump function of impellers. The swirls become smaller and weaker with the increase of viscosity. So the swirls cannot reach the top and the bottom of the tank and secondary flow appears there and forms two small swirls. The size of those swirls becomes smaller with the increase of the fluid viscosity. The simulation flow patterns are consistent with those from experiments.

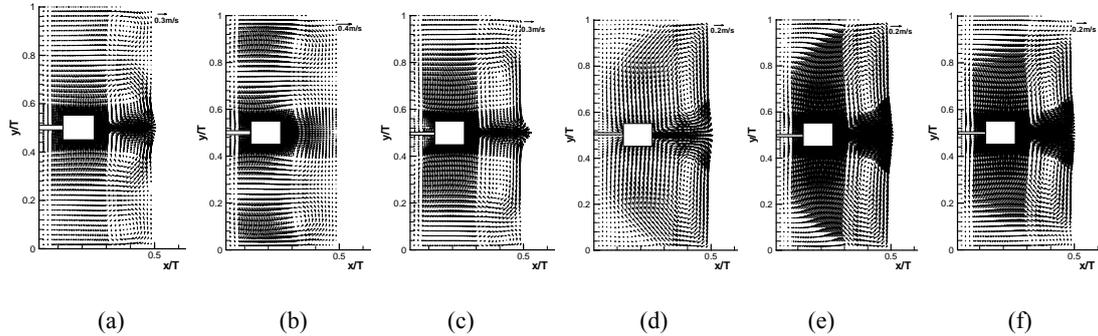


Figure 5: Simulated velocity vectors with various glycerine concentrations in the mid-baffle plane at $N=1.0 \text{ r}\cdot\text{s}^{-1}$: (a) water($\mu=1.0\text{mPa}\cdot\text{s}$); (b) 20% glycerine/water($\mu=2.0\text{mPa}\cdot\text{s}$); (c) 40% glycerine/water($\mu=4.8\text{mPa}\cdot\text{s}$); (d) 60% glycerine/water($\mu=12.2\text{mPa}\cdot\text{s}$); (e) 80% glycerine/water($\mu=62.5\text{mPa}\cdot\text{s}$); (f) 100% glycerine($\mu=873\text{mPa}\cdot\text{s}$)

Comparison between CFD simulation and PIV measurement of velocities

Comparison between CFD simulation and PIV measurement of radial and axial velocity vectors at

various heights in mid-baffle plane with the rotation speed of $1.0 \text{ r}\cdot\text{s}^{-1}$ are illustrated in Fig.6. The simulation results are consistent with the measurement results.

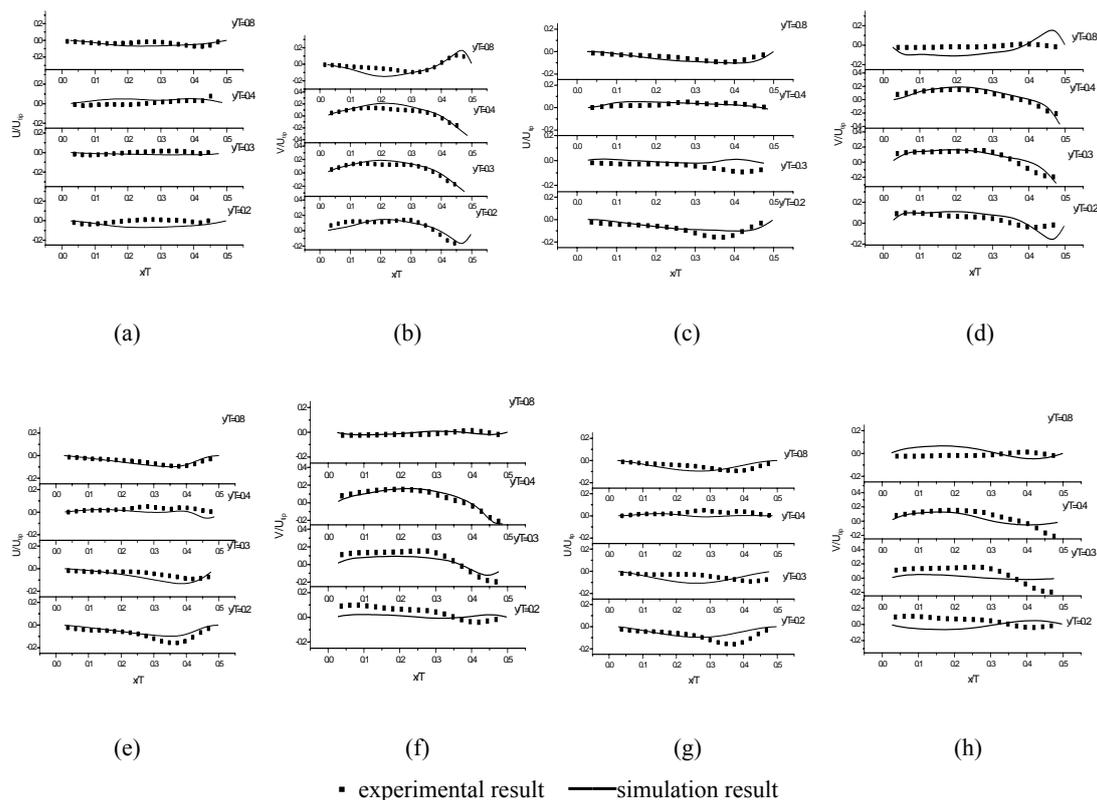


Figure 6: Comparison between CFD simulation and PIV measurement of velocities in bulk region at $N=1.0 \text{ r}\cdot\text{s}^{-1}$: (a) radial velocity ($\mu=2.0\text{mPa}\cdot\text{s}$); (b) axial velocity ($\mu=2.0\text{mPa}\cdot\text{s}$); (c) radial velocity ($\mu=12.2\text{mPa}\cdot\text{s}$); (d) axial velocity ($\mu=12.2\text{mPa}\cdot\text{s}$); (e) radial velocity ($\mu=62.5\text{mPa}\cdot\text{s}$); (f) axial velocity ($\mu=62.5\text{mPa}\cdot\text{s}$); (g) radial velocity ($\mu=873\text{mPa}\cdot\text{s}$); (h) axial velocity ($\mu=873\text{mPa}\cdot\text{s}$)

CONCLUSION

In this paper, computational fluid dynamics (CFD) simulation and digital particle image velocimetry (PIV) measurement have been carried out to study the flow field of viscous fluid in a stirred tank agitated by a four-blade Rushton turbine. The working medium is the mixtures of water and glycerine with various concentrations. An apparent symmetric double loop flow pattern is found in the stirred tank. The existence of baffles is benefit for the fluid mixing. The results show the mean velocity and the flow patterns change with the fluid viscosity. They all decrease with the increase of the fluid viscosity. With the increase of the fluid viscosity, secondary flow appears and forms two small swirls. The size of those swirls becomes smaller with the increase of the fluid viscosity and disappears finally. The commercial code of CFX4.4 with the sliding grids was used to simulate the flow field. The CFD simulations were compared with the experimental PIV data. The result of the CFD simulations shows reasonable agreement with experiments, with respect to the flow field and velocity components.

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