14th International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering
Kobe, Japan (23.-25. October 2023)

Analysis of Flow Behavior and Evaluation of Agitation Performance by Impeller Using UVP

Hiroya Okumura[1] , Kohei Takasaka[1] , Naoto Ohmura[1] , A Ishihata[2]

[1] Department of Chemical Science and Engineering, Kobe University
[2] Sanko Astec, Inc.

Mixing is an industrial process that promotes reaction and heat transport. Flow velocity profile is an important indicator for estimating mixing performance. Because many industrial processes deal with opaque fluids with non-Newtonian properties, optical measurements are not suitable when measuring the velocity of such fluids. This study, therefore, used a cloudy aqueous CMC solution, which is difficult for light to penetrate, and the flow velocity profile was obtained by a UVP measuring system. The mixing performance of two types of impeller (Parallel Paddle® (PP) and disk turbine impeller (DT)) was examined. The velocity profile measurements by UVP successfully identified isolated mixing regions (IMRs) in which intermixing does not occur between the IMR and its surrounding active mixing region in a laminar mixing field. It was also found that the PP exhibited good mixing performance with relatively smaller IMRs than the disk turbine.

Keywords: mixing, stirrer, Parallel Puddle®, UVP

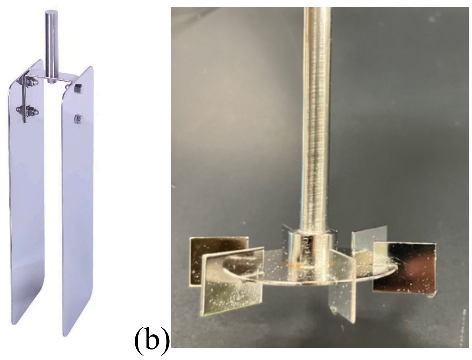
1. Introduction

Mixing is an important unit operation in chemical industries to enhance not only homogenization but also heat and mass transfer by adding appropriate flow motion in a mixing device. Improved mixing performance contributes to lower costs of production processes and higher quality products. Impellers are widely used equipment in the stirring process, mainly to convert the power of rotation into mixing and other effects in the tank. The mixing characteristics, which are the primary and most important aspects of impeller performance, depend on the flow pattern in a mixing device. For example, if there are multiple circulating flows, each independent of the others, the overall mixing performance can be poor. Conversely, if there is interaction among these circulating flows through well-developed turbulent flow motions, the overall mixing can be assumed to be good.

PIV (Particle Image Velocimetry) is a powerful method for determining flow patterns by measuring the velocity field.[1] However, it requires the fluid to be transparent due to its optical nature. As an alternative method, the UVP (Ultrasonic Velocity Profiler) utilizes the Doppler effect of ultrasonic waves to measure particle velocity,[2]making it suitable for both transparent and non-transparent fluids. In this experiment, an aqueous CMC (carboxy-methyl-cellulose) solution was used as a typical example of a cloudy and non-Newtonian fluid to investigate the effectiveness of UVP measurements.

Due to the shear-thinning properties of the CMC solution, the fluid near the impeller experiences strong shear, resulting in lower viscosity and increased fluidization. In contrast, the fluid farther away from the impeller retains high viscosity and exhibits poor fluidization. As a result, a phenomenon occurs where the flow is divided into active and inactive flow regions. [3]

The purpose of this study is to evaluate the performance of two types of impellers, PP and DT, on a highly viscous CMC solution using UVP measurement. Both impellers employed in this study generate radial discharge flow. Figure 1 (a) illustrates the PP, developed by Sanko Astec, Inc., which is a medium-sized impeller with relatively large blades and a large passing area. Figure 1 (b) shows the DT, a commonly used small agitation blade in various industries. In this study, a standard six-bladed DT was utilized.



(a) (b)

Figure 1: (a) PP, (b) six-bladed DT

2. Material and Methods

To prepare a 3 wt% CMC solution, dissolve 20.76 g of CMC in 6.92 L of tap water and fill an acrylic vessel with an inner diameter of 0.210 m as the operating fluid. CMC has a molecular structure with numerous branched chains resulting shear-thinning rheological properties. The PP and DT were positioned at the center of the container, as depicted in Figure 2, and rotated at specified rotational speeds. The PP operated at 120 rpm, while the DT operated at 780 rpm, providing equivalent power. Table 1 displays the key dimensions for the agitation tank and agitator blades geometry. A UVP-DUO-Mx (Met-Flow S. A.) was utilized to measure the flow velocity. A 4 MHz transducer was employed, and the main measurement parameters included a sound velocity of 1500 m/s and a sampling interval of 36 ms.

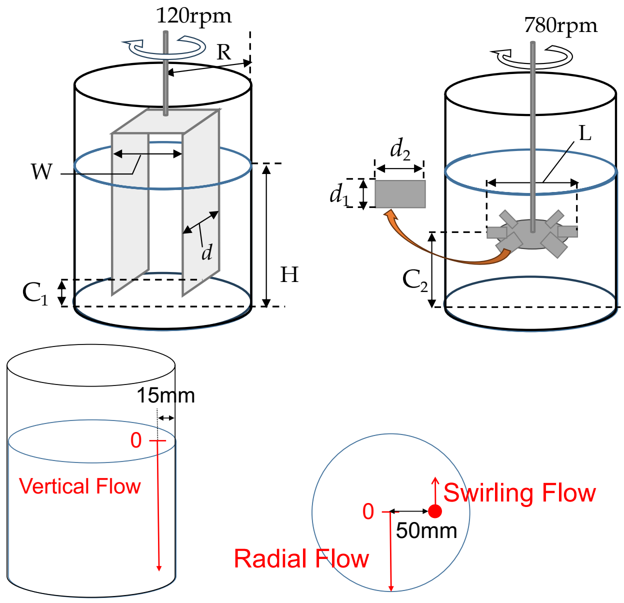


Figure 2: Schematics of experimental equipment

Table 1: Geometrical dimensions of experimental apparatus in mm

R	H	W	d	C_1	L	d_1	d_2	C_2
105	200	44	70	40	72	18	14	100

Particles of Copolyamid with a particle size ranging from 80 - 200 μm and a density of 1.07 g/m3 were added to the working fluid at a concentration of 0.1 wt% and well dispersed. Due to the small Stokes number of these particles, which is much smaller than 1, they can be considered to move precisely along the streamlines.

3. Results and Discussion

3.1 Radial Flow

Figure 4 shows the time-averaged radial distribution of radial velocity for the PP. The tops of the agitator blades are out of the liquid surface, so the agitator blades are located 40-200 mm from the bottom of the agitator tank.

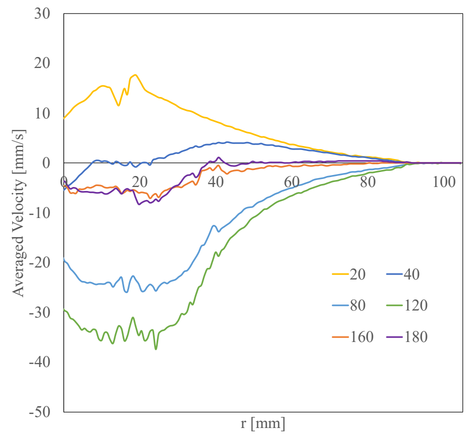


Figure 4: Radial flow velocity profile of the PP

From Figure 4, it can be read that a large outward flow, or discharged flow, exists in the region where the agitation blade is present. Inward flow was observed in the area below the impeller blades at a height of 20 mm, indicating a large circulation. At 160 and 180 mm, which are located at the top of the tank, the velocity was close to zero, indicating a mixture of both outward and inward flow. Figure 5 shows the detailed time-averaged radial distribution of radial velocity at height near the impeller blade tip. The location where the averaged velocity is zero is thought to be where the center of the secondary circulating flow is located.

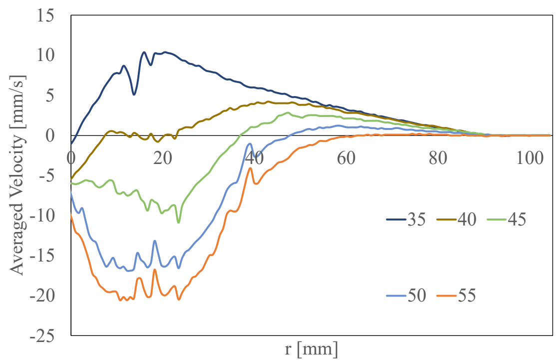


Figure 5: Radial flow velocity profile near the tip of the PP

Figure 6 shows the radial distribution of time-averaged radial velocity on the disk turbine blade. Although there are regions where the velocity exceeds the measurement limit, the discharge flow at a height of

100 mm and the circulating flow seen above and below the discharged flow can be seen, confirming the general features of flow.

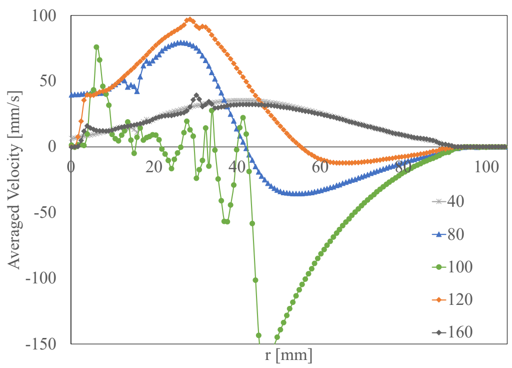


Figure 6: Radial flow velocity profile of the DT

3.2 Swirling Flow

Figure 7 compares the averaged velocity (V_θ) of the circumferential flow at different heights at r=50 for the two kinds of impellers under the same power consumption. It can be seen that the PP has a higher velocity at the top where the agitator blade is present, which is naturally due to its close to the rotating impeller blade and therefore sufficient momentum transport. The disc turbine blades show higher values in all regions, simply due to the higher rotational speed of the agitator blades under the same power consumption conditions.

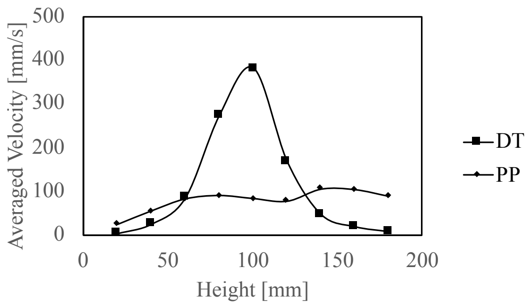


Figure 7: Swirling flow velocity profile of the two impellers

Figure 8 shows the nondimensional time averaged circumferential velocity (Vθ) averaged by the radial direction, which is divided by the rotational speed of the impeller and the tank inner diameter. This dimensionless velocity of the PP is greater than that of the disk turbine blade over the entire region. This means that the PP is stronger than the turbine blade in swirl flow formation.

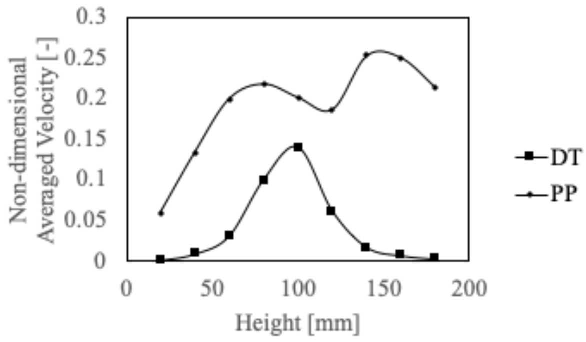


Figure 8: Swirling flow non-dimensional velocity profile of the two impellers

3.3 Vertical Flow

Figure 9 compares the time-averaged axial velocity (Vz) in each height at r = 90 mm with the two impellers. Here the upward flow is positive. PP has downward flow throughout the tank, but its value is small. On the other hand, the disk turbine blades show vertical flow separation originating from the discharged flow from the blades. PP have relatively little vertical fluid motion.

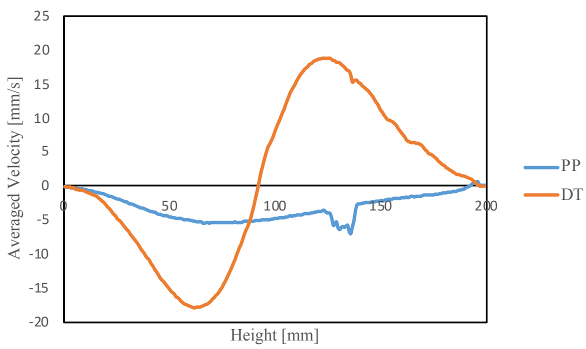


Figure 9: Vertical flow velocity profile of the two impellers

A characteristic behavior can be observed in the mixing of CMC, as depicted in the decolorization experiment presented in Figure 3. The decolorization experiment is based on the oxidation-reduction of iodine, which proceeds according to the following chemical reaction equation.

$2Na_2S_2O_3+I_2 \rightarrow 2NaI+Na_2S_4O_6$

Decolorization experiments are one of the most effective methods for mixing behavior and evaluation and are frequently used.[4]

Iodine is dissolved in the fluid at 0.001 mol/L, and 1.5 times the amount of $Na_2S_2O_3$, a decolorizing reagent, is added near the surface of the fluid to achieve chemical equilibrium.

This behavior is believed to result from the division of the fluid into regions of low viscosity and active flow, as well as regions of high viscosity and mild flow. The region near the impeller blade corresponds to the former, where the decolorization process occurs rapidly. The presence of a wide area of active flow contributes to process efficiency, which is an essential requirement for an impeller. Quantitative analysis of this region serves as an evaluation of the impeller performance as revealed through flow analysis.

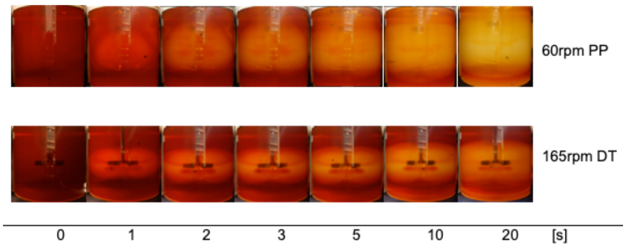


Figure 3: Results of CMC decolorization experiment

Finally, the size of the isolated mixing region (IMR) was estimated from the flow conditions.

The results for the radial and vertical flows indicate that the DT has relatively strong and large vortex flow at the top and bottom. This is not significantly different from the flow behavior in a Newtonian fluid,[5] and a stable IMR is considered to exist at the two locations. On the other hand, for PP, the discharge flow is generated from the entire paddle, but at the same time, the same amount is drawn into the center from the lower region of the paddle. The PP has a relatively small vortex flow area.

As for the magnitude of the IMR, specific values could not be determined in this experiment. The same can be said for the PP, which has an IMR of about 15 mm in the vertical direction. Similarly, PP is considered to have an IMR of about 10 mm in the height direction.The volume of the IMR in DT is estimated to be roughly 4 times that of PP. It can be concluded that under the conditions of this experiment, PP has a smaller IMR than DT due to the relatively small vortex flow, resulting in better mixing performance.

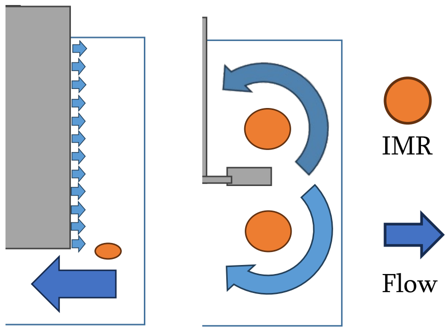


Figure 10: Schematic diagram of half of a tank with IMR and flow conditions

4. Conclusions

It was found that PP has a relatively strong influence on the swirling flow, while the DT has a relatively strong influence on the vertical flow in the flow domain. Since the agitation of the PP strongly forms a swirling flow, it is thought that converting the flow into a vertical flow will improve the mixing property. In the future, we intend to try to improve the mixing using the PP by inserting baffles.

References

[1] Ramin Z, et al.: A mixing study in a double-Rushton stirred tank, Computers & Chemical Engineering, July (2009), 1240-1246.

[2] Madhavi V, et al.: Solid suspension in stirred tanks: UVP measurements and CFD simulations, The Canadian Journal of Chemical Engineering, October (2011), 1112-1121.

[3] Arratia, P.E., et al.: Mixing of shear-thinning fluids with yield stress in stirred tanks, AIChE Journal, July(2006), 2310-2322

[4] Etchells, A. W., et al.: Blending in unbaffled and baffled mechanically agitated vessels – Effect of Reynolds number and liquid height, Chemical Engineering Research and Design, August (2023), 599-605

[5] Yek, W. M., et al.: Enhanced mixing of Newtonian fluids in a stirred vessel using impeller speed modulation, The Canadian Journal of Chemical Engineering, November (2009), 839-845