Korean J. Chem. Eng., **27**(1), 1-5 (2010)
DOI: 10.1007/s11814-009-0287-3

RAPID COMMUNICATION

Flow visualization and numerical analysis of a new mixing equipment with vibratory fins

Yoshihito Kato*, Setsuro Hiraoka*, Shogo Fukumoto*, Yutaka Tada*, Yuichiro Nagatsu*, Ryushin Ohmasa, Sung Tae Koh***, and Young Sei Lee****,†**

*Department of Life & Material Engineering, Nagoya Institute of Technology, Gokisocho, Showaku, Nagoya 466-8555, Japan
**Japan Techno Co. Ltd., 2-14-10 Kugahara Otaku, Tokyo 146-0085, Japan,
***Department of Chemical Engineering, Dongyang University, Young-ju 750-711, Korea
****School of Applied Chemical Engineering, Kyungpook National University, Sangju, Gyeongbuk 742-711, Korea
(*Received 13 November 2008 • accepted 18 May 2009*)

Abstract−The mixing performance of a new type of mixing equipment which has several fin oscillators on a pair of shafts with a vibrating motor was investigated. This mixing equipment, which is mainly used for industrial plating processes, was usually operated at a vibrating frequency of about 40 Hz with the amplitude 1 mm. The flow visualization in this equipment showed that the flow in the vessel at laminar flow region was vertically divided into two distinct symmetric regions. The numerical simulation of the flow and the mixing patterns agreed well with the visualization result at laminar flow region.

Key words: Mixing, Fluid Mechanics, Hydrodynamics, Simulation, Vibration, Flow Visualization

INTRODUCTION

Mixing equipment is widely used in industrial processes. Most of the vessels have a rotating impeller. In the turbulent flow region, a turbine, paddle and propeller are usually used in cylindrical vessels with some baffles. Recently, a new type of mixing equipment, which has several fin oscillators on a pair of shafts with a vibrating motor, was developed by Ohmasa. This mixing equipment is normally operated at a vibration frequency of 30 Hz to 60 Hz and amplitude 1 mm to 10 mm. The vibration of the fins in the vessel causes a turbulent discharge flow from the fin tips like a jet flow, which establishes high mixing performance in the vessel. The equipment has a wide space to soak materials at the center of the vessel; it has been used for many commercial plating processes. The equipment has the following advantages.

(1) Non-foaming on the liquid free surface
(2) Excellent penetration of the liquid into small holes
(3) Excellent suspension of particles from the vessel bottom surface

Authors reported the mixing performance of this equipment as follows: mixing time, circulation time, power consumption and turbulent velocity profile [6-8]. In our previous papers, it was found that the optimum vibrating frequency for mixing was restricted to about 45 Hz, complete mixing was achieved with three to four circulations of the liquid in the vessel, power consumption had the maximum value at the optimum vibrating frequency, and the power consumption was constant in the range of the liquid viscosity, 1-500 mPa·s. When the equipment was operated at laminar flow condition, the characteristic phenomena were observed. However, there is not enough quantitative data for the design of the equipment yet. In this paper, the mixing phenomena of the equipment in the laminar flow region are shown by flow visualization and numerical analysis.

EXPERIMENTAL

A schematic diagram of the experimental apparatus is shown in Fig. 1. Used is a rectangular vessel made of the transparent vinyl chloride resin, 500 mm×500 mm×400 mm. A vibrating motor is equipped on the vessel with some springs. Several fins are equipped on a pair of vibration shafts. The number of fins can be varied easily from 1 to 6, and it was fixed at two in this experiment fundamentally. The geometry of the fin and its supporting plate is shown in

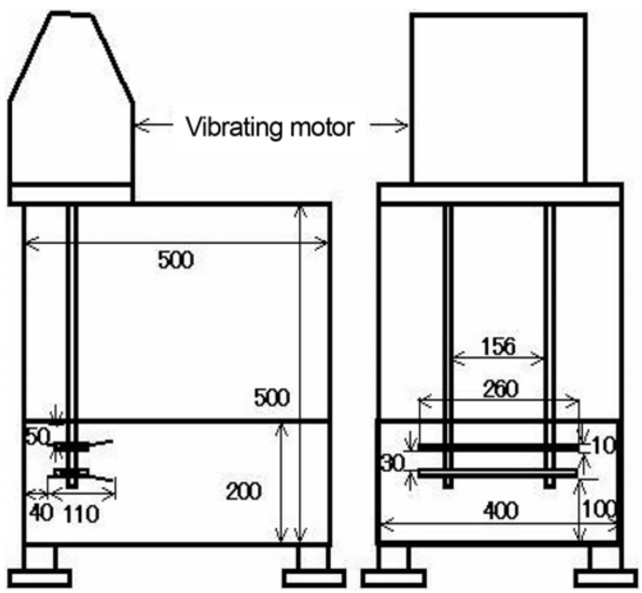


Fig. 1. Vibratory type agitated vessel.

† To whom correspondence should be addressed.
E-mail: ysl@knu.ac.kr

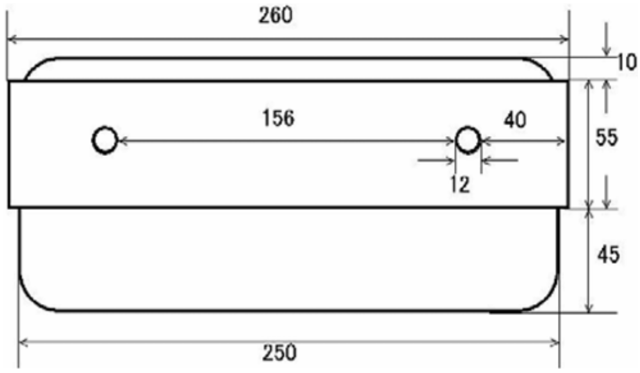


Fig. 2. Geometry of fin.

Fig. 2. The fin, the supporting plate and the shaft are made of stainless steel. The mixing liquid is desalted water or glycerol and corn starch-syrup solution for various viscosities. The height of liquid is 200 mm. Since it was found that the optimal frequency for mixing was 45.7 Hz from the previous research [7], unless it was mentioned, the frequency was fixed at this frequency. The lower fin was attached downward and the upper one was attached upward.

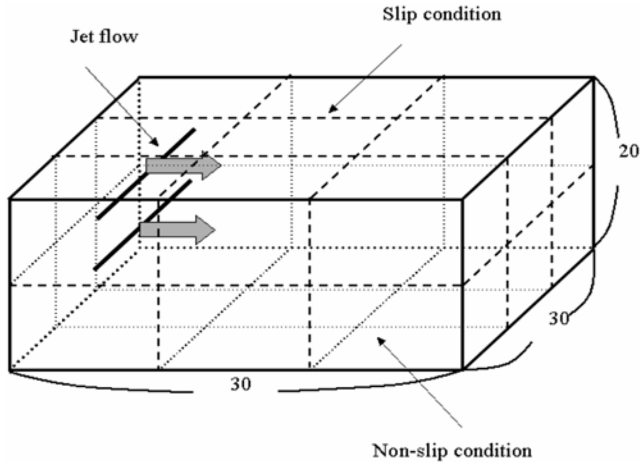
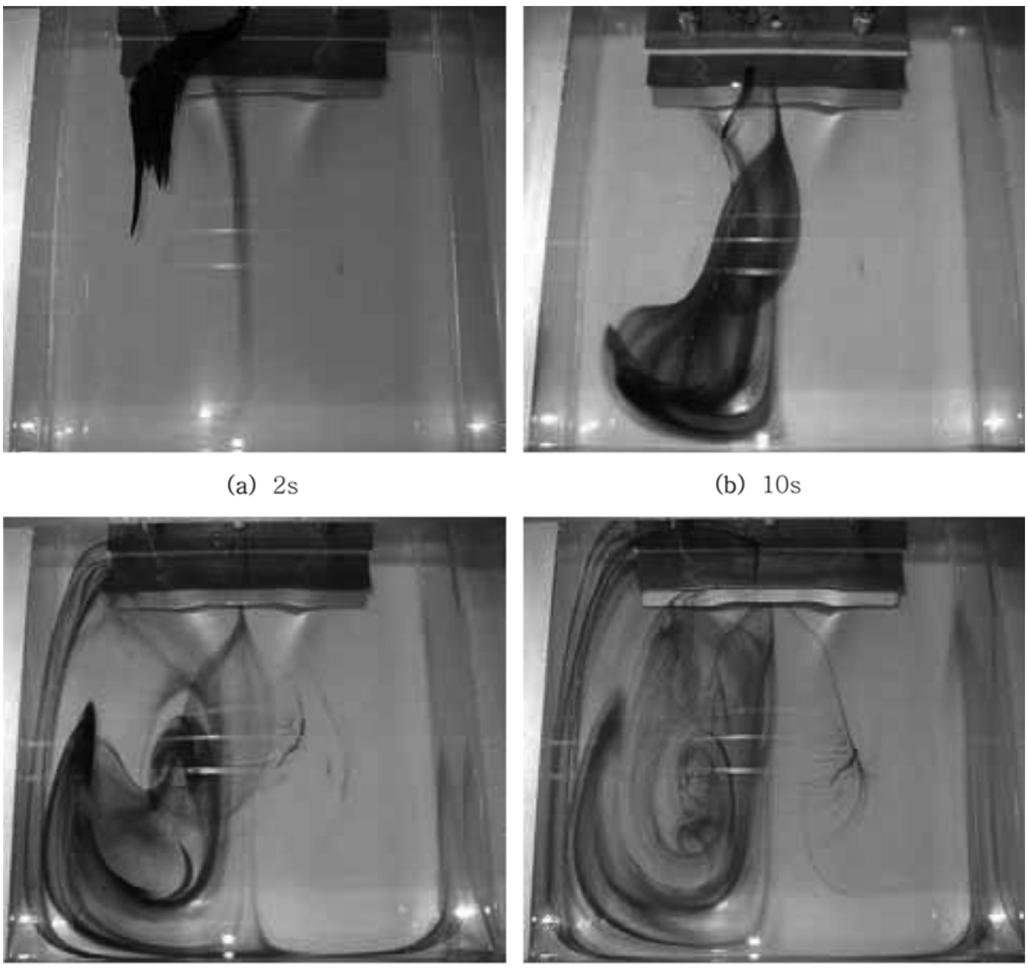


Fig. 3. Vessel for simulation of flow pattern.

VISUALIZATION METHOD OF MIXING PROCESS

The mixing processes were visualized by using the coloring method of starch/iodine solution, which is generally used to measure the



(a) 2s (b) 10s (c) 20s (d) 30s

Fig. 4. Mixing pattern by colorization method (top view).

mixing time and the mixing visualization and to discover a dead space in the mixing vessel. The density and the viscosity of the corn starch syrup solution were 1,100 kg/m^3 and 300 mPa·s, respectively.

1. Visualization Method of Flow Pattern

The flow patterns were visualized by a tracer method. Nylon particles moving in the vessel, the average diameter of which was 200 μm, were lightened by a laser slit beam. Photographs were taken with exposure time 1 s.

2. Numerical Analysis

The velocity and pressure profiles in laminar flow were simulated by the original code, in which the equation of continuity and Navier-Stokes equation were solved by SOLA (HSMAC) method. The numerical simulation program made by our research team for the analysis of laminar flow movement was used. And the experiments were in good agreement with the calculation results using the software. The gravity term in Navier-Stokes equation was neglected.

$$\frac{\partial u_i}{\partial x_i}=0 \tag{1}$$

$$\rho\left(\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}\right)=-\frac{\partial p}{\partial x_i}+\mu\frac{\partial^2 u_i}{\partial x_j^2} \tag{2}$$

The non-slip condition was chosen at all fluid-solid boundaries in the simulation of laminar flow region, i.e., we considered it as a wall because the liquid free surface was flat. The discharge flow from the vibratory fins was assumed to be the jet flow having a uniform velocity profile at the tip of the fins, i.e., we have described the fin vibration as a jet stream without considering the vibration of fins because the type of flow in an agitated vessel is laminar.

The discharge velocity was set to 1.0 m/s, which was the average value measured by LDV. It was also assumed that the liquid temperature was uniform and the liquid density (1,100 kg/m^3) and the viscosity (300 mPa·s) were constant as a Newtonian fluid. The number of meshes (30 : 30 : 20) and the boundary conditions are shown in Fig. 3.

Mixing processes were simulated by the virtual particle tracing method, which was better than the numerical method solving the diffusion equation to obtain the mixing pattern in the laminar flow region. After the velocity profile was calculated at steady state, some virtual particles were put in front of the fins. The positions of the particles after a small time interval were integrated with the Runge-Kutta method using the following equation to obtain the streak line of the particles.

$$x_{i+1}=x_i+u_i\,dt \tag{3}$$

RESULTS AND DISCUSSION

1. Visualization of Mixing Process

Fig. 4 shows the photographs from the vessel top, where the mixing region was divided into two distinct regions. First the coloring liquid spread around the left-side region as shown in Figs. 4(a) and (b), and then it spread into the center of the left-side region, but it hardly spread into the right-side region as shown in Figs. 4(c) and (d). Fig. 4 illustrates the pattern observed by only one side of the vessel using a colored liquid; eventually it means symmetry. Fig. 7 illustrates the result of calculation. Good agreement is shown between calculation and experiment.

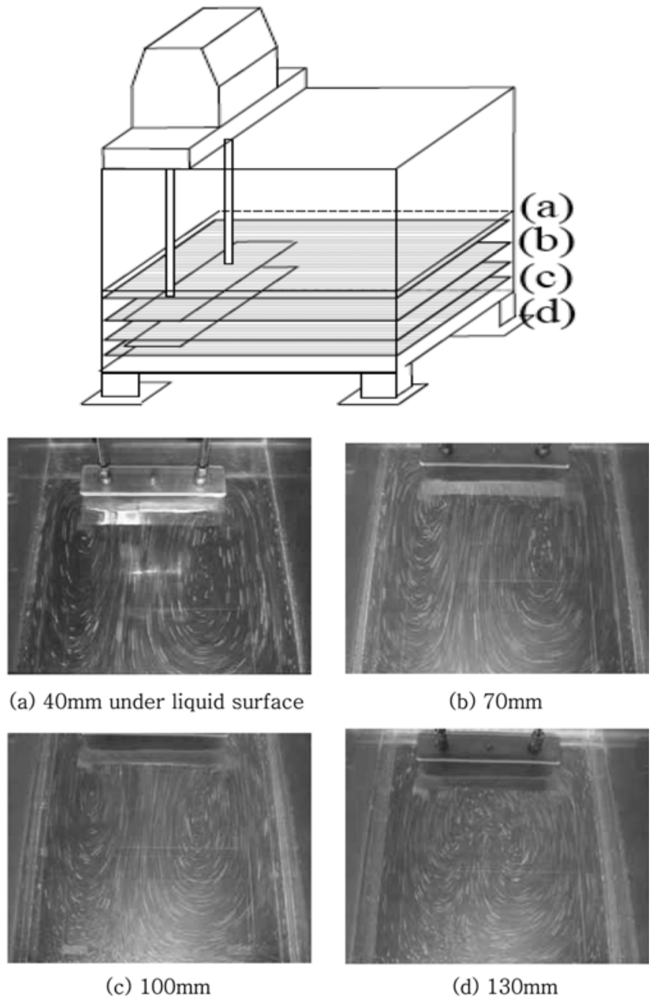


Fig. 5. Flow visualization by trace method (top view).

2. Visualization of Flow Pattern

Fig. 5(a) shows the top view of the visualization of the flow pattern in the mixing vessel, where the slit light was projected at the level 40 mm under the liquid surface. The two large vortices were observed in the laminar flow of liquid viscosity of which was 300 mPa·s. The two vortices were stable and their flow almost symmetric. Fig. 5(b) and (c) at the level 70 mm and 100 mm show the same results as Fig. 5(a), and Fig. 5(d) at the level 130 mm shows a similar result. It was found that the mixing region was divided into two distinct regions at laminar flow.

3. Numerical Analysis

The side and the top views of the velocity profiles are shown to compare the numerical analysis results with the flow visualization results in Fig. 6. The simulated velocity profiles coincided qualitatively with the flow visualization, and symmetrical vortices were reproduced well.

Based on the simulation results of the velocity profiles, the streak lines of the virtual particles are shown in Fig. 7 for the top view and Fig. 8 for the side view, respectively.

Figs. 7 and 8 show that the two large vortices dividing the vessel into two distinct regions. To obtain better liquid mixing in the mixing equipment with vibratory fins operating in laminar region, it is im-

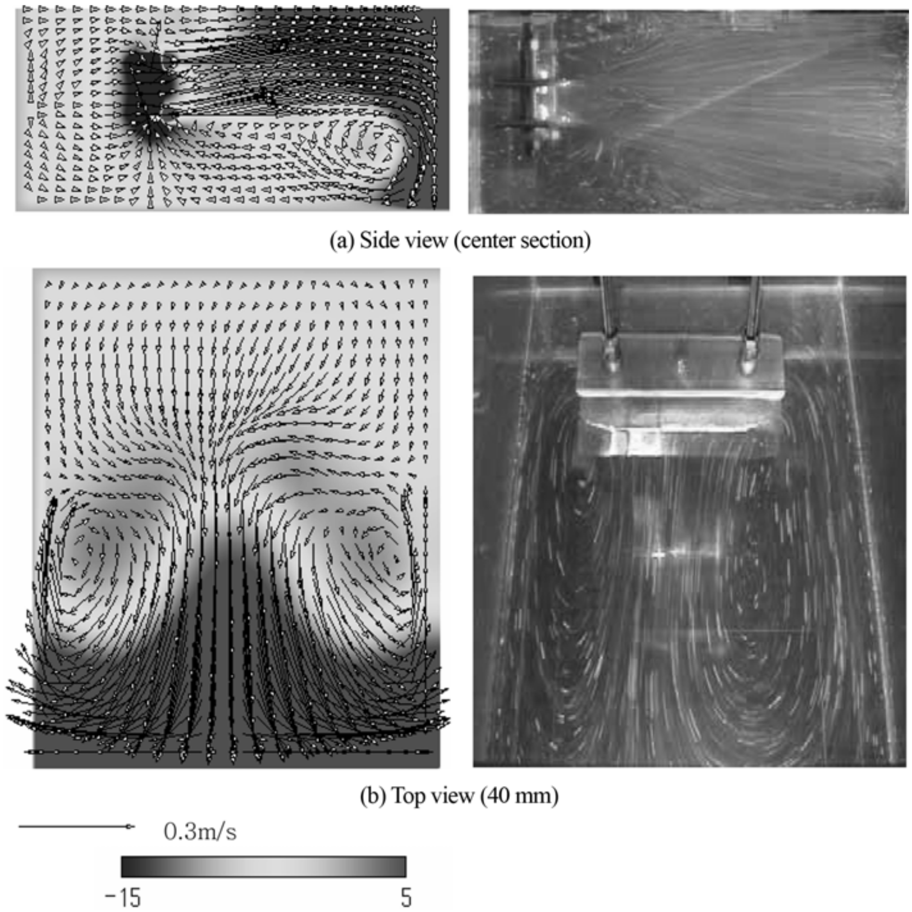


Fig. 6. Velocity vector and pressure profile of simulation result.

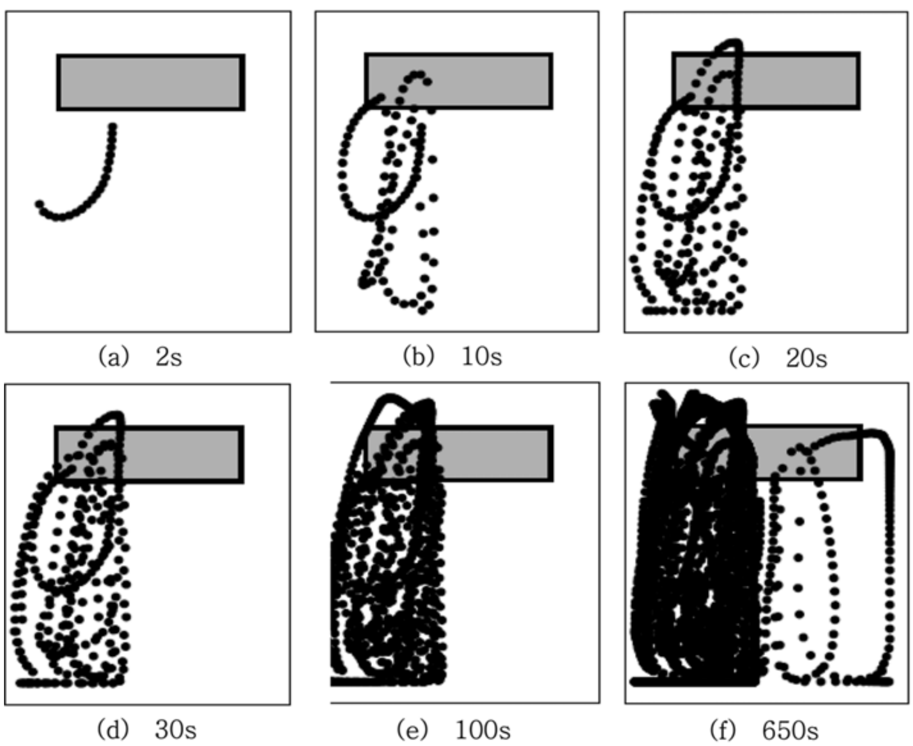


Fig. 7. Streak line of virtual particles (top view).

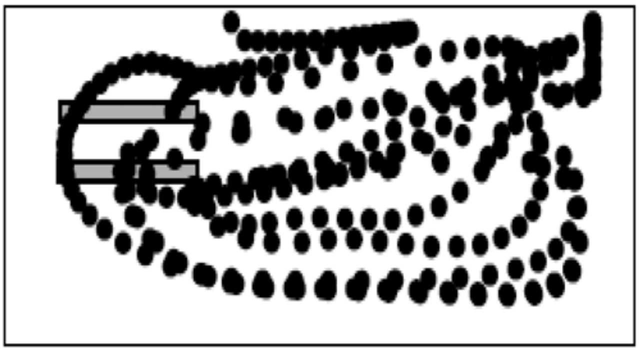


Fig. 8. Streak line of virtual particles at 30 s (side view).

portant to generate only one large flow in the vessel by rearranging the vibratory fins.

CONCLUSION

The following findings were obtained from the flow visualization in a new type mixing equipment with oscillating fins. When the equipment is operated at laminar flow, a pair of symmetrical large vortices was generated to divide the vessel into two distinct regions vertically. The flow pattern at laminar flow in the equipment can be predicted by using the numerical simulation with the assumption that a discharge flow from the vibratory fins is a jet.

ACKNOWLEDGMENTS

This study was supported by Kyungpook National University Grant (2009).

NOMENCLATURE

p : pressure [Pa]
t : time [s]
u : liquid velocity [m/s]
x : distance [m]
μ : liquid viscosity [Pa·s]
ρ : liquid density [kg/m^3]

REFERENCES

1. Y. S. Lee, S. G. Lee and J. S. Kim, *Korean Chem. Eng. Res*, **33**, 46 (1995).
2. Y. S. Lee, M. G. Kim and Y. Kato, *Korean Chem. Eng. Res*, **39**, 536 (2001).
3. S. Hiraoka, Y. Tada, Y. Kato, A. Matsuura, T. Yamaguchi and Y. S. Lee, *J. Chem. Eng. Japan*, **34**, 1499 (2001).
4. Y. S. Lee and Y. Kato, *J. Korean Ind. Eng. Chem.*, **16**, 698 (2005).
5. R. Ohmasa, *Kagaku Souchi*, **36**, 100 (1994).
6. Y. Kato, S. Hiraoka, Y. Tada, K. Mase, R. Ohmasa, T. Yamaguchi, S. T. Koh and Y. S. Lee, *J. Chem. Eng. Japan*, **34**, 649 (2002).
7. Y. Kato, S. Hiraoka, Y. Tada, A. Matuura, S. Fukumoto, R. Ohmasa, S. T. Koh and Y. S. Lee, *Kagaku Kogaku Ronbunshu*, **29**, 596 (2003).
8. Y. Kato, S. Hiraoka, Y. Tada, A. Matuura, S. Fukumoto, R. Ohmasa, S. T. Koh and Y. S. Lee, *Kasika Jyouhou Gakkai Ronbunshu*, **23**, 88 (2003).