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EFFECT OF OPERATING CONDITIONS ON FLUID FLOW OVER A HIGH SPEED ROTARY BELL-CUP ATOMIZER

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ABSTRACT

Using the volume of fluid (VOF) method, we analyze two-dimensional fluid flow over high-speed rotary bell-cup atomizers. The fluid behavior is analyzed and the liquid film thickness is quantitatively evaluated. The atomizer is flat in shape and has a paint supply hole. The bell rotational speed obtained is 15,000, 25,000, and 35,000 rpm; and the liquid flow rate obtained is 150, 300, 450, and 600 mL/min. The liquid used in this experiment is assumed to be water and the gas is assumed to be air. The results show that the liquid flows through the bell-cup surface toward the edge and forms a liquid film. At the measuring point, the film is initially thick but it then decreases to a practically constant value. The increase in the bell rotational speed causes the film thickness to decrease. Furthermore, the increase in the rotational speed causes the film thickness to become constant, whereas the increase in the liquid flow rate causes the film thickness to increase. These results show that the rotational speed and flow rate strongly affect the thickness of the film.

INTRODUCTION

Paint application is conducted to improve the durability and enhance the beauty of the coated material. The painting process is necessary in manufacturing; in fact, the consumption of paint serves as a measure of civilization. Table 1 shows the consumption of paint in Asia. The data in the table indicate that huge quantities of paint are consumed and the demand for paint is increasing. This trend shows the increasing importance of paint application.

Table 1 Paint consumption [1]

	2006	2009	2014 (Forecast)
Market Size ('000 tonnes)	10953	13883	20321

High-speed rotary bell-cup atomizers are widely used in industrial painting such as automotive painting. Because automobiles are parked outdoors for a long period of time, they are exposed to many elements including sunlight, temperature change, and chemicals such as de-icing chemicals. Therefore, a paint that is robust against these factors is required. An automobile is considered as a status symbol, and therefore it needs to be stylish. For these reasons, the quality requirement for automobile painting is very important as compared to the other industrial painting techniques. Although the bell-cup offers high productivity and high quality as compared to the other painting machines, higher and higher levels of productivity and quality are nevertheless desired.

The bell-cup revolves at a high speed and the paint is supplied through the paint supply holes. The centrifugal force pushes the paint to flow over the bell-cup surface toward the bell-cup edge and results in the formation of a liquid film. Next, the paint flows out of the bell-cup edge and is redirected toward the automobile body by shaping airflows that come from behind the bell-cup. Finally, droplets in the air are formed and these droplets are blown on the target. In addition, these droplets help in determining the coating quality.

As Kazama reported, the droplets are strongly affected by the liquid film on the bell-cup surface [2]. By comparing bell-cups with different shapes, Kazama showed that the size distribution of sprayed liquid droplets depends on the liquid film, which means the phenomenon of flow on the bell-cup surface is significant to control the droplets.

In the present study, we analytically compute the flow on a high-speed rotary bell-cup atomizer. It allows us to quantitatively analyze the fluid behavior and the liquid film thickness.

NOMENCLATURE

f	[-]	VOF function
h	[μm]	Film thickness
p	[Pa]	Pressure
r	[mm]	Radial axis
t	[ms]	Time
u	[m/s]	Axial velocity
v	[m/s]	Radial velocity
w	[m/s]	Circumferential velocity
x	[mm]	Central axis
Greek alphabet		
ε	[%]	Relative error of film thickness
ρ	[kg/m^3]	Density

NUMERICAL ANALYSIS

Figure 1 shows an analytical object, which consists of a two-dimensional flow over a high-speed rotary bell-cup atomizer. Herein, we focus on the flow around the paint supply holes and assume that the bell-cup surface is flat in shape. The liquid is supplied from the paint supply hole and later flows over the surface due to the centrifugal force. The air flows around the bell-cup due to the rotation of the bell-cup. The no-slip condition is applied to the boundary of the bell-cup surface and the inlet boundary condition is applied to the paint supply holes.

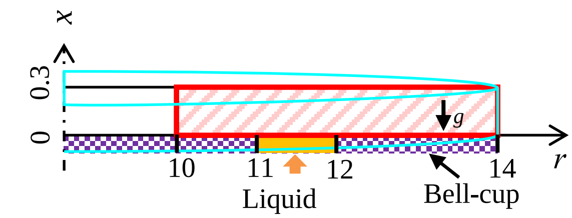


Figure 1 Analytical object

We consider a gas–liquid two-phase flow and use the volume of fluid (VOF) method. The fluids are assumed to be viscous and incompressible and the fluid flow is governed by the following momentum equation:

$$\frac{\partial \phi}{\partial t} + \nabla \cdot (\mathbf{u}\phi) = -\frac{1}{\rho}\nabla \mathrm{p} + \frac{1}{\rho}\nabla \cdot (\mu \nabla \phi) \quad (1)$$

where ϕ is defined as

$$\phi = u, v, w \quad (2)$$

The continuity equation is

$$\nabla \cdot \mathbf{u} = \mathbf{0}, \quad (3)$$

and the VOF equation is

$$\frac{\partial f}{\partial t} + \nabla \cdot (\mathbf{u}f) = 0, \quad (4)$$

where f is the VOF function, which is defined as

$$f = \begin{cases} 1 & \text{for the cell inside fluid 1} \\ 0 & \text{for the cell inside fluid 2} \end{cases} \quad (5)$$

The governing equations are discretized via the finite volume method. A staggered grid is used as the computational grid, a Simplified marker and cell (SMAC) is used as the coupling scheme, and algebraic multigrid solvers (AMGS) are used as the matrix solver.

Table 2 shows the numerical conditions. The operating conditions correspond to real conditions in automotive painting. Bell rotational speed ranged from 15,000–35,000 rpm and the liquid flow rate ranged from 150–600 mL/min. The liquid used in this experiment is assumed to be water with density, ρ, of 1000 kg/m^3; viscosity, μ, of 1 mPa·s; and surface tension coefficient, σ, of 70 mN/m. In this experiment, the gas is assumed to be air with ρ = 1 kg/m^3 and μ = 0.01 mPa·s.

Table 2 Numerical conditions

Mesh size ($r \times x$) [μm]	3.3×3.3
Operating condition	
Liquid flow rate [mL/min]	150, 300, 450, 600
Rotational speed [rpm]	15000, 25000, 35000
Liquid property	
Density [kg/m^3]	1000
Viscosity [mPa·s]	1
Surface tension coefficient [mN/m]	70
Gas property	
Density [kg/m^3]	1
Viscosity [mPa·s]	0.01

VALIDITY

To confirm that the mesh size is sufficiently small for this analysis, we examine the grid dependence on film thickness. Table 3 shows the numerical conditions. We assume that the finest mesh corresponds to the thinnest film, as shown in Table 2. We discuss the grid dependence under this condition because, under high rotational speed and at a low flow rate, the film is expected to be thin.

Figure 2 shows the dynamics of the film thickness with varying mesh size, and Fig. 3 shows the relative error, ε, which is calculated according to the following expression:

$$\varepsilon = \frac{\left|h_{2.0\ \mu\text{m}} - h_{3.3\ \mu\text{m}}\right|}{h_{2.0\ \mu\text{m}}} \times 100. \qquad (6)$$

The results of the analysis differ in the range 0.5–1 ms. Outside this time range, the values obtained are almost the same. In particular, the relative errors obtained are < 1% after a span of 2.87 ms. We focus the film thickness after it becomes constant. Therefore, a 3.3 × 3.3 μm mesh provides sufficient numerical accuracy for our studies.

Table 3 Numerical conditions to examine grid dependence

Mesh size ($r \times x$) [μm]	2.0×2.0, 3.3×3.3
Operating condition	
Liquid flow rate [mL/min]	150
Rotational speed [rpm]	35000
Liquid property	
Density [kg/m^3]	1000
Viscosity [mPa·s]	1
Surface tension coefficient [mN/m]	70
Gas property	
Density [kg/m^3]	1
Viscosity [mPa·s]	0.01

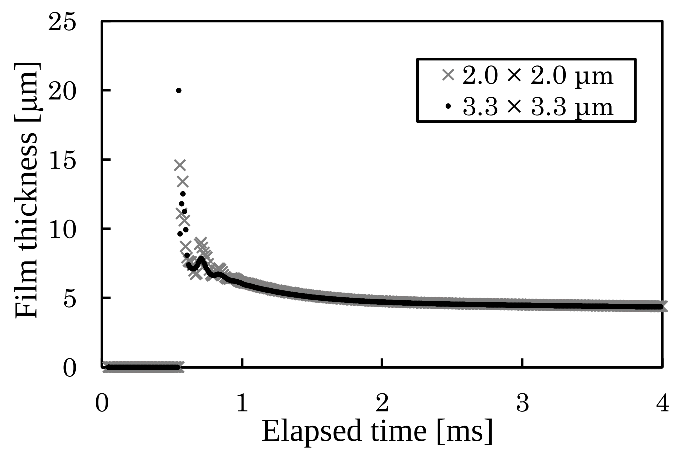


Figure 2 The grid dependence on film thickness

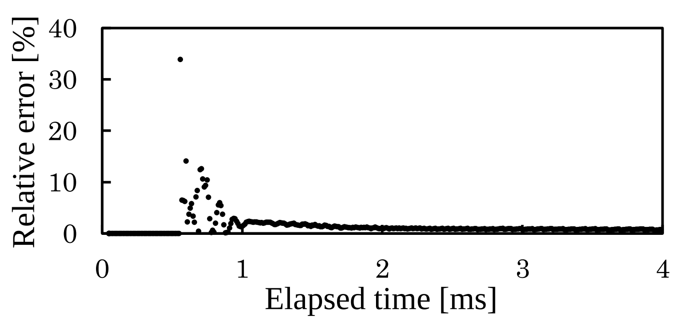
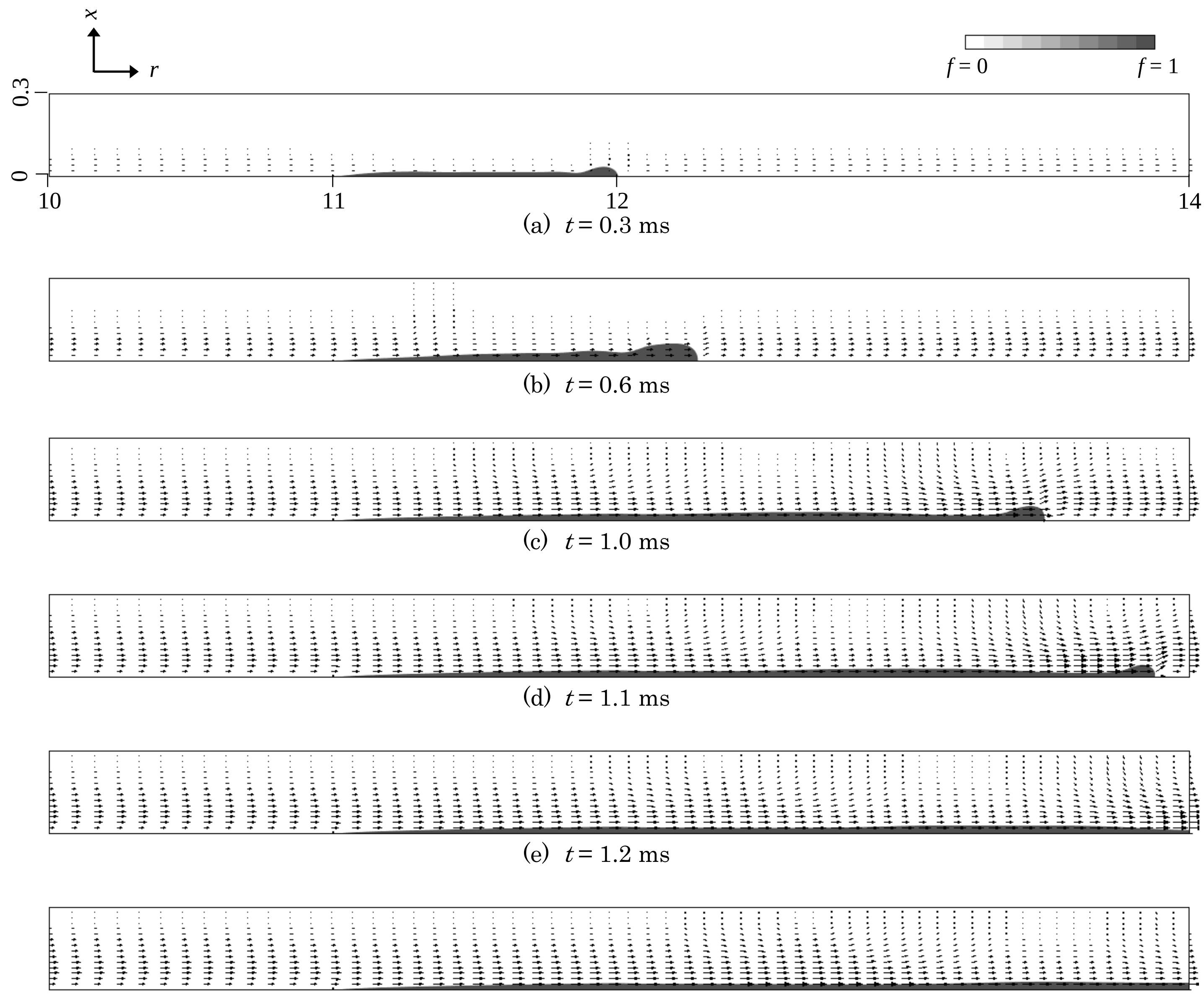


Figure 3 Relative error of film thickness for using different-sized meshes

RESULTS AND DISCUSSION

Figure 4 shows the fluid behavior at 15,000 rpm. Initially, the fluid rises in the paint supply hole without flowing out of the hole. Next, the fluid flows along the bell-cup surface toward the edge and forms a liquid film, which then rises and forms a film head. Figure 5 shows details of the flow field and Fig. 6 shows the time-averaged radial velocities. At $x = 0.3$ mm, the bell-cup rotation scarcely affects the fluid, and thus the fluid velocity obtained is low. Far from the bell-cup, with decreasing x, the fluid velocity increases because the fluid near the bell-cup is easily influenced by the bell-cup rotation. Near the bell-cup, with decreasing x, the velocity decreases because the radial velocity is zero on the bell-cup surface because of the friction between the fluid and the bell-cup. Due to the balance between the effect of bell-cup rotation and friction, the gas near the liquid level attains the maximum velocity. The velocity gradient in the liquid layer is larger than the velocity gradient in the air layer. In addition, Fig. 7 shows the momentum of the fluid. Although the gas flows very fast, it has an insignificant effect on the liquid flow because the momentum of the gas is much smaller than that of the liquid.



(a) $t = 0.3$ ms

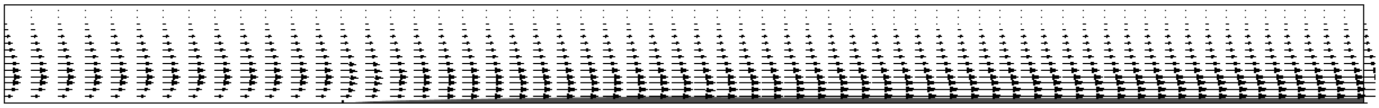
(b) $t = 0.6$ ms

(c) $t = 1.0$ ms

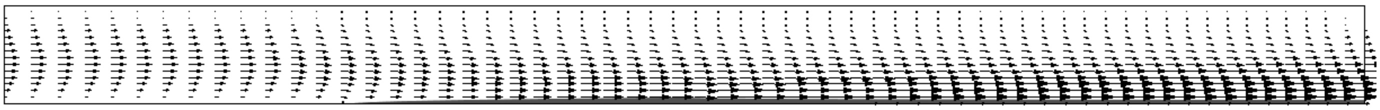
(d) $t = 1.1$ ms

(e) $t = 1.2$ ms

(f) $t = 1.3$ ms



(g) t = 3.0 ms



(h) t = 7.0 ms

Figure 4 Distribution of VOF function and the resultant of radial and axial velocities
(15,000 rpm, 300 mL/min)

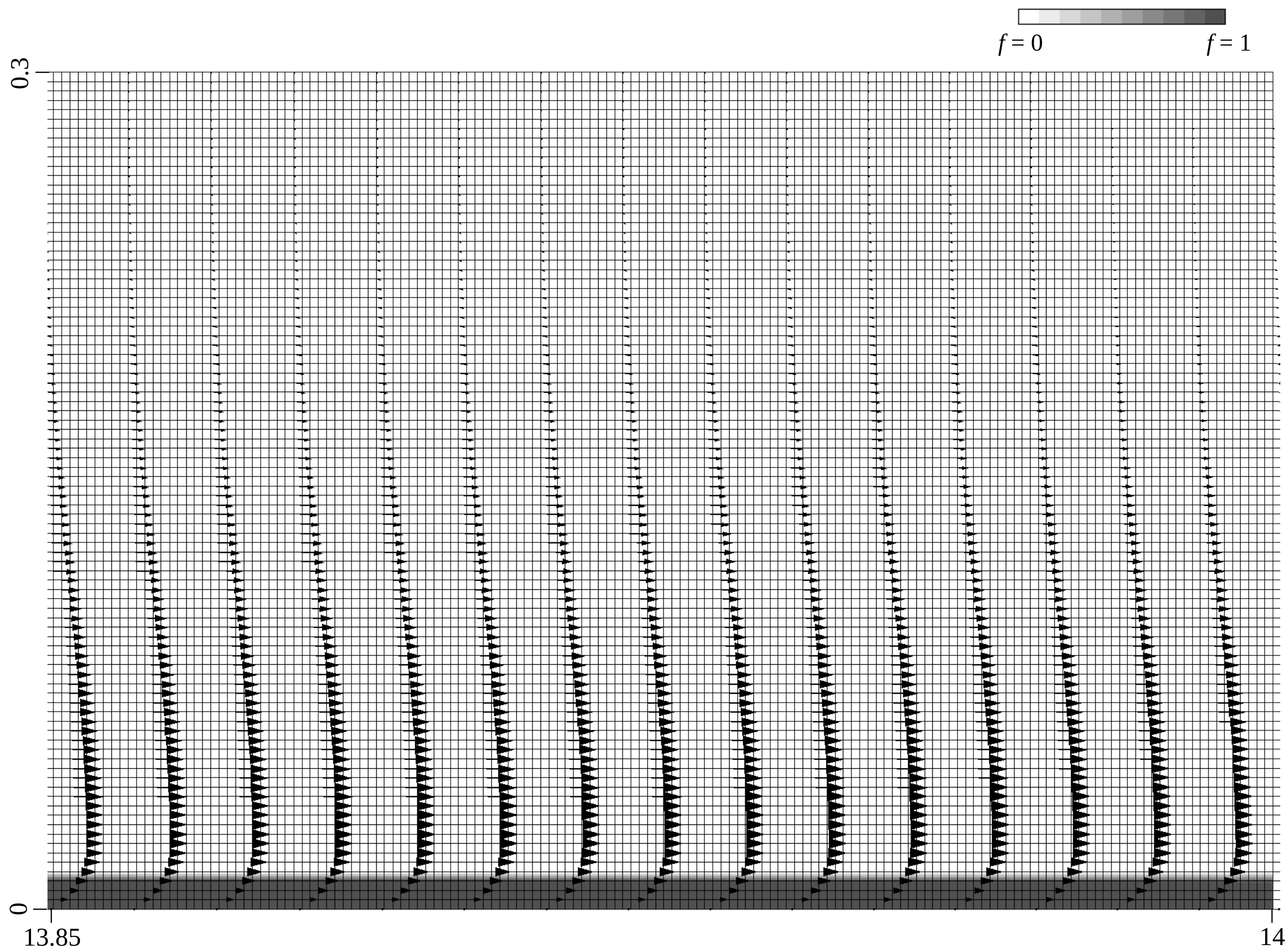


Figure 5 Distribution of VOF function and the resultant of radial and axial velocity
(magnification, 15,000 rpm, 300 mL/min, t = 7.0 ms)

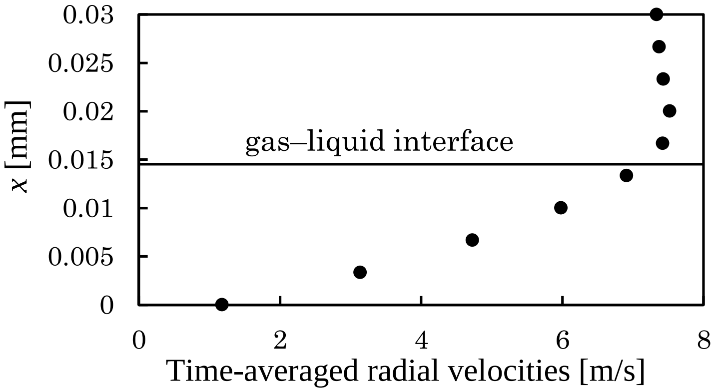


Figure 6 Time-averaged radial velocities in the range 5–15 ms (15000 rpm, 300 ml/min, r = 13.4 mm)

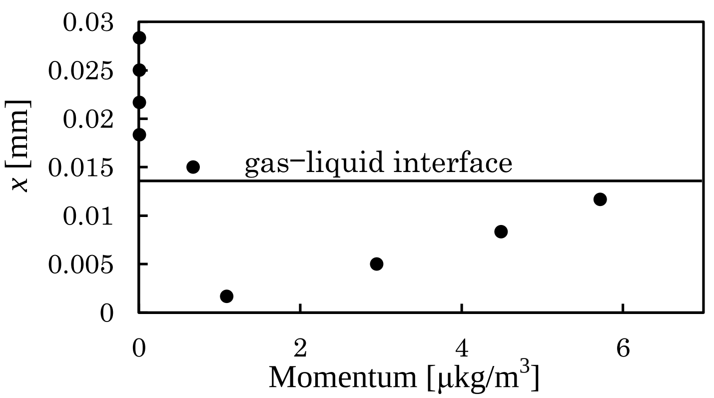
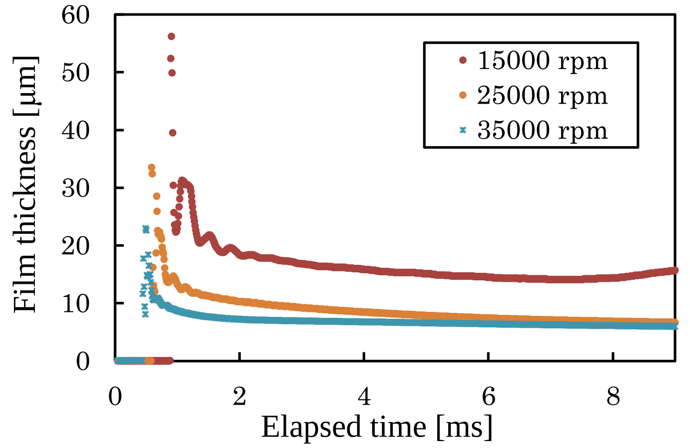
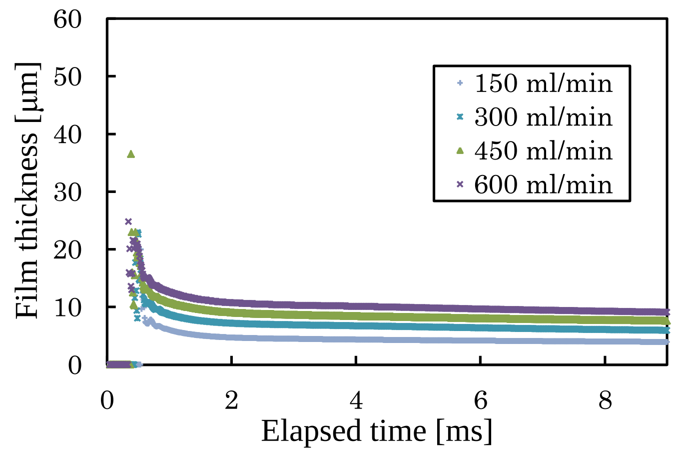


Figure 7 Fluid momentum (15,000 rpm, 300 ml/min, r = 13.4 mm, t = 7 ms)

Figure 8 shows the temporal change of the film thickness at r = 13.4 mm. Initially, the film thickness is zero because the fluid does not reach measuring point. The film thickness is highest in the range 0.5–1.3 ms because the liquid film reaches the measuring point at this time and, as observed in Fig. 4, the film head is raised. Finally, the film thickness decreases and becomes practically constant, which indicates the possibility that every time the bell-cup operation starts, coarse droplets are formed.



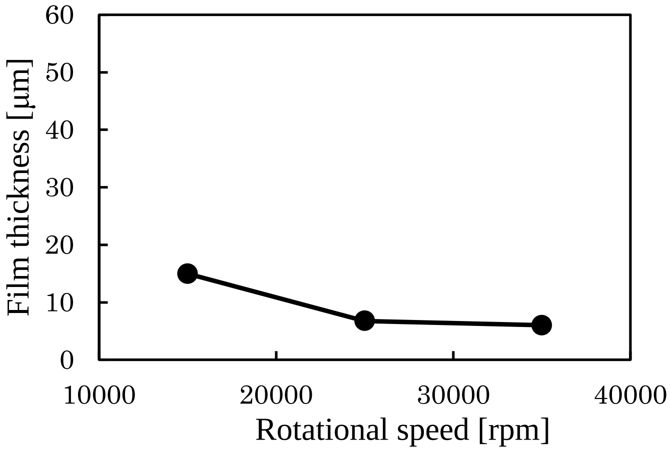
(a) Comparison of rotational speed



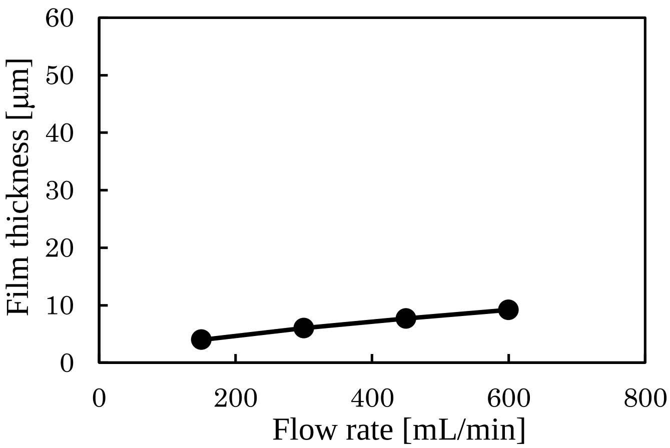
(b) Comparison of flow rate

Figure 8 Temporal change of the film thickness (r = 13.4 mm)

Figure 9 shows relationships between operating conditions and film thickness. In particular, Fig. 9(a) shows the effect of rotational speed upon the film thickness. The increase in the bell rotational speed causes the film thickness to decrease because an increase in the speed of rotation increases the centrifugal force. Furthermore, an increase in the rotational speed causes the film thickness to become almost constant. Figure 9(b) shows the effect of flow rate on the film thickness: An increase in the liquid flow rate causes the film thickness to increase. These results show that the rotational speed and the flow rate strongly affect the film thickness.



(a) Effect of rotational speed



(b) Effect of flow rate

Figure 9 Relationship between operating conditions and film thickness (the average film thickness ranges from 8 to 9 ms)

CONCLUSIONS

Herein, we presented a study of liquid flow over a high-speed rotary bell-cup atomizer. We analyzed the gas–liquid two-phase flow using the VOF method and found the following results:

- The liquid supplied to the bell-cup flows along the bell-cup surface toward the edge and forms a liquid film.
- Under the numerical conditions and after a certain period of time, the film maintains almost constant thickness (in the range4–15 μm).

- The increase in the bell rotational speed causes the film thickness to decrease.
- The increase in the liquid flow rate causes the film thickness to increase.

In conclusion, the rotational speed and the flow rate are found to be dominant factors in determining the liquid film thickness.

REFERENCES

[1] R. Adams, “Asia/Pacific paint consumption will exceed 20 million tonnes in 2014”, *Focus on Pigments*, **10**,1-3 (2010)

[2] S. Kazama, “Steady-state Paint Flow under High Centrifugal Force: Atomization in Spray Painting”, *JSAE Review*, **24**, 489-494 (2003)