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Liquid film flow on a high speed rotary bell-cup atomizer

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A B S T R A C T

In a high-speed rotary bell-cup atomizer, which is mainly used in the automotive industry, atomization is achieved by disintegration of a thin liquid film at the bell-cup edge. To obtain the hydrodynamic behavior of the liquid film as it passes over the bell cup, the liquid-film formation was simulated using the volume of fluid method under various conditions of the rotational speed, flow rate, liquid viscosity, and surface tension coefficient, based on industrial painting conditions. The liquid supplied from the liquid supply nozzle to the bell-cup surface flowed radially upon rotation of the bell cup and formed a film, which reached steady-state. We clarified the flow field depended on the rotational speed, flow rate, and liquid viscosity, and was independent of the surface tension coefficient. Based on these results, an equation for the liquid film thickness was proposed. In addition, the unsteady behavior of film with flow fluctuation in liquid supply was also investigated; the fluctuations persisted at the edge of the bell-cup atomizer. The proposed equation can be applied to this case regardless of the normalized amplitude of the fluctuation up to 50%. Thus, in this condition, unsteady film flow may be described in the proposed equation, which assumes a steady flow.

Introduction

High-speed rotary bell-cup atomizers, which are widely used in industrial painting, such as automotive painting, spray liquid paint by centrifugal force. The bell-cup painting process can be roughly divided into three regions: near field, transport field, and target field (Im et al., 2004). In the near field, the paint supplied through the liquid supply nozzle flows over the bell-cup surface by centrifugal force, which results in the formation of a liquid film. The liquid film flows off the bell-cup edge as ligaments and disintegrates into droplets. The atomized droplets transit through the transport field, which is the space between the bell cup and target, and adhere to the target (target field). Till date, research has concentrated primarily on transport field. Some studies (Colbert and Cairncross, 2005, 2006; Domnick et al., 2005, 2006; Toljic et al., 2011, 2012; Viti and Kulkarni, 2008; Yasumura et al., 2011a,b) computed the droplet trajectory in the transport field using a separated flow model and evaluated the transfer efficiency or the coating-deposition rate. In such numerical analyses, the liquid disintegrated in the near field was not calculated, and the initial conditions such as drop-size distribution, position, and velocity were independently specified without consideration of the atomization process. Kazama (2003), Panneton (2002), and Tanasawa et al. (1978) performed spray experiments with several types of rotary atomizers and showed the shape of the rotating body affects drop-size distribution. Kazama (2003) pointed out that, based on empirical observation, the liquid film on the bell-cup surface appeared to differ in flow patterns with types of bell cups. He inferred that the difference in drop-size distribution is because of these liquid film patterns. Therefore, a detailed rheological characterization of the liquid film in the near field is desirable to understand the process and to enable precise prediction and evaluation of process performance. Despite the importance of this phenomenon, few studies exist of near-field liquid film formation. Previously, our research group discussed liquid film patterns on a bell-cup surface, and the effect of these patterns on the disintegration patterns (Ogasawara et al., 2010). However, the rheological characteristics of these liquid films in the near field are not completely understood.

The considerable literature on liquid film on a rotating body deals almost exclusively with spinning disk reactors. Numerous

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studies have focused the measurement of film thickness using a variety of techniques (Burns et al., 2003; Ghiasy et al., 2012; Leshev and Peev, 2003). However, to understand the characteristics of a film, a common and effective approach for measuring thin-film thickness on a rotating body remains to be established. Although Wood and Watts (1973) measured the flow rate of a liquid film using tracer particles, this investigation of spatially-averaged flow, and velocity distribution in a liquid film has received little attention. Until now, very few numerical analyses have been reported that deal with the formation of a liquid film on a rotating body. De Caprariis et al. (2012) simulated a spinning disk reactor by using Ansys Fluent 12. Because they targeted the reaction–precipitation process that occurs when using a spinning disk reactor, they mainly focused on the chemical reaction and offered little information on the hydrodynamic behavior of the liquid film. However, these experiments on spinning disk reactor with relatively large diameters and low rotational speed (up to several thousand rpm) compared to the painting industry, so the data have no applicability to high-speed bell cups. Moreover, although a pulsatile pump is used to supply the liquid to the bell-cup, only a few publications are available in the public domain concerning flow fluctuation due to the pump.

In the present paper, to obtain film thickness and velocity distribution on a high-speed bell-cup atomizer (rotation speed up to 55,000 rpm), we numerically computed the flow on a rotary bell-cup atomizer. We investigated the influence of the operating conditions, liquid properties, and flow fluctuations on the liquid film thickness and velocity distributions and propose an equation based on a regression analysis to predict the liquid film thickness.

Methods

Analytical object

The computational domain of a high-speed rotary bell-cup atomizer is shown in Fig. 1. The liquid is supplied from the liquid supply nozzle located in $11 < r < 12$ mm. Because the curvature of the bell-cup surface near the nozzle is very small, we assumed the computational bell cup shape is completely flat. The inflow boundary condition was used at the liquid supply nozzle on the bell-cup surface. The no-slip boundary condition was applied to the bell-cup surface. Shear force was imposed in the circumferential direction and as a function of bell-cup rotational speed. The paint supplied from the nozzle flows over the bell-cup surface due to centrifugal force. For other boundaries, the outflow boundary conditions were used.

Governing equations

We considered a gas–liquid two-phase flow and used the volume of fluid (VOF) method (Hirt and Nichols, 1981). The fluids were assumed to be viscous, laminar and incompressible. In single-phase flow over a rotating disk, laminar flow occurs up to the rotational Reynolds number 1.5×10^5. The rotational Reynolds number in this calculation was from 1.2×10^3 to 2.9×10^6 (4.1×10^4 in base condition), and the flow is laminar flow under most conditions. As is obvious, this is not applicable strictly to multiphase flow. In case of liquid film on a rotating disk, not only rotational Reynolds number but also the film thickness may affect the flow pattern, and the flow regime cannot be classified in terms of only Reynolds number. In addition, the consistent comparison between the series of various rotational Reynolds number, the turbulence model is not used. In the future, the flow regime of liquid film flow on a rotating body should be investigated both experimentally and numerically, which is important but beyond our paper's scope. The fluid flow is governed by the following momentum equation:

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

where p is the pressure, S_ϕ is the source term, t is the time, u is the fluid velocity vector, μ is the fluid viscosity, ρ is the fluid density, and ϕ is the velocity components

$$\phi = u, v, w. \tag{2}$$

The continuity equation is

$$\nabla\cdot\mathbf{u} = 0, \tag{3}$$

and the VOF equation is

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

where c is the color function, which is defined as

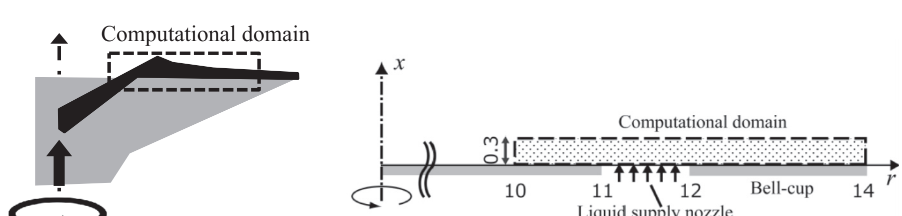
$$c = \begin{cases} 1 & \text{for a cell inside fluid 1} \\ 0 & \text{for a cell inside fluid 2} \end{cases} \tag{5}$$

The function was smoothed (Yabe et al., 2003), and the physical properties of the two immiscible fluids were calculated using a weighted average based on the smoothed VOF function:

$$\rho = \rho_1\tilde{c} + \rho_2(1-\tilde{c}), \tag{6}$$

$$\mu = \mu_1\tilde{c} + \mu_2(1-\tilde{c}). \tag{7}$$

The governing equations are discretized via the finite volume method in a coordinate system at rest. The convection term of the momentum equation was discretized by using the Chakravarthy–Osher total variation diminishing scheme, with the monotone upstream-centered scheme for conservation laws (MUSCL) approach (Chakravarthy and Osher, 1985). The diffusion term was discretized with the second-order central difference scheme. For discretization of the VOF equation, the compressive interface capture scheme for arbitrary meshes (CICSAM) scheme (Ubbink, 1997), which blends the Hyper-C scheme with the ultimate quickest (UQ) differencing scheme through a weighting factor, was utilized because of its good performance in maintaining the sharpness of the fluid interface. The simplified marker and cell



(a) Schematic diagram (b) Detail view of the analytical object

Fig. 1. Analytical object.