Simulation Research on Characteristics of Paint Deposition on Spherical Surface

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Abstract. In order to describe the gas-liquid two-phase coupling flow process of paint deposition on spherical surface, the Euler-Lagrangian method is adopted to establish the model of paint deposition on spherical surface, including continuous phase model, discrete phase model and impingement and sticking model. By comparing and analyzing the simulation results of flat and spherical surface in XZ-plane, the uniformity of the paint film on spherical surface is better than that on flat. As the spherical surface diameter increases, the distribution range of the paint film expands, the film thickness decreases, and the deposition rate improves. The characteristics of paint deposition on spherical surface are verified by experiments.

1. Introduction

Robotic painting is a mechanized and automatic painting technology[1-3], where the spray gun is usually under the predetermined path provided through off-line programming. Fully understanding the characteristics of paint deposition process on the workpiece to be painted is important for obtaining the path through off-line programming. Air spray gun is one type of the common spray guns, and the characteristics of the paint deposition process of using it to paint flat workpiece have been studied by many researchers. But there are few studies on the paint deposition process of painting spherical surface, which is also a common curved surface in industry.

Paint deposition process is a gas-liquid two-phase transient flow phenomenon, which is usually simulated by applying CFD (computational fluid dynamics) [6-7]. The Euler-Lagrangian method is a commonly-used method for studying paint deposition, which treats the air as a continuous phase obtained by solving the time-average N-S equation, and treats the atomized paint droplets as a discrete phase obtained by capturing the motion of paint droplets. And the Euler-Lagrangian method is widely adopted to study paint deposition by most researchers, such as Flynn[8], Ye[9], Chen[10] and Hilton[11].

Therefore, in this paper, the Euler-Lagrangian method is used to establish a paint deposition model to study the characteristics of paint deposition on spherical surface. Simulation cases on flat and spherical surface with different diameters are simulated. The characteristics of paint deposition on
spherical surface are contrastively analyzed. And Simulation results are verified by experiments.

2. Paint deposition model

The spray flow field is a coupling flow field of the continuous phase and the discrete phase, which is described by adopting the Euler-Lagrangian method.

2.1 Continuous phase model

During the spraying process, the ambient temperature remains constant. Therefore, the gas phase flow mainly considers the mass conservation equation and the momentum conservation equation.

The mass conservation equation is

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0$$

(1)

in which $\rho$ is the air density and $u_i$ is the air velocity in the $i$ direction.

The momentum conservation equation is

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

(2)

where $p$ is the air pressure, $\mu$ is the air viscosity, and $u_i'$ is the pulsating speed in the $i$ direction.

Besides, Realizable $k-\varepsilon$ turbulence model is applied, which can avoid the situation that the positive stress is negative due to the extremely high time-average strain rate.

2.2 Discrete phase model

The paint droplets are mainly affected by gravity and air impact force in the spray flow field. In the Cartesian coordinate system, the force balance equation of the paint droplet in the $x$ direction is

$$\frac{d u_p}{dt} = F_{p_x}(u - u_p) + \frac{g_x (\rho_p - \rho)}{\rho_p}$$

(3)

in which $\rho_p$ is the paint density, $u_p$ is the velocity of the paint droplet and $F_{p_x}(u - u_p)$ indicates the unit mass drag of the paint droplet.

2.3 Paint impingement and sticking model

When spraying, the discrete paint droplets impinge on the workpiece surface and stick to form the paint film, which is described by the mass conservation and the momentum conservation.

The mass conservation shows as follows

$$\frac{\partial h}{\partial t} + \nabla \cdot \left[ h \nabla h \right] = \frac{n_{k,1}}{\rho_i}$$

(4)

in which $h$ is the height of paint film, $\nabla \cdot \left[ h \nabla h \right]$ is the flow velocity of the newly formed paint liquid film and $n_{k,1}$ is the paint mass source of unit area, which is given by $n_{k,1} = \alpha_d \rho_i V_{d,i} A$.

The momentum conservation is
The liquid phase consists of 71 discrete particle parcels, which are distributed in the circular region of the paint hole by adopting the Rosin-Rammler distribution. The density of the liquid phase is 1200kg/m$^3$, and the viscosity is 0.0979kg/(m·s). According to the DPM model in ANSYS Fluent, the workpiece is set as the wall-film model. The time step is $\Delta t = 1 \times 10^{-4}$ s, and the spraying time is 0.5s.

\[
\frac{\partial hV_i}{\partial t} + \nabla_i \cdot \left[ h V_i \frac{\mathbf{r}}{\rho_i} \right] = h V_i P_i + \frac{\mathbf{r}}{2\rho_i} h + \frac{3}{h} \mathbf{V}_i - \frac{3\mathbf{V}_i}{h} \frac{\mathbf{V}_i}{h}
\]  

(5)

Where the transient term and the convection term are shown on the left successively. On the right, the first term is the combined effect of the gas flow pressure, the normal component of gravity along the surface and the surface tension of the liquid film; the others are the tangential component of gravity along the surface, the viscous shear stress at the intersection interface between the gas phase and the liquid phase and the viscous stress of the liquid film, respectively.

3 Simulation cases setup

The geometric model of spray nozzle adopted in simulation is shown in Figure 1. The paint hole with a diameter of 1.1mm lies in the center of the spray nozzle. Concentric with the paint hole is the central air hole—a ring with an outer diameter of 2mm and an inner diameter of 1.6mm. And there are two identical assistant air holes with a diameter of 0.5mm on each side of the central air hole. On the horn mouth of the spray nozzle are two shaping air holes respectively, and the one closer to the paint inlet hole has a diameter of 0.6mm while the further 0.8mm.

![Figure 1. Geometric model of spray nozzle](image1)

The simulation cases are conducted by spraying spherical surfaces with diameters of 380mm, 440mm and 550mm. The spraying distance is set at 180mm from the paint hole to the workpiece surface, and the axis of the spray nozzle is perpendicular to the workpiece. The computational domain is meshed by polyhedral mesh method as shown in Figure 2. And a comparative case is carried out by spraying a 400mm×400mm flat plate.

![Figure 2. Mesh of computational domain](image2)

The central air hole, the assistant air hole and the shaping air hole are set as pressure inlets with 1.5atm, 1.5atm and 0.8atm, respectively, of which the hydraulic diameters are set as 0.4mm, 0.4mm and 0.6mm, and the turbulent intensities are kept the same as 5%. The liquid phase consists of 71 discrete particle parcels, which are distributed in the circular region of the paint hole by adopting the Rosin-Rammler distribution. The density of the liquid phase is 1200kg/m$^3$, and the viscosity is 0.0979kg/(m·s). According to the DPM model in ANSYS Fluent, the workpiece is set as the wall-film model. The time step is $\Delta t = 1 \times 10^{-4}$ s, and the spraying time is 0.5s.

4. Simulation results and analysis

Figure 3 shows the contours of the air velocity in XZ-plane in two spray flow fields simulated on flat and spherical surface. To obtain appropriate contour shapes, the variation range of the air velocity is limited to 0-20m/s, and the XZ-plane is chosen to illustrate. According to the change of the air velocity,
the spray flow field is approximately divided into two parts: the diffusion zone and the deposition zone. The former refers to the area where the liquid paint is discretized and diffuse, while the latter is the area in which a large number of paint droplets deposit on the workpiece.

![Velocity contour](image1)

**(a)** Change of air velocity above flat

![Velocity contour](image2)

**(b)** Change of air velocity above spherical surface

**Figure 3.** Change of air velocity above different workpieces

Figure 4 shows the contours of the paint film thickness on flat and spherical surface. 24.5μm is the maximum value of paint film thickness on spherical surface, which is much smaller than 29.7μm on flat, and the elliptical rings of paint film on spherical surface are more obvious than that on flat, which indicates that the uniformity of paint film on spherical surface is better than that on flat.

![Thickness contour](image3)

**(a)** Thickness distribution on flat

![Thickness contour](image4)

**(b)** Thickness distribution on spherical surface

**Figure 4.** Spatial distribution of paint film thickness on different surfaces

Figure 5 shows the comparison of the thickness distribution of paint film on different workpieces in XZ-plane between simulation and experiment. The simulations and experiments of painting the three spherical surfaces with different diameters and the flat were carried out under the same painting parameters. In Figure 5, the curves are obtained by fitting the thickness data of simulation cases, while the dots represent the points on the paint films at an interval of 5mm, and their data are the averages of the film thicknesses measured three times by a thickness gauge at every point.

As is shown in Figure 5, the larger the spherical surface diameter is, the more similar the thickness distribution on is to that on flat. Besides, when the diameter increases, the distribution range of the paint film enlarges and the height of the paint film increases, which indicates that the deposition rate improves.
Figure 5. Thickness distribution on different workpieces in XZ-plane (curve: simulation, dot: experiment)

5. Conclusions

According to the contrastive analysis of simulation cases and the verification of experiments, the characteristics of paint deposition on spherical surface are revealed, and two conclusions are obtained:

(1) Comparing with flat, spherical surface has a great influence on paint deposition, which leads to smaller paint film thickness, more obvious the elliptical rings and better uniformity.

(2) As the spherical surface diameter increases, the distribution range of the paint film expands, the film thickness decreases, and the deposition rate improves.

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