New Spraying Modelling of Special Surfaces for Environmental Protection

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Abstract. Research on spraying models of special profiles has a great significance on optimizing spraying quality, saving paint and protecting environment and health of workers. This article establishes a paint deposition model including the spray flow field model and impact adhesion model based on the Euler-Euler method. The model is solved by using polyhedral mesh to divide the fluid calculation domain and the coupled SIMPLE algorithm to compute the governing equations. The methods of spraying along the bus bar and circumferential spraying are applied to simulate and test the conical surface and the arc surface successively. Results of the experiments demonstrate the errors of the four cases are all less and confirm that the established paint deposition model is suitable for spraying research on conical outer surface.

1. Introduction
There are a large number of special profiles in the industry, such as conical surfaces, V-shaped surfaces, arc surfaces and spherical surfaces. In the process of spraying these special shapes, a large amount of organic solvents and other harmful substances diffuse into the atmosphere, polluting the environment and endangering the health of workers. Research on spraying models of special profiles is of great significance for improving spraying quality, saving paint, protecting the environment and protecting the health of workers [1].

Computational fluid dynamics is an effective method to explore the mechanism of paint deposition [2-3], which includes Euler-Lagrangian method and Euler-Euler method. The Euler-Lagrangian method [4] can track and calculate the movement of a single paint droplet in detail, and obtain information such as the movement trajectory of the droplet [5], the velocity and pressure of the droplet and the air phase, but the computational burden is quite large, resulting in the general computers are difficult to meet the numerical simulation conditions. The Euler-Euler method uses the same set of numerical methods for the two phases of gas and liquid. It has a small amount of calculation, and can better describe the turbulent mixing process of a large number of droplets in the airflow. The Euler-Euler method is a powerful method to study the mechanism and model of paint deposition [6].

In this paper, the Euler-Euler method is utilized to establish a paint deposition model composed of a spray flow field model and an impact adhesion model. The rationality of the paint deposition model of external surface is analyzed through simulation, and the correctness of the model is verified through experiments.
2. Spray Model

2.1. Spray Flow Field Model

The Euler-Euler method takes the coating droplet phase as a continuous fluid similar to the air phase, and the spray flow field model is represented by a unified governing equation (when the subscripts $s$ are $a$ and $p$, they are the air phase and the coating droplet phase respectively). The ambient temperature remains constant during the spraying process, the heat transfer phenomenon in the two-phase flow can be ignored, so in the whole control system only the mass and the momentum are conserved and equations can be written as:

$$\frac{\partial (\alpha_s \rho_s)}{\partial t} + \nabla \cdot (\alpha_s \rho_s \mathbf{v}_s) = 0$$  \hspace{1cm} (1)

$$\frac{\partial}{\partial t} (\alpha_s \rho_s \mathbf{v}_s) + \nabla \cdot (\alpha_s \rho_s \mathbf{v}_s) = -\alpha_s \nabla p + \nabla \cdot \mathbf{\tau}_s + F_{d,s} + \alpha_s \rho_s \mathbf{g}$$  \hspace{1cm} (2)

where $\alpha_s$ is volume rate of $s$ phase ($\text{m}^3/\text{s}$); $\rho_s$ is the density of $s$ phase ($\text{kg}/\text{m}^3$); $\mathbf{v}_s$ is the velocity of the $s$ phase ($\text{m}/\text{s}$); $p$ is the pressure of the phases ($\text{N}/\text{m}^2$); $\mathbf{\tau}_s$ is the viscous stress of the $s$ phase ($\text{N}/\text{m}^2$); $F_{d,s}$ is the drag force ($\text{N}/\text{m}^3$); $\mathbf{g}$ is the acceleration due to gravity ($\text{m}/\text{s}^2$). 

The coating droplets in the spray flow field can be regarded as an ideal spherical shape, and the density ratio of air to droplets is far less than 1, so $F_{d,s}$ is calculated using the Schiller-Naumann drag model. The drag force of air phase to the droplet phase is:

$$F_{d,s} = 0.75C_D \rho_s \alpha_s \mathbf{v}_a \cdot (\mathbf{v}_a - \mathbf{v}_p)$$  \hspace{1cm} (3)

where $C_D = 0.44$ is the drag coefficient.

Due to the insufficient development of turbulence near the wall of the spray cone, the standard wall function and the standard $k$-$\varepsilon$ model are used to close the momentum equation. Introducing the standard $k$-$\varepsilon$ model which contains the turbulent kinetic energy $k$ ($\text{m}^2/\text{s}^2$) and the turbulent energy dissipation rate $\varepsilon$ ($\text{m}^2/\text{s}^3$) to the transport equations, then the equations can be written as:

$$\frac{\partial (\rho_m k)}{\partial t} + \nabla \cdot (\rho_m k \mathbf{u}_m) = \nabla \cdot \left[ \left( \mu + \frac{\rho_m C'_u k^2}{\sigma_k} \right) \nabla k \right] + G_{k,m} - \varepsilon \rho_m + S_{k,m}$$  \hspace{1cm} (4)

$$\frac{\partial (\rho_m \varepsilon)}{\partial t} + \nabla \cdot (\rho_m \varepsilon \mathbf{u}_m) = \nabla \cdot \left[ \left( \mu + \frac{\rho_m C'_\varepsilon \varepsilon^2}{\sigma_k} \right) \nabla \varepsilon \right] + C_{1\varepsilon} \frac{\varepsilon}{k} G_{k,m} - C_{2\varepsilon} \rho_m \varepsilon^2 + S_{\varepsilon,m}$$  \hspace{1cm} (5)

where $\rho_m$ is the density of the mixed phase ($\text{kg}/\text{m}^3$); $\mathbf{u}_m$ is the speed of the mixed phase ($\text{m}/\text{s}$); $\mu$ is the dynamic viscosity of the mixed phase ($\text{N} \cdot \text{s}/\text{m}^2$); $k^2$ is the turbulence velocity scale; $C'_u$, $C_{1\varepsilon}$, $C_{2\varepsilon}$, $\sigma_k$ and $\sigma_\varepsilon$ are constants with values of 0.09, 1.44, 1.92, 1.0 and 1.3 respectively; $G_{k,m}$ is the turbulent energy term ($\text{kg}/\text{m} \cdot \text{s}^3$) produced by the average velocity gradient; $S_{k,m}$ and $S_{\varepsilon,m}$ are the additional terms of turbulence between the two phases.

2.2. Adhesion Model

The sprayed coating droplets arrive near the wall, and a certain control body is taken to establish a conservation equation. Comparing the situation before and after the collision, the mass and momentum of the coating droplet have changed. Adding the mass and momentum of the coating droplet phase are
as source terms to the conservation equation of the wall liquid film, the mass conservation equation and momentum conservation equation of the liquid film are established respectively. At last, by solving the continuous equations the thickness of the liquid film can be obtained.

The quality source term is:

$$\dot{m}_i = \alpha_i \rho_d V_{d,i} A$$  \hspace{1cm} (6)

where $V_{d,i}$ is the normal velocity of the coating droplet phase along the wall (m/s); $\alpha_d$ is the volume fraction of the coating droplet phase; $\rho_d$ is the coating droplet phase density (kg/m$^3$); $A$ is the wall area (m$^2$).

After adding the mass source term, the mass conservation equation can be described as:

$$\frac{\partial h}{\partial t} + \nabla \cdot (h \cdot V_i) = \frac{\dot{m}_i}{\rho_i}$$  \hspace{1cm} (7)

where $h$ is the height of the wall film (m); $\rho_i$ is the wall film density (kg/m$^3$); $V_i$ is the average liquid film velocity (m/s).

The momentum source term is:

$$\dot{q}_i = \dot{m}_i V_d$$  \hspace{1cm} (8)

where $V_d$ is the velocity vector of the coating droplet phase (m/s).

After adding momentum source term the momentum conservation equation can be described as:

$$\frac{\partial h V_i}{\partial t} + \nabla_s \cdot (h V_i V_i) = -\frac{h \nabla P_L}{\rho_i} + g_i h + \frac{3}{2} \frac{\tau_{hs}}{h} V_i + \frac{\dot{q}_i}{\rho_i}$$  \hspace{1cm} (9)

where $P_L$ is liquid film pressure; $\nabla_s$ is surface gradient operator. The two terms on the left-hand side of the equation, represent phase transient change and convective transport respectively. Each terms on the right side sequentially represents: the air flow pressure, the effect of the tension of the liquid film surface expansion and the gravity component on the vertical wall, the effect of gravity on the direction parallel to the coating film, the effect of the viscous shear force at the interface between the air and the liquid film, and the effect of the viscous force between the liquid film and the wall surface.

3. Numerical Simulation Calculation

3.1. Model and Spraying Method

The simplified model of the air cap of the external mixing atomizing spray gun for calculation is shown in Figure 1(a). The diameter of the coating inlet hole is 1.1mm, the outer and inner diameters of the central atomization hole are 2mm and 1.6mm, the diameter of the four auxiliary atomization holes is 0.5mm, and the diameter of the fan pressure hole is 0.8mm. The coordinate system is shown in Figure 1(b) and Figure 1(c). The origin is at the center of the paint inlet hole, the $Z$ axis is along the center axis of the air cap toward the spraying direction, the $X$ axis is the direction of the center line of the auxiliary atomization hole, and the $Y$ axis is the direction perpendicular to the plane where the pressure hole of the sector is located, while it keeps perpendicular to the $X$ axis.
For reasons that the conical surface and the arc surface are typical representatives of special surfaces, the contrast study of static spraying is carried out on the conical surface of 60° cone angle and the arc surface with radius of 180mm. The radius of curvature of the bottom center of the spray cone for the outer surface of the spray cone is 180mm. On the outer surface, the cone angle is \( \alpha \), the curvature radius of the bottom center of the spray cone is \( R_1 \), and the radius of the cone section where the bottom center of the spray cone is located is \( R \) (Figure 2):

\[
R = R_1 \cos \frac{\alpha}{2}
\]

Figure 2. Schematic of painting position on outer conical surface.

As shown in Figure 3, the spraying methods on the conical surface and the arc surface are spraying along the bus bar and spraying along the circumferential direction. The former means that the bottom center of the spray cone moves on the busbar in spraying process; The latter means that the bottom center of the spray cone moves on the cross-sectional circle of a cone or cylinder. When spraying, the direction of the spray gun axis is consistent with the normal direction of the conical surface and the arc surface.

Figure 3. Methods of spraying outer surfaces.
3.2. Calculation Domain and Parameter Settings

The spraying apex angle is 60°, the radius is 290mm. The length of conical bus bar is 580mm, and the radius and height of the arc surface are 180mm and 300mm respectively. The calculation domain and parameter settings are as shown in figure 4. In the figure, the gray grid area was the boundary of the pressure outlet, the black grid area was the wall surface of the target to be sprayed, and the blue area was the spray gun position. The fluid calculation domain was divided by a polyhedral grid.

The spray flow field is a two-phase mixed flow field: the first phase is air and the second phase is coating. The operating environment is one standard atmosphere, and the acceleration of gravity is 9.81m/s². The air pressures from the central atomization hole, the auxiliary atomization hole and the fan pressure hole are respectively 120kpa, 100kpa and 110kpa. The relative parameters of the coating from the inlet hole are as follows: Its density is 1.2×10³ kg/m³, the viscosity is 0.09686 kg/(m·s), the surface tension coefficient is 0.0287194N/m, and the mass flow rate is 0.00132kg/s. In the whole spraying process the spraying distance is kept the value 180mm.

The coupled SIMPLE algorithm is utilized to solve the algebraic equations discretized by the second-order upwind style. The iteration time step is set to 1×10⁻⁴ s, and the iteration time is 0.5s. With 500 iterations the residual error is 1×10⁻⁴.

(a) Spraying conical outer surface along bus bar  
(b) Circumferential spraying conical outer surface  
(c) Spraying outer surface of the arc along bus bar  
(d) Circumferential spraying arc outer surface

Figure 4. Fluid regions and computing domain meshing.

4. Experiments

In order to verify the simulation results, two sets of experiments were set up and carried out according to the simulation content. A stopwatch was used to measure and record the spraying time during spraying. During the drying process, the coating film was not touched. A coordinate axis was established in the center of the dry paint film and measured with a coating thickness gauge. The coordinate value of a point and the coating film thickness were recorded every 10mm. The dry film thickness was divided by the spraying time to get the coating film thickness growth rate.

The shapes of the simulated paint film and the shapes of the test coating film are shown in Figure 5(a) and Figure 5(b). The shapes of the simulated coating film are roughly the same as the experiment. The comparison of the simulation result and the experiment result of the coating film thickness growth rate (the ratio of the dry film thickness to the spraying time) is shown in Figure 6. The simulation results and the experimental results are generally consistent. The error is mainly due to the speed at the center of the experimental coating film is lower than the simulation, and the two sides are slightly higher than the simulation. This is because some of the components of the wet film formed in the experiment evaporated during the drying and curing process, which caused the coating film to move weakly around under the action of gravity and the surface tension of the coating.
5. Conclusion
The shapes of the paint film from the simulation and the experiment is roughly the same, as well as the paint film thickness growth rate, indicating that the established paint deposition model is suitable for the study of spraying of conical outer surface and arc surface. This method can be applied to guide the spray modelling of special surfaces.

Figure 5. Simulation of film and experimental diagram.

Figure 6. Growth rate of coating thickness.

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