Numerical Simulation of Characteristics of Spray Flow Field on the Conical Surface

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Abstract. Aiming at the gas-liquid two-phase flow process in the spray flow field on the conical outer surface, based on Euler-Euler method a spray film forming model is proposed. A polyhedral mesh was utilized to divide the fluid computing domain and the coupled SIMPLE algorithm was adopted to solve the model. The results show that the spray shape on the outer surface of the cone is similar to that on the outer surface of the arc, and both are in the shape of an elliptical cone; in the area far away from the wall surface, the difference of surface has almost no effect on the spray cone angle. In terms of the spraying speeds of the two spraying methods within the area close to the outer surface of the cone, for the circumferential spraying, the spray normal speed is higher than that of spraying along the busbar, and the maximum tangential speed is lower. Meanwhile, both the two speeds are almost equal to that of spraying the arc surface; for spraying along the busbar, the spray normal speed is higher than that of the arc outer surface, and the maximum tangential speed is lower.

Keywords: Characteristic, Numerical simulation, Spray flow field, Conical surface.

1. Introduction

Industrial products have a large number of tapered outer surfaces, such as fighter jet noses, rocket fairings, tapered tanks and tapered tubes. The tapered outer surface directly affects the spray flow field, and the spray flow field directly affects the uniformity, smoothness and coating efficiency of the coating. Studying the characteristics of the spray flow field on the outer surface of the cone is of great significance for revealing the rules of spraying film formation, optimizing spraying trajectories, and improving spraying quality[1].

Computational fluid dynamics is an effective method to explore the mechanism of spray coating[2]. The methods include Euler-Lagrangian method[3] and Euler-Euler method[4]. Most of the existing air spray simulations use the discrete phase model. The discrete phase model is modeled by Euler-Lagrangian method, which can track and calculate the movement of a single droplet in detail, and better describe the turbulent mixing process of droplets in the airflow[5]. However, as the number of particles increases, the calculation time of the discrete phase model will increase exponentially. Besides, the model is very sensitive to the mesh accuracy of the area near the spray gun and the target spray wall, which leads to the grid division has a great influence on the spray flow field and the formation of the liquid film on the wall. Therefore, it is quite difficult to describe the flow of large quantities of paint droplets in the spray flow field with a discrete model.

The Euler-Euler method can effectively solve the problems in current researches. This method treats both air and coating droplets as continuous phases, and both phases are processed in the Euler coordinate system, which can completely consider various turbulent transport processes of the particle...
phase and obtain the spatial distribution of particle velocity and concentration. Its calculation burden is smaller than the Euler-Lagrangian method, so Euler-Euler method is well-accepted by engineering practice. This method was first applied to the simulation of multiphase flow field by Harlow[6], and YE et al.[7], A. Andreini et al.[8], Chen et al.[9] applied it to spraying simulation.

In this paper, the Euler-Euler method is applied to establish a spray film forming model composed of a spray flow field model and an impact adhesion model. The characteristics of the spray flow field on the outer surface of the cone are revealed through simulation analysis.

2. Mathematical Model

2.1. Spray Flow Field Model

In the Euler-Euler method, different phases are treated as coexistent and interpenetrating continuous media. The ratio of each phase to the control body is its volume fraction, and each phase has its own independent conservation equation. During the simulation spraying process, the ambient temperature remains unchanged, and the heat transfer phenomenon in the two-phase flow can be ignored. Therefore, only the mass conservation equation and the momentum conservation equation are established:

The mass conservation equation is:

$$\frac{\partial (\alpha_n \rho_n)}{\partial t} + \frac{\partial (\alpha_n \rho_n v_n)}{\partial x_i} = 0$$  \hspace{1cm} (1)

The momentum conservation equation is:

$$\frac{\partial (\alpha_n \rho_n v_n)}{\partial t} + \frac{\partial (\alpha_n \rho_n v_n v_n)}{\partial x_i} = -\alpha_n \frac{\partial \rho}{\partial x_j} + \frac{\partial \tau_n}{\partial x_j} + F_{d,n} + \alpha_n \rho_n g$$  \hspace{1cm} (2)

The Schiller-Naumann drag force model is:

$$F_{d,n} = 0.75 \frac{C_D}{\rho} \frac{v_n - v_p}{v_n} (v_n - v_p)$$  \hspace{1cm} (3)

where $\rho_n$ is the density of n phase (kg/m$^3$); $v_n$ is the velocity of n phase (m/s); $p$ is the pressure of the phases (N/m$^2$); $\tau_n$ is the viscous stress of n phase (N/m$^2$); $F_{d,n}$ is the drag force (N/m$^3$); $g$ is the acceleration due to gravity (m/s$^2$), and the drag force coefficient $C_D$ generally takes a value of 0.44. The momentum equation was closed by using the standard wall function and the standard $k-\varepsilon$ model due to insufficient turbulence development in the near-wall area of the sprayed cone.

The $k$ equation is:

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \mu \frac{\partial k}{\partial x_i} \right] - \frac{1}{\varepsilon \sigma_k} \frac{\partial}{\partial x_i} \left[ \frac{\mu}{\varepsilon \sigma_k} \frac{\partial k}{\partial x_i} \right] + C_{k,m} G_{k,m} - \varepsilon \rho + S_{k,m}$$  \hspace{1cm} (4)

The $\varepsilon$ equation is:

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \mu \frac{\partial \varepsilon}{\partial x_i} \right] + \frac{C_{\varepsilon}}{C_{k,m}} G_{k,m} / k - C_{2,\varepsilon} \rho {\varepsilon}^2 / k + S_{\varepsilon,m}$$  \hspace{1cm} (5)

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

2.2. Adhesion Model
The sprayed coating droplets approach the wall, and a certain control body is taken to establish a conservation equation. Both the mass and momentum of the droplet change before and after the impact. The mass and momentum of the coating droplet phase are added as source terms to the conservation equations of wall liquid film, the mass conservation equation and momentum conservation equation of the liquid film are established respectively. The thickness of the liquid film is obtained by solving the continuous equations.

The mass conservation equation after introducing the mass source term:

$$\frac{\partial h}{\partial t} + \partial (h \cdot V_i) = \alpha_d \rho_d V_{dn} A / \rho_l$$  \hspace{1cm} (6)

Momentum conservation equation after adding momentum source term:

$$\frac{\partial h V_i}{\partial t} + \partial (h V_i V_j) = -(h \cdot P_i) \partial x_j + g, h + 3 \tau_p \rho_l / (2 \rho_l) - 3 \nu V_l / h_l + \alpha_d \rho_d V_{dn} A V_d / \rho_l$$  \hspace{1cm} (7)

where $V_{dn}$ is the normal velocity of the paint droplet phase along the wall (m/s); $\alpha_d$ is the volume fraction of the paint droplet phase; $\rho_{d}$ is the paint droplet phase density (kg/m$^3$); $A$ is the wall area (m$^2$). $h$ is the height of the wall film (m); $\rho_l$ is the wall film density (kg/m$^3$); $V_l$ is the average liquid film velocity (m/s); $V_d$ is the velocity vector of the paint droplet phase (m/s).

3. Calculation Results and Analysis

3.1. Spray Mist Shape and Velocity Distribution

The spray flow fields of the arc outer surface and the conical outer surface are obtained by simulation, and it is found that the spray cones are all elliptical cones. This is because the spray cone is compressed in the $XZ$ plane and expanded in the $YZ$ plane due to the impact of the airflow from the fan pressure holes at both sides of the air caps, as shown in Figure 1. The effects of these two outer surfaces on the spray flow field in the long axis and short axis directions are similar, and the spray flow field has a greater larger scale on the long axis ($YZ$ plane) of the spray cone than that on the short axis ($XZ$ plane), so is the thickness distribution of the final coating film.

![Figure 1. Amplitude comparison of spraying along the busbar.](image)

(a) Arc outer surface spraying  
(b) Conical outer surface spraying

In the two spraying methods of arc outer surface and conical outer surface, the droplet velocity cloud diagram in the long axis direction ($YZ$ plane) is shown in Figure 2. Among them, the spray cone section of $YZ$ plane is similar to an isosceles triangle with the nozzle as the apex. The droplet velocity distribution is corrugated as a whole. As the distance from the nozzle increases, the droplet velocity decreases. At the same distance from the nozzle, the droplet velocity is approximately equal, when it approaches the nozzle, the droplet velocity drops faster.
3.2. Lateral Expansion of Spray flow Field

The spray cone angle refers to the angle between the contour lines of the two spray cones on the YZ plane of the spray flow field[10]. It represents the maximum lateral extension of the spray cone shape, and determines the range of coating film formed by spraying. The spray cone is shown in Figure 3. According to the jet theory, the half-value width of the jet's velocity can indicate the degree of lateral expansion of the jet. In the YZ plane, the half velocity width Y (U50%) is corresponding to the value of Y coordinate when the axial velocity is half of the velocity on the nozzle axis. The relationship between the lateral expansion degree of the liquid phases of two kinds of surfaces in the Y direction and the value of Z coordinate is shown in Figure 4.

The relationship can be approximated as a linear and the spray cone angles under different spraying modes were fitted. When spraying along the busbar, the spray cone angle of the arc outer surface was 77.3°, and the conical outer surface was 77.5°; when spraying circumferentially, the spray cone angle of the arc outer surface was 77.4°, and the conical outer surface was 78.6°.

Figure 3. Schematic of the spray cone.
Spray the outer surface of the arc along the bus bar
Spray the tapered outer surface along the bus bar
Spray the outer surface of the arc along the circumferential direction
Spray the tapered outer surface along the circumferential direction

Figure 4. Lateral expansion degree of spray utilizing different painting methods

Due to the effect of turbulent kinetic energy, there are slight fluctuations in the extent of spray lateral expansion, resulting in different spray cone angles, but within the range of 0.01 ~ 0.14m of the axial distance (that is, the range away from the wall), the difference of the surfaces sprayed has almost no effect on the spray cone angle.

3.3. Near-wall Spray Flow Field

From equation (6) to equation (9), it can be seen that the main parameters affecting the film formation of paint droplets are the normal velocity and tangential velocity of the droplet phase on the wall, so studying the distribution of the two speeds on the two surfaces has a great significance.

In order to describe the distribution of the normal velocity and tangential velocity of the spray droplets along the wall, the coordinates of the spray surface along the busbar are defined as shown in Figure 5. In Figure 5, $Z_i$ is the normal direction away from the wall, $Y_i$ is the direction parallel to the wall, and $O_i$ is the intersection of the spray gun axis and the wall.

Figure 6. Distribution of liquid normal velocity along the surface.

Figure 7. Distribution of maximum tangential velocity of liquid along the wall.

It can be seen from the figure that during circumferential spraying, the near-wall normal speeds of the two surfaces are almost the same, and higher than the near-wall normal speeds of spraying along the busbar. The maximum tangential velocity near the wall of the two shapes is also the same, and they are respectively lower than the maximum tangential velocity of spraying along the busbar. When spraying along the busbar, the normal speed of the conical surface near the wall is higher than that of the arc surface, and the maximum tangential speed is lower.
4. Conclusions
(1) In different spraying methods, the shape of the spray on the outer surface of the cone and the outer surface of the arc is similar, and both are ellipse cones. The spray cone angle by the circumferential spraying method is larger than that by the busbar spraying method. In the area away from the wall, the difference of outer surfaces has almost no effect on the spray cone angle.

(2) In the area close to the conical surface, for the circumferential spraying and the busbar spraying, the normal speed and maximum tangential speed of two kinds of the outer surfaces are almost the same, the spray normal speed of the former is higher than that of the latter, and the maximum tangential speed is opposite. When spraying along the busbar, the spray normal speed on the conical outer surface is higher than that of the arc outer surface, and the maximum tangential speed is lower.

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References
[1] Chen Yan, Hu Jun, Zhang Gang, Chen Wenzhuo, Pan Haiwei, Lou Bowen. Research on Characteristics of Paint Deposition on Spherical Surface [J]. Journal of Hunan University (Natural Sciences), 2019, 46(06):37-46.
[2] Chen Yan, ChenWenzhuo, He Shaowei, et al. Spray flow characteristics of painting cylindrical surface with a pneumatic atomizer [J]. China Surface Engineering, 2017, 30(6): 122–131.
[3] D. Dapelo, J. Bridgeman. Euler-Lagrange Computational Fluid Dynamics simulation of a full-scale unconfined anaerobic digester for wastewater sludge treatment[J]. Advances in Engineering Software, 2018, 117.
[4] Fluid Dynamics - Computational Fluid Dynamics; Reports from Khalifa University of Science and Technology Describe Recent Advances in Computational Fluid Dynamics (Cfd Modelling of Hydrate Slurry Flow In a Pipeline Based On Euler-euler Approach)[J]. Journal of Technology, 2020.
[5] W. Edelbauer, D. Zhang, R. Kopun, B. Stauder. Numerical and experimental investigation of the spray quenching process with an Euler-Eulerian multi-fluid model[J]. Applied Thermal Engineering, 2016, 100.
[6] Harlow F H, Amsden A A. Numerical calculation of multiphase fluid flow[J]. Journal of Computational, 1975, 17(1):19-52
[7] Ye Q, et al. Using dynamic mesh models to simulate electrostatic spray-painting[C]. High Performance Computing in Science and Engineering'05. Berlin: Springer, 2006, 5: 173–182.
[8] A. Andreini, D. Bertini, B. Facchini, S. Puggelli. Large-Eddy Simulation of a Turbulent Spray Flame Using the Flamelet Generated Manifold Approach[J]. Energy Procedia, 2015, 82.
[9] Chen W, Chen Y, Zhang W, et al. Paint thickness simulation for robotic painting of curved surfaces based on euler-euler approach[J]. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2019, 41(4): #199.
[10] Dong Zhiyong. Jet mechanics[M]. Beijing: Science Press, 2005.