

Article

Numerical Investigation of Film Formation Characteristics and Mechanisms through Airless Spraying on Spherical Surfaces

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Abstract: This paper focuses on key engineering issues, particularly the overall turbulent transport of paint spray and coating film distribution characteristics, in the process of airless spraying film formation. By deeply considering the geometric features of spherical surfaces and their impact on the near-wall region of the flow field, an airless spraying film formation model consisting of the Eulerian multiphase model, the realizable $k-\epsilon$ turbulence model, and the Eulerian Wall Film model was established. Through numerical simulations of static spraying on the inner and outer walls of spherical surfaces with different radii, the influence of geometric features on the spray flow field and film formation characteristics on spherical surfaces was investigated. Subsequently, based on numerical simulations of dynamic spraying on different nozzle trajectories, the film formation characteristics were analyzed, and the optimal spray trajectory planning method was determined. Additionally, this study examined the coating distribution characteristics during dynamic spraying on spherical surfaces with varying geometric dimensions. Finally, a kind of chlorinated rubber anti-corrosion primer was chosen to carry out spraying experiments, which validated that the airless spray coating model and the corresponding numerical simulation methods established in this paper were reasonable and feasible for investigating the film formation characteristics on spherical surfaces. This work is expected to further promote the application of airless spray techniques in machinery, automotive, shipbuilding, and aviation industries.

Keywords: airless spraying; spherical surface; numerical simulation; film formation characteristics



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1. Introduction

In the field of engineering and metal manufacturing, prolonged exposure of metal surfaces to media such as air, moisture, and soil often leads to corrosion damage, which can result in economic losses or, in severe cases, safety accidents. Applying coatings to metal surfaces through spraying is an effective method of preventing metal corrosion. Spraying techniques include air spraying [1–3], electrostatic spraying [4,5], plasma spraying [6], and airless spraying [7]. Among these methods, airless spraying involves pressurizing the paint material to approximately 20 MPa, then spraying it through an orifice to rapidly atomize and then adhere to the coating, which offers superior coating quality, spraying efficiency, adhesion, and environmental friendliness. Additionally, due to the unique principle of airless spraying, the atomization of the coating occurs without air assistance, thus avoiding film defects caused by impurities in compressed air.

In various types of spraying operations, performing spray coating is inevitable on complex surfaces, which in this paper refers to surfaces with a certain curvature or irregularities, as opposed to flat surfaces. Spherical surfaces, as a typical and highlighted example of complex geometries, have a significant impact on the spray flow field and film formation characteristics in airless spraying, leading to challenges in controlling coating thickness

and planning spray trajectories. Therefore, conducting research on the film formation characteristics of airless spraying on spherical surfaces is beneficial to establishing a foundation for spray trajectory planning and automated spraying. In the future, this research will also promote further application of airless spraying in machinery, automotive, shipbuilding, and aviation industries.

Early researchers primarily investigated film formation characteristics through experimental studies. Domnick et al. [8] were the first to utilize a Phase Doppler Anemometry (PDA) system to measure droplet velocity and size during the spraying process, exploring the effects of air velocity, spraying distance, and coating speed on the distribution of coating thickness. Additionally, Ye et al. [9], also from the same research group, used PDA (Dantec, Skovlunde, Denmark) and a Spraytec particle size analyzer (Urbundle, IA, USA) to measure the velocity distribution of the coating by altering initial and boundary conditions, thereby obtaining the local coating thickness on the surface of the workpiece to be sprayed.

As research on the film formation process deepened, the drawbacks of experimental methods gradually became apparent. In contrast, with the continuous development of computational fluid dynamics (CFD) theory and the improvement of supporting hardware, CFD began to offer faster computation speed, higher efficiency, and instant visualization of results compared to experimental methods. Its advantages, such as low cost, strong analytical capabilities, and broad applicability, make numerical CFD simulations the preferred method for investigating the film formation characteristics of airless spraying.

The film formation process of airless spraying is essentially a turbulent multiphase flow. In selecting multiphase flow models, researchers commonly use the Euler–Lagrange approach [10–13] and the Euler–Euler approach [14,15]. In the Euler–Euler approach, all phases share the same set of conservation equations, resulting in lower computational cost compared to that of the Euler–Lagrange approach. During simulations, the Euler–Euler approach better describes the turbulent mixing process of the coating in the gas phase and provides detailed information on the spatial distribution of the liquid phase, making it more suitable for engineering problem studies.

Current numerical simulation methods for turbulence include direct numerical simulation (DNS) [16,17], large eddy simulation (LES) [18,19], and Reynolds-averaged Navier–Stokes simulation (RANS) [20,21]. Among these, RANS is the most widely used turbulence simulation method in engineering. It predicts fluid flow by statistically averaging the mass, momentum, and energy transport equations, and solves the N–S equations by coupling the unenclosed turbulent stress with turbulent viscosity.

Among numerical simulation studies of film formation on special surfaces, Osman et al. [22,23] discussed factors affecting the coating thickness on flat areas with concave–convex features, but their study did not involve the influence of surface geometry features on the spray flow field and coating thickness. Wu et al. [24] investigated the spray characteristics on vertical interpenetrating cylindrical surfaces and identified the optimal spray parameters for different pipe diameters and spray positions.

As a common complex surface in industry, spherical surfaces possess characteristics such as high curvature and varying angles, which significantly affect the diffusion process of the spray flow field, thereby impacting coating thickness and uniformity. Therefore, it is crucial to explore the effects of spherical surfaces on the flow field and film formation characteristics in airless spraying. However, research on the film formation characteristics of spherical surfaces remains scarce. In this paper, the Euler–Euler approach combined with a turbulence model and a wall-adhesion model was used. Through modeling and numerical simulations, the film formation characteristics of airless spraying on spherical surfaces was investigated. This paper reveals the differences in coating characteristics caused by variations in surface features and spray parameters, providing a reference for the study and engineering application of similar surface coatings.

2. Modeling

Airless spraying is essentially a turbulent flow of liquid paint droplets in a gas–liquid two-phase flow and liquid phase acceleration behavior in the air, which can be divided into a paint atomization process and a film formation process by a time sequence. The film formation process studied in this paper can further be divided into the spray motion process and the adhesion film formation process.

2.1. Spray Transfer Model

For any control volume in the flow field, the continuity equation for the gas–liquid two-phase volume fraction in airless spraying can be expressed as:

$$\frac{\partial}{\partial t}(\varphi_g \rho_g) + \nabla g(\varphi_g \rho_g \mathbf{v}_g) = S_g + \dot{m}_{lg} - \dot{m}_{gl} \quad (1)$$

$$\frac{\partial}{\partial t}(\varphi_l \rho_l) + \nabla g(\varphi_l \rho_l \mathbf{v}_l) = S_l + \dot{m}_{gl} - \dot{m}_{lg} \quad (2)$$

where t represents time (s) and ρ_g and ρ_l represent the densities (kg/m^3) of the air phase and the paint phase, respectively. $\mathbf{v}_g$ and $\mathbf{v}_l$ represent the velocity vectors (m/s) of the air phase and the paint phase, respectively. S_g and S_l represent the mass source terms of the air phase and the paint phase, respectively. $\dot{m}_{lg}$ represents the mass transfer from the paint phase to the air phase, and correspondingly, $\dot{m}_{gl}$ is the mass transfer from the air phase to the paint phase.

For any grid, there are the following constraints on φ_g and φ_l :

$$\varphi_g + \varphi_l = 1 \quad (3)$$

Due to the extremely short duration of the spraying process, the modeling assumes that no mass or heat transfer occurs between the gas and liquid phases. Therefore, it is only necessary to establish the mass conservation equation for the gas–liquid two-phase flow:

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

The momentum conservation equation can be expressed as:

$$\frac{\partial}{\partial t}(\varphi_q \rho_q \mathbf{u}) + \nabla \cdot (\varphi_q \rho_q \mathbf{u} \mathbf{u}) = \nabla \cdot \boldsymbol{\tau}_q - \varphi_q \nabla p + \mathbf{F}_{d,q} \quad (5)$$

where φ_q , ρ_q , and $\mathbf{u}$, respectively, represent the volume fraction of the gas or liquid phase, gas or liquid phase density (kg/m^3), and gas or liquid phase velocity (m/s). When the subscript q is g or l , it represents the air phase or paint phase, respectively; p represents the pressure exerted by the combined action of two phases (N/m^2); μ is the dynamic viscosity ($\text{N}\cdot\text{s}/\text{m}^2$); $\mathbf{g}$ represents the local gravitational acceleration (m/s^2), and $\mathbf{f}$ represents the source term generated by surface tension σ .

Because the droplets in the spray flow field can be approximately regarded as spherical, the subscript q in Equation (5) is l , and the pulling force of air on the droplet is:

$$\mathbf{F}_{d,l} = \frac{\rho_l \alpha_l}{\tau_l} (\mathbf{v}_g - \mathbf{v}_l) \quad (6)$$

where τ_l is the relaxation time of the droplet, which has the following form:

$$\tau_l = \frac{4\rho_l d_l^2}{3\mu_g C_D Re_l} \quad (7)$$

where d_l is the droplet diameter, and C_D and Re_l are the drag coefficient and droplet Reynolds number, respectively, which are:

$$C_D = \begin{cases} 24(1 + 0.15Re^{0.687})/Re & Re \leq 1000 \\ 0.44 & Re > 1000 \end{cases} \quad (8)$$

$$Re = \frac{\rho_g d_l |\mathbf{v}_g - \mathbf{v}_l|}{\mu_g} \quad (9)$$

The interaction of the drag force of the gas phase and liquid phase causes the drag exerted by the droplets on the air to equal the sum of the drag forces that the air exerts on droplets of different sizes. Therefore, we have:

$$\mathbf{F}_{d,g} = -\sum \mathbf{F}_{d,l} \quad (10)$$

2.2. Turbulence Model of Flow Field

For the turbulent flow of the gas phase and liquid phase during film formation, the realizable k - ε model in the RANS two-equation turbulence model is used for turbulence prediction. The transport equations for turbulent kinetic energy k and turbulent dissipation rate ε in the realizable k - ε model are expressed as follows:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}[(\mu + \frac{\mu_t}{\sigma_k}) \frac{\partial k}{\partial x_j}] + G_k + G_b - \rho \varepsilon \quad (11)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j}[(\mu + \frac{\mu_t}{\sigma_\varepsilon}) \frac{\partial \varepsilon}{\partial x_j}] + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} G_b \quad (12)$$

where σ_k and σ_ε represent the Prandtl numbers of k and ε , respectively. $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.2$. The rest constants are:

$$C_1 = \max \left[0.43, \frac{\frac{k}{\varepsilon} \sqrt{2S_{ij}S_{ij}}}{\frac{k}{\varepsilon} \sqrt{2S_{ij}S_{ij}} + 5} \right], C_{1\varepsilon} = 1.44, C_2 = 1.9.$$

where G_k represents the turbulent kinetic energy generation term caused by the average velocity gradient, and G_b is the turbulent kinetic energy generation term caused by buoyancy, which can be written as follows:

$$G_k = -\rho \overline{u_i' u_j'} \frac{\partial u_j}{\partial x_i} \quad (13)$$

$$G_b = -g_i \frac{\mu_t}{\rho Pr_t} \frac{\partial \rho}{\partial x_i} \quad (14)$$

where Pr_t is the turbulent Prandtl number, and g_i represents the gravity vector in the i -th direction. In Equation (12), $C_{3\varepsilon}$ is a constant that characterizes the degree of influence of buoyancy on turbulent dissipation rate, which is expressed as:

$$C_{3\varepsilon} = \tanh \left| \frac{v}{u} \right| \quad (15)$$

where v represents the velocity component of the fluid in the direction of gravity, and u represents the velocity component of the fluid in the direction perpendicular to gravity.

2.3. Paint Deposition Model

A paint droplet deposition model was established based on the Eulerian Wall Film (EWF) model. The paint phase in the spray flow field undergoes changes in mass and momentum before and after impacting the wall surface. Therefore, when establishing the conservation equations for the droplet control volume, the mass and momentum of the paint phase are introduced as source terms into the wall film control equations. By establishing the wall film motion equations, the flow and thickness of the liquid film on the

wall surface can be solved, including the mass and momentum conservation equations for the liquid film, which are expressed as follows:

$$\frac{\partial \rho_l h}{\partial t} + \nabla_s \cdot (\rho_l h \mathbf{v}_l) = \dot{m}_l \quad (16)$$

$$\frac{\partial \rho_l h \mathbf{v}_l}{\partial t} + \nabla \cdot (\rho_l h \mathbf{v}_l \mathbf{v}_l) = -h \nabla_s p_l + \mathbf{g}_\tau \rho_l h + \frac{3}{2\rho_l} \tau_{fs} - \frac{3\mu_l}{h} \rho_l \mathbf{v}_l + \dot{\mathbf{q}}_l \quad (17)$$

In Equation (16), ρ_l is the liquid film density, ∇_s is the surface gradient operator, h is the liquid film thickness, $\mathbf{v}_l$ is the liquid film velocity, and $\dot{m}_l$ is the mass source of the liquid film per unit wall area. In Equation (17), the left-hand terms represent transient and convective effects, respectively. The first item on the right represents the effects of airflow pressure, gravity component perpendicular to the wall, and surface tension. The second item represents the gravity effect along the film direction. The third and fourth items represent the viscous forces at the gas–liquid and liquid–solid interfaces based on the secondary film velocity distribution. The fifth term represents the action of the momentum source $\dot{\mathbf{q}}_l$ in the liquid film equation.

When the paint phase is captured by the wall surface, its mass and momentum are removed from the multiphase flow and then added as source terms to the mass conservation equation and momentum conservation equation of the wall film, respectively. The mass source term of the liquid film is:

$$\dot{m}_l = \alpha_l \rho_l \mathbf{v}_{ln} A \quad (18)$$

where $\mathbf{v}_{ln}$ is the component of the liquid phase velocity $\mathbf{v}_l$ perpendicular to the wall, and A is the wall area. The momentum source term of the liquid film is:

$$\dot{\mathbf{q}}_l = \dot{m}_s \mathbf{v}_l \quad (19)$$

where $\mathbf{v}_l$ is the velocity vector of the paint phase.

3. Simulation and Experimental Details

3.1. Geometric Model of Fluid Regions and Meshing

In this study, a 17B25-type airless sprayer (China Shipbuilding Industry Corporation Changjiang Technology Co., Ltd., Chongqing, China) was used as the basis for the nozzle geometric model. The geometric structure was simplified but retained key structural parameters. Additionally, a three-dimensional rectangular coordinate system was defined based on the nozzle geometry, with the spray emission axis set as the Z-axis and the direction perpendicular to the Z-axis within the spray fan plane set as the Y-axis. The nozzle models and the established three-dimensional rectangular coordinate system are shown in Figure 1.

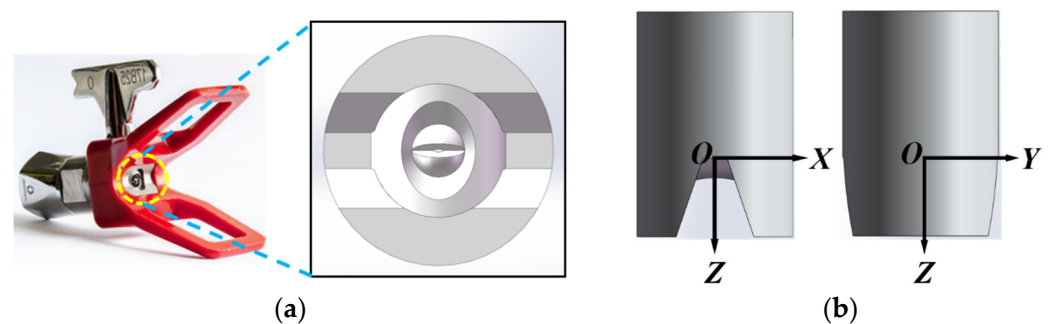


Figure 1. Models of an airless atomizer nozzle. (a) Structure of nozzle; (b) created coordinate system based on nozzle.

During static spraying, the spraying distance was set to 300 mm, and the Z-axis was kept perpendicular to the surface of the workpiece. During dynamic spraying, the concept of “latitude lines” was introduced, with spraying trajectories selected along the 0°, 30°, and 60° latitude lines of the inner and outer walls of a spherical surface. For the film formation process during static spraying, the fluid regions for spraying on spherical surfaces with radii of 200 mm, 300 mm, and 400 mm are shown in Figure S1. Polyhedra were chosen for meshing, with mesh refinement in the nozzle area, and prismatic meshes were used to define the boundary layer of the wall surface. Meshes of fluid regions of static spraying on inner and outer spherical surface are illustrated in Figure S2.

A sliding mesh model was used to achieve dynamic spraying on spherical surfaces. To avoid the impact of mesh differences on the numerical simulation results, the fluid regions for spraying along different trajectories were integrated. Dynamic spraying simulations for different trajectories were achieved by moving the fluid regions within the same flow field mesh. The fluid regions and meshes for dynamic spraying on the inner and outer wall of the spherical surface are shown in Figure S3 and Figure S4, respectively.

3.2. Set-Up and Boundary Conditions

In the simulation of static spraying, the nozzle orifice was defined as the “mass flow inlet”, with a mass flow rate of 0.0338 kg/s, which corresponded to a spray pressure of 15 MPa. The nozzle geometry and the film formation surface were set as “wall”, with the wall being stationary and non-sliding. The other surfaces were defined as “pressure outlet”. Through experimental measurements, the paint properties were determined as follows: viscosity of 0.2 Pa·s, surface tension of 0.0356 N/m, and density of 1305 kg/m³.

In the simulation of dynamic spraying, the interfaces between the sliding and static fluid regions were set as “interface”, while other boundary conditions were the same as for static spraying. For spherical surfaces with radii of 200 mm, 300 mm, and 400 mm, the sliding mesh speeds were set to 0.625 rad/s, 0.833 rad/s, and 1.250 rad/s, respectively. The airless spraying numerical model was solved using a PC-SIMPLE algorithm. The total time for static spraying was 0.4 s with a time step of 0.0005 s. For dynamic spraying, the time step remained the same as for static spraying, but the number of time steps was adjusted based on the sliding mesh speed to ensure that the total distance traveled by the fluid region was consistent.

3.3. Mesh Independence Validation

To ensure the reliability and accuracy of the numerical simulation results, while keeping the local refinement size at the nozzle unchanged, the maximum global mesh size was gradually refined, resulting in six different mesh configurations for mesh independence validation. With the computational model and boundary conditions remaining constant, numerical simulations for film formation in airless spraying on spherical surfaces were performed using meshes of different sizes. The variation curves of the liquid phase velocity along the Z-axis in the spray flow field are shown in Figure 2. Velocity–Z_{paint} showed a trend of a rapid decrease followed by a slower decrease along the Z-axis, with no significant differences in results among the various meshes. The curves for the Z-axis range of 150 mm to 300 mm were magnified, as shown in the right-hand figure. It is evident that the results for mesh sizes of 67 K and 98 K differed significantly from those of other meshes, and further mesh refinement yielded similar results. Therefore, it can be concluded that when the global mesh size was 7 mm or smaller, the numerical results were not significantly affected by mesh size. To balance solution accuracy and computational cost, a maximum global mesh size of 5 mm was selected for subsequent simulation calculations.

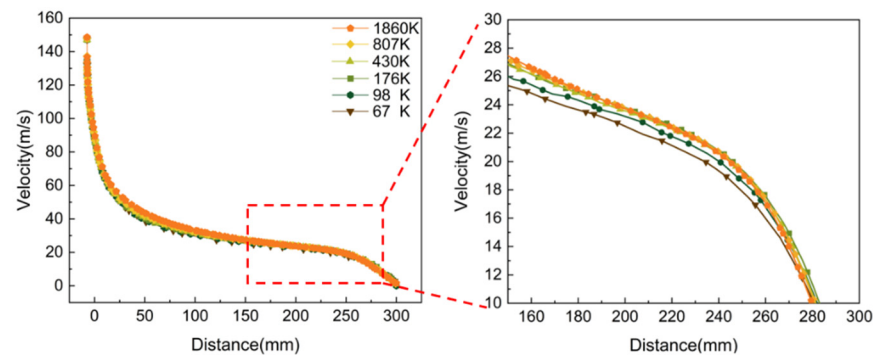


Figure 2. Velocity variation curves of liquid phase Z-axis under different meshes.

3.4. Experimental Details

In this paper, a G46 airless spraying machine and a ZPQ9 automatic spray gun (China Shipbuilding Group Changjiang Technology Co., Ltd., China) were used for the spraying experiments, powered by a W-0.98/8 air compressor (Luodi Electromechanical Technology Co., Ltd., Zhejiang, China). A self-regulating automatic spraying device with a variable-speed track and corresponding control system was used for automated spraying based on the planned spraying trajectories. The J06-1 chlorinated rubber anti-corrosion primer (South Painting Co., Ltd., Chongqing, China) was chosen as the airless spraying paint. The equipment used in the spraying experiment is shown in Figure S5, and the physical parameters of chosen paints are illustrated in detail in Table S1.

The spherical workpieces for spraying experiments are made of galvanized steel plates, which are formed using a point pressing method. Some locations are reinforced with steel bars and welded to a base. The surface of the workpieces underwent ST3-grade rust removal to ensure good adhesion of the coating. In the spraying experiments, the physical parameters of the coating, the spray pressure, and the speed of gun movement were consistent with those of the numerical simulation. After spraying, the workpieces were left for natural drying, with the actual drying time for the coating being approximately 10 h. Subsequently, the dry film thickness was measured using an AR932 coating thickness gauge (Wanchuang Electronic Products Co., Ltd., Dongguan, China). After calibrating the instrument, measurement points were set every 1 cm, and each point was measured three times. The average of these three measurements was taken as the film thickness data for that point, provided that the error did not exceed 1 μm .

4. Results and Discussion

4.1. Film Formation Characteristics of Static Spraying

4.1.1. Spray Flow Field Characteristics

The spray flow fields for the inner and outer walls of spherical surfaces with different radii are similar. Therefore, the spray flow field characteristics for the inner and outer walls of a spherical surface with a radius of 300 mm are presented for analyzing.

It can be observed in Figure 3 that the paint phase moved towards the wall in a typical fan-shaped pattern, with a maximum velocity of 151.44 m/s right after exiting the nozzle. As the spray flow field developed towards the wall, it impacted the wall at approximately 20 m/s. In the near-wall region, the uncoated paint phase began to spread outwards from the wall and eventually dispersed from the exit boundary of the flow field.

Figure 4 further illustrates the variation of velocity vectors in the YZ plane over time to study the evolution of flow field characteristics. It can be observed from Figure 4a that velocity decreased significantly due to momentum exchange and turbulent mixing between the paint and air in the spray boundary's free shear layer, while the potential core retained a higher velocity. The velocity difference between the center and the edge caused the boundary spray to be entrained back into the spray, resulting in symmetric vortices on both sides of the spray. As the spray flow field continued to develop, it contacted the wall at 15 ms, with a noticeable decrease in velocity. The direction of the spray front velocity

changed from normal to the wall at the contact point to tangential to the wall, transitioning into a wall jet, as shown in Figure 4b. At 50 ms, due to the wall effects in the near-wall region and the free development characteristics of the spray away from the wall, the spray, which moved tangentially along the wall, generated boundary layer separation. This resulted in the formation of a swirling boundary layer, with the vortices gradually diffusing and decreasing along the wall, while the boundary layer paint continued to advance towards the spherical surface's exit boundary, as shown in Figure 4c. Figure 4d shows the fully developed spray flow field at 400 ms. The image has been zoomed in on specific areas, labeled as ①, ②, ③, and ④ on the right. In ①, noticeable liquid phase recirculation is observed. In ②, boundary layer separation and vortex formation are evident. In ③, the spray transitions from the free jet region to the impact region, with the velocity vector direction changing from normal to the wall to tangential to the wall. In ④, it can be seen that part of the recirculating spray returns to the wall jet region, while a smaller portion returns to the free jet region.

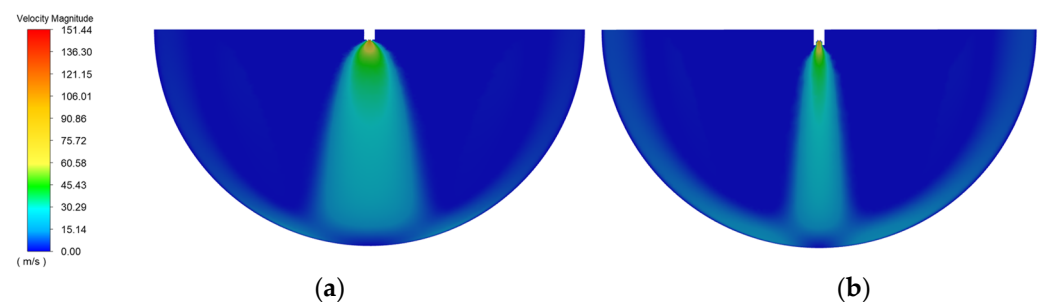


Figure 3. Velocity contours of inner surface flow field. (a) YZ plane; (b) XZ plane.

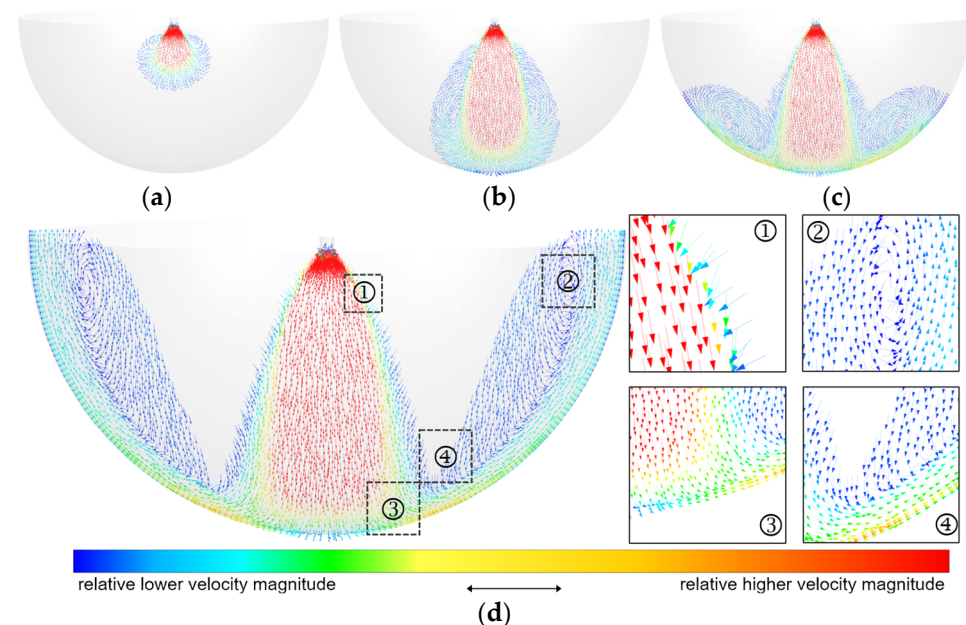


Figure 4. Vectors of YZ plane of inner spherical surface. (a) $t = 2.5$ ms; (b) $t = 15$ ms; (c) $t = 50$ ms; (d) $t = 400$ ms.

It can be seen from Figure 4 that the normal velocity of the paint phase relative to the wall directly affected the accumulation efficiency of the paint phase, thereby influencing the coating film thickness. Therefore, a curve located 10 mm from the normal distance to the wall was selected to study the distribution of normal and tangential velocities. Since the spray flow field exhibited typical circular wall impact jet characteristics, the XZ plane flow field was not the focus of this study. Instead, the distribution characteristics of the YZ plane flow field were emphasized. The velocity distribution curves in the near-wall

region for spraying on inner spherical surfaces with different radii exhibited a similar trend, as shown in Figure 5a. As the liquid phase flow field developed from the spray center towards the Y direction, the normal velocity initially decreased rapidly, eventually reducing to 0 m/s. Due to vortex effects and recirculation in the flow field, the velocity continued decreasing to negative values and then returned to 0 m/s. However, the normal velocity was higher for smaller spherical radii due to the curvature of the film formation wall. It can be found that the tangential velocity at the origin was 0 m/s under different radii, meaning that it was completely perpendicular to the wall. As the spray expanded laterally, the tangential velocity gradually increased, reaching its maximum value around 100 mm, which was higher than the corresponding normal velocity at that point. The paint phase predominantly moved along the wall boundary layer here, making it difficult to form a coating film. As the Y value further increased, the tangential velocity started to decrease, with a brief rise due to vortex effects, ultimately decreasing to 0 m/s. Comparatively, the larger the radius of the spherical inner wall, the faster the increase in tangential velocity. Additionally, it was observed that the increase in tangential velocity in the near-wall region was faster than the decrease in normal velocity as the spray expanded along the Y -axis.

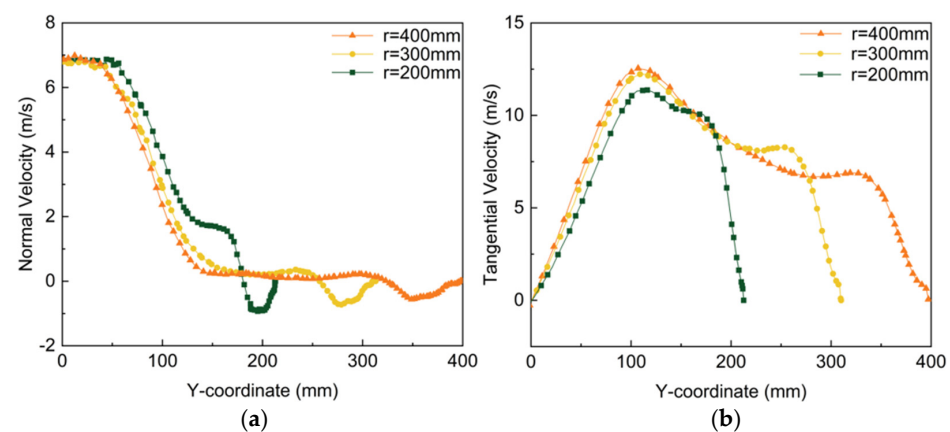


Figure 5. Near-wall velocity curves of inner spherical surfaces. (a) Normal velocity; (b) tangential velocity.

Figure 6 shows the velocity contours for spraying on the outer wall of the spherical surface. It can be observed that the paint initially spread in a fan-shaped pattern with a velocity of 150.16 m/s and the spray impacted the wall at approximately 20 m/s. After the paint front contacted the wall, it began to curl downward and spread tangentially along the wall. Finally, the uncoated spray eventually dispersed from the pressure outlet at the boundary of the flow field.

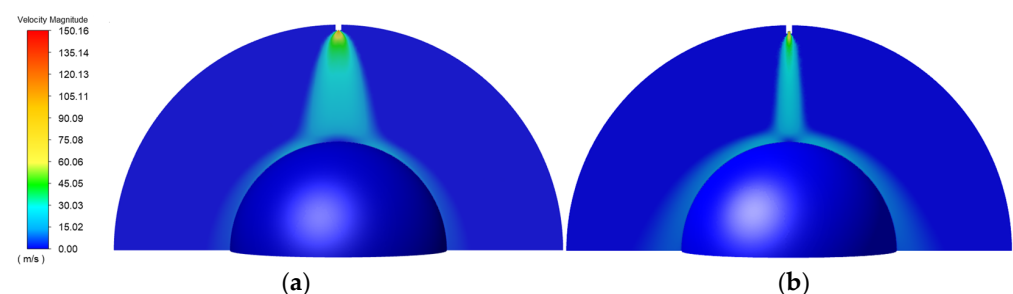


Figure 6. Velocity contours of outer spherical surface flow field. (a) YZ plane; (b) XZ plane.

Figure 7 shows the changes in velocity vectors in the YZ plane over time during spraying on the outer wall of the spherical surface. Figure 7a,b is similar to the conditions observed during inner wall spraying. From Figure 7c, it can be seen that after impacting the wall, the spray flow field transitioned from a free jet to a downward wall jet. Due to

boundary layer separation, vortices were formed and continued to diffuse tangentially along the wall, gradually decreasing in size. Figure 7d shows the vector distribution of the fully developed flow field.

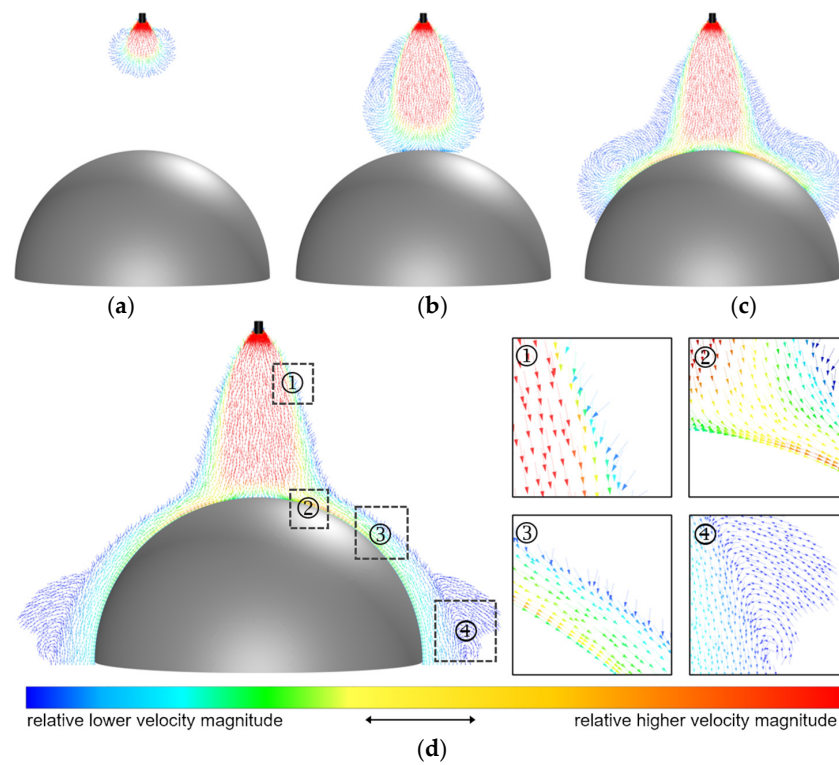


Figure 7. Vector of YZ plane of outer spherical surface. (a) $t = 2.5$ ms; (b) $t = 15$ ms; (c) $t = 50$ ms; (d) $t = 400$ ms.

Figure 8 shows the normal and tangential velocity distribution curves during spraying on the outer wall at different radii, which demonstrates the same overall trend as observed during inner wall spraying. Additionally, as the radius of the spherical surface decreases, the normal velocity decreases and the tangential velocity increases of more rapidly. This is due to the increasing curvature of the spherical surface as the radius decreases. As seen in Figure 7②, the angle between the velocity and the tangential direction of the wall continuously decreases with smaller radius. This results in a larger tangential component of the flow field velocity, making the reduction in normal velocity and increase in tangential velocity more pronounced.

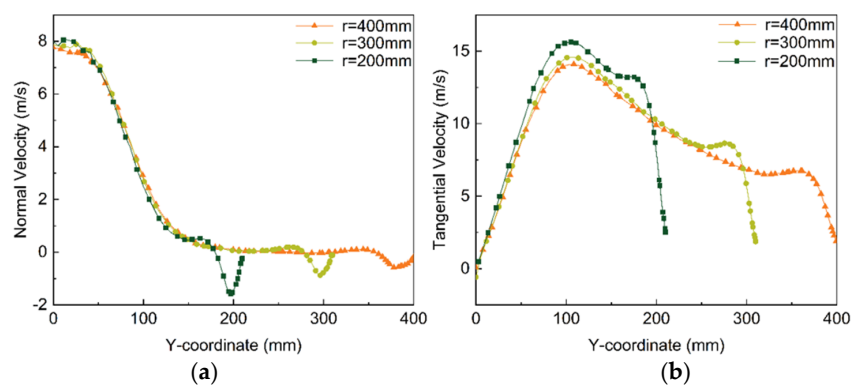


Figure 8. Near-wall velocity curves of outer spherical surfaces. (a) normal velocity; (b) tangential velocity.

4.1.2. Paint Deposition Characteristics

As shown in Figure 9, the main film formation area is elliptical in shape. Regardless of radius, with a deposition characteristic where the film is thicker in the central region and thinner around the edges. A splatter-like dispersed film is observed around the main film formation area. As analyzed in the previous section, this is due to the increase in normal velocity in different areas near the wall caused by vortex flow during the tangential movement along the wall surface. The film length and width vary in size due to scaling differences for different radii, but the actual film length and width remain largely consistent.

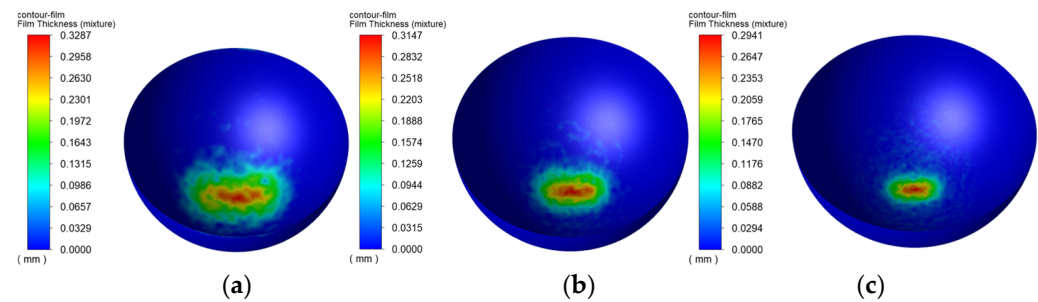


Figure 9. Film thickness contours of static spraying on inner spherical surfaces. (a) $r = 200$ mm; (b) $r = 300$ mm; (c) $r = 400$ mm.

As shown in Figure 10, when the spherical surface radius is 200 mm, the film thickness reaches the highest peak of 328.7 μm . As the radius increases, the maximum film thickness decreases, with values of 314.7 μm and 294.1 μm for spherical surfaces with radii of 300 mm and 400 mm, respectively. It can be observed that as the radius of the spherical surface increases, the maximum film thickness decreases, but the film formation length along the long axis increases. As analyzed in the previous section, due to the increase in the radius of spherical surface, the normal velocity near the wall decreases while the tangential velocity increases, resulting in a lower deposition efficiency of the paint phase. Thus, the film thickness increases as the radius decreases for spraying on the inner wall of the spherical surface.

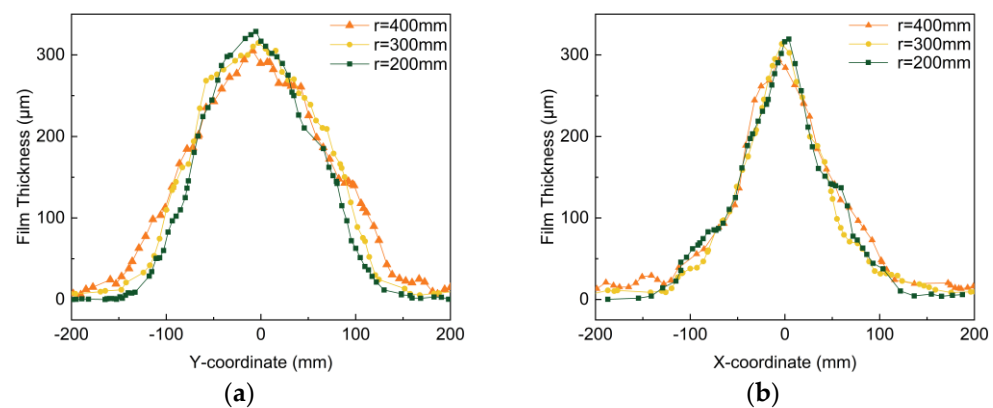


Figure 10. Film thickness curves of inner spherical surfaces. (a) Long axis; (b) short axis.

As shown in Figure 11, it can be observed that the film distribution pattern for spraying on the outer wall of spherical surfaces with different radii is generally similar, with a central area of higher thickness and a surrounding area of lower thickness, following an elliptical pattern. However, unlike the film formation on the inner wall of the spherical surface, there is no discrete distribution of the film around the central area of the film formation.

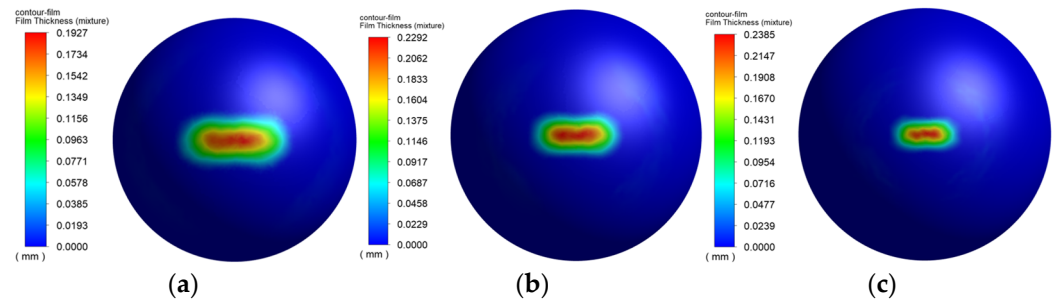


Figure 11. Film thickness contours of static spraying on outer spherical surfaces. (a) $r = 200$ mm; (b) $r = 300$ mm; (c) $r = 400$ mm.

Film thickness distribution curves for the outer wall of spherical surfaces with different radii are shown in Figure 12. When the radius of the spherical surface was 200 mm, the film thickness was relatively low, 192.7 μm . As the radius increased, the film thickness gradually increased, reaching 229.2 μm and 238.5 μm for radii of 300 mm and 400 mm, respectively. As analyzed in the previous section, with an increase in the spherical surface radius, the curvature of the outer surface decreased and approached a characteristic similar to a plane. The increase in the tangential velocity and the slower decrease in the normal velocity relative to the wall during the spray adhesion process enhanced the liquid phase accumulation efficiency. Consequently, the film thickness increased with the radius. Additionally, as the radius of the spherical surface increased, both the length of the long axis and the width of the short axis of the film also increased.

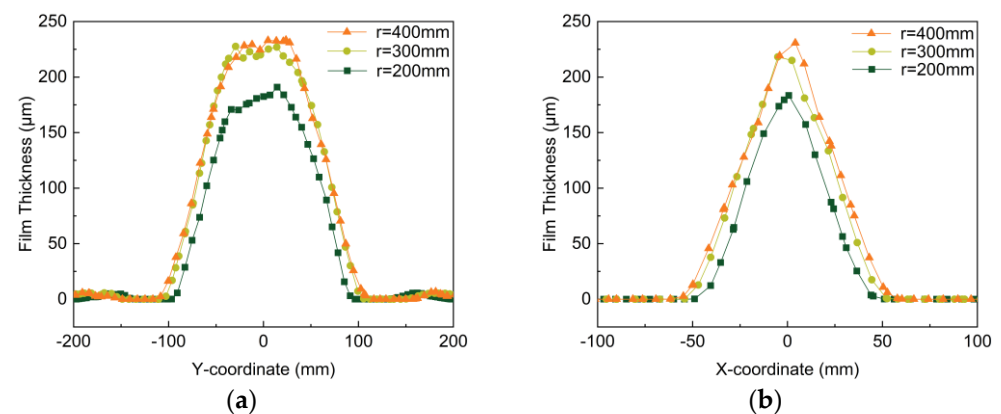


Figure 12. Film thickness distribution curves of static spraying on outer spherical surfaces. (a) Long axis; (b) short axis.

4.2. Film Formation Characteristics of Dynamic Spraying

4.2.1. Varying Spraying Trajectory

The distribution of the film thickness for dynamic spraying along different trajectories on the inner wall of a spherical surface with a radius of 300 mm is shown in Figure 13. Similar to static film formation, dynamic spraying resulted in a film with a thicker center and thinner edges, with an overall dispersed distribution around the perimeter. As the latitude of the spraying trajectory increased, the maximum film thickness shifted towards higher latitudes, and the eccentric distribution of the maximum thickness became more pronounced. To precisely describe the uniformity of the film thickness, the relative standard deviation (RSD) [24] was introduced to characterize the degree of dispersion of the sampled data relative to its mean value. The calculation formula is given by Equation (20):

$$\text{RSD} = \frac{\sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}}}{\bar{x}} \times 100\% \quad (20)$$

The smaller the RSD value, the better the uniformity of the film thickness obtained from the spraying. To minimize calculation errors, thickness data below 10 μm were excluded from the statistics. Figure 13d compares the maximum film thickness and RSD statistics for different spraying latitudes. The maximum film thicknesses for different spraying angles were 125.8 μm , 141.5 μm , and 218.9 μm , with corresponding RSDs of 62.17%, 70.23%, and 83.54%, respectively. It can be observed that as the spraying latitude increased, both the maximum film thickness and RSD showed an upward trend, indicating a deterioration in film uniformity. Specifically, the eccentric distribution of the maximum film thickness at different latitudes increased the difficulty of controlling film thickness uniformity in actual spraying operations.

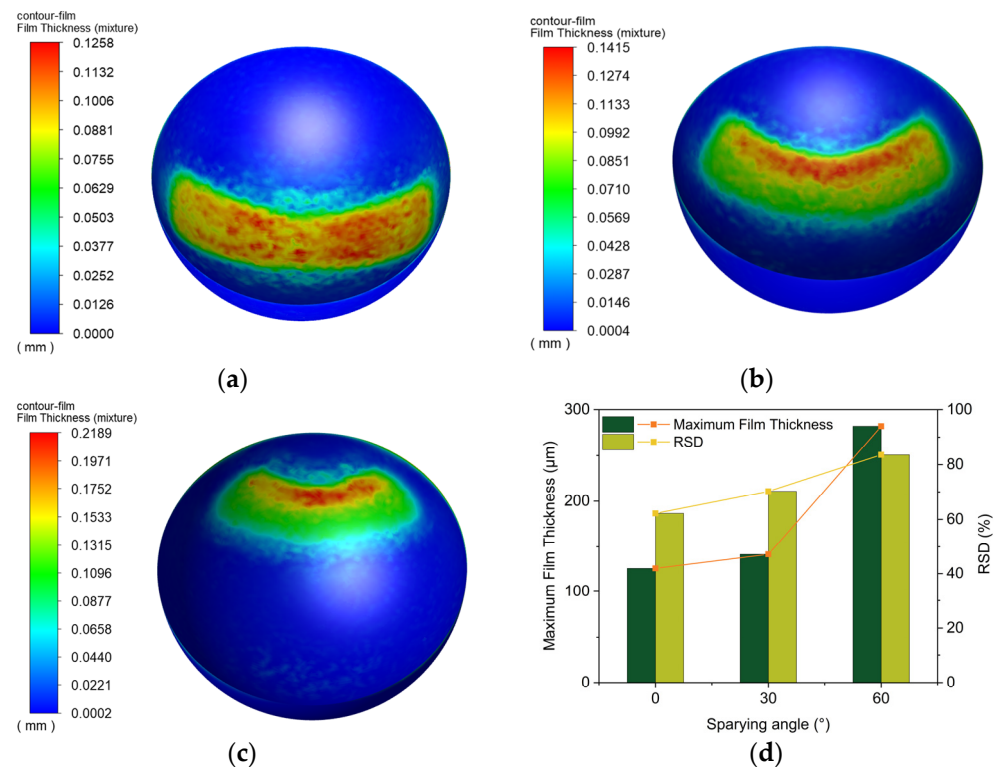


Figure 13. Film thickness and RSDs of dynamic spraying on different latitudes of inner spherical surfaces. (a) Spray along the 0° latitude line; (b) spray along the 30° latitude line; (c) spray along the 60° latitude line; (d) maximum film thickness and RSD values.

Dynamic spraying film can be categorized based on the direction of the spray gun movement and the direction of the film's long axis. The film thickness values along the latitude lines and the long axis from the film thickness contours were sampled as shown in Figure 14. In the spray gun movement direction, the film thickness exhibited fluctuations but remained relatively stable, with a noticeable increase in thickness as the spraying latitude rose. When spraying along the 0° latitude line, the long axis of the film exhibited a parabolic distribution. The higher the spraying latitude, the more pronounced the trend of the film thickness peak shifting towards higher latitudes became.

The film thickness contours and the RSD statistics for dynamic spraying on the outer wall of the spherical surface at different spraying latitudes are shown in Figure 15. Similar to the inner wall spraying, the film exhibited a characteristic of being thicker in the center and thinner around the edges. As the spraying latitude increased, both the maximum film thickness value and the RSD values increased, showing an eccentric distribution of the film thickness. The maximum film thickness values for spraying at 0°, 30°, and 60° latitudes were 115.2 μm , 171.5 μm , and 223.7 μm , respectively, with RSD values of 54.95%, 58.24%, and 72.70%.

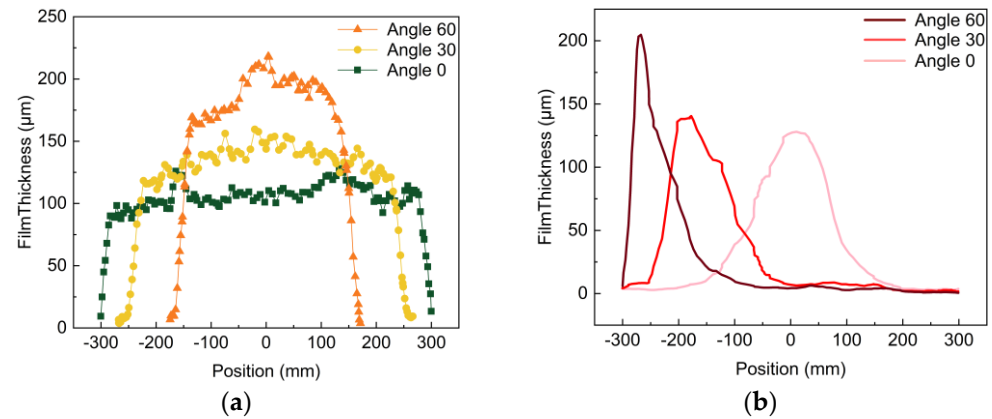


Figure 14. Film thickness curves of dynamic spraying on different latitudes of inner spherical surfaces. (a) Direction of motion; (b) direction of long axis.

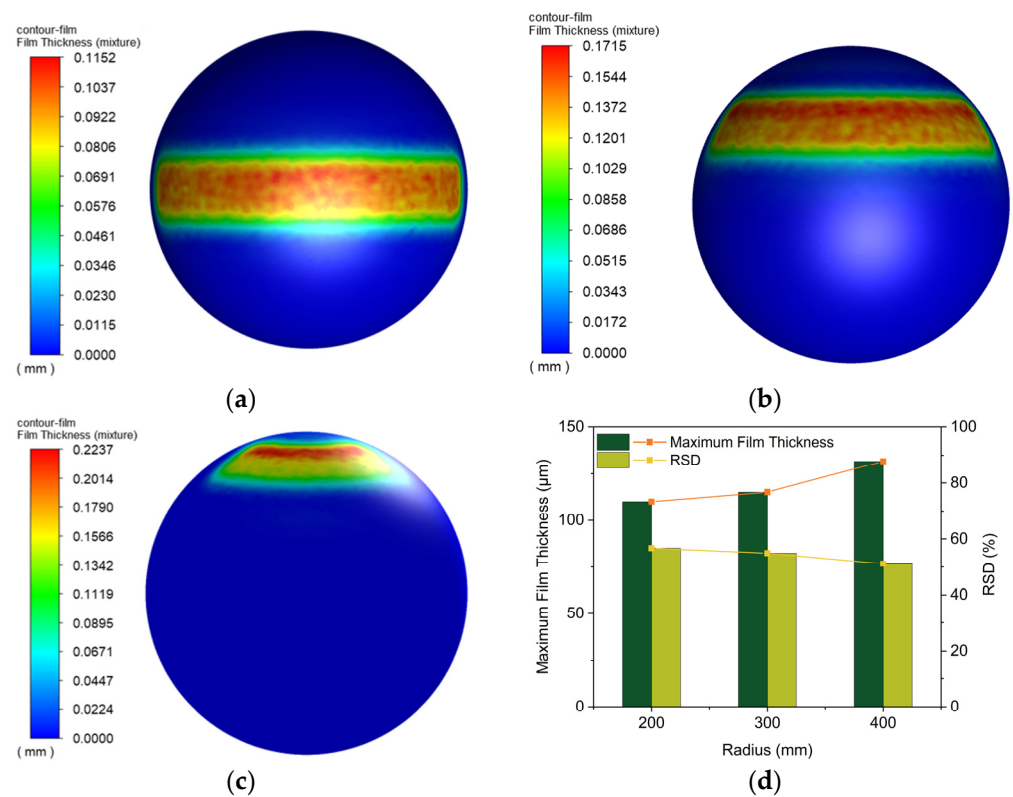


Figure 15. Film thickness and RSD of dynamic spraying on different latitudes of outer spherical surfaces. (a) spray along the 0° latitude line; (b) spray along the 30° latitude line; (c) spray along the 60° latitude line; (d) maximum film thickness and RSD values.

The distribution curves of film thickness are shown in Figure 16. As the spraying latitude increases, it is evident that the film thickness significantly rises, while the distribution of film thickness remains uniform at the same latitude. Additionally, the film thickness distribution still shows a peak that deviates from the center of the film, trending towards higher latitudes.

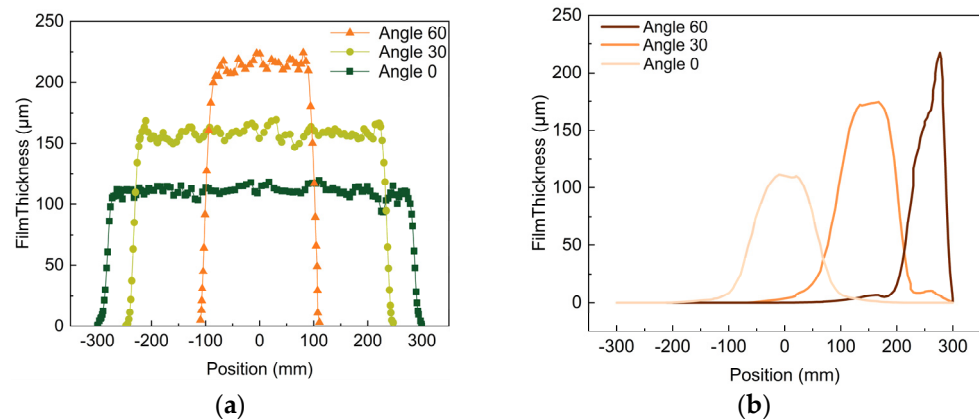


Figure 16. Film thickness curves of dynamic spraying on different latitudes of outer spherical surfaces. (a) Direction of motion; (b) direction of long axis.

To study the eccentric distribution of film thickness, Figure 17 illustrates a schematic of the flow field at a certain moment during spraying along the α° latitude. Since the spray axis passed through the center of the sphere for both the inner and outer wall spraying, the schematic for inner and outer wall spraying was similar; here, inner wall spraying is used as an example. As shown in Figure 17, the spraying angle is α , the spray diffusion half-angle is β , and the red dashed line represents the edge of the spray after linear processing. Points A and B are the intersections of the spray flow field with the wall on either side. If the radius of the spherical surface is R and the angular velocity of the dynamic fluid region is ω , the linear velocity of point B at a low latitude during spraying is given by:

$$V_A = \omega \cdot R \cdot \cos(\alpha - \beta) \quad (21)$$

The linear velocity at point A is similarly given by:

$$V_B = \omega \cdot R \cdot \cos(\alpha + \beta) \quad (22)$$

and the velocity difference between the two points is:

$$V_{B-A} = \omega \cdot R \cdot [\cos(\alpha + \beta) - \cos(\alpha - \beta)] = 2\omega \cdot R \cdot \sin\alpha \sin\beta, \left(0 < \alpha < \frac{\pi}{2}\right) \quad (23)$$

Except for α , all other parameters in the above equations are constants. Therefore, it can be observed that as the spraying latitude increases, the velocity difference between points A and B gradually increases. Since film thickness is negatively correlated with linear velocity, this indicates that for both the inner and outer walls of the spherical surface, with higher spraying latitudes, the film thickness at higher latitudes becomes greater, while at lower latitudes it becomes thinner. Consequently, the eccentric distribution observed in the long axis of the film becomes more pronounced.

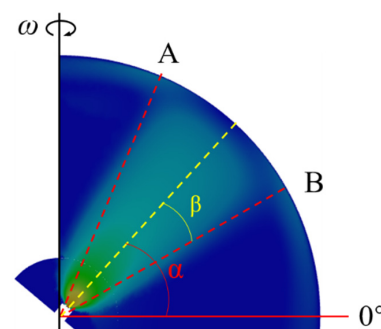


Figure 17. Schematic of spraying on different latitudes of spherical surfaces.

4.2.2. Varying Geometric Dimensions

It is evident that to ensure that film thickness and uniformity in actual processes meet relevant standards, spraying should be performed along the 0° latitude line for both the inner and outer walls of the spherical surface. This section focuses on dynamic spraying along the 0° latitude line for spherical surfaces with radii of 200 mm, 300 mm, and 400 mm, and investigates the impact of surface characteristics on film formation.

The film formation cloud maps for the inner walls of spherical surfaces with different radii are shown in Figure 18, exhibiting the same film thickness distribution trend as discussed in previous sections. The film thickness curves along the spray gun movement direction and the long-axis direction for different radii are plotted in Figure 19. As the radius of the spherical surface decreased, the inner wall film thickness increased, with maximum film thicknesses reaching 133.1 μm , 125.8 μm , and 112.0 μm , respectively. Additionally, the inner wall of the spherical surface with a smaller radius showed a larger film length. Based on the analysis of static spraying film formation characteristics, the mechanism was as follows: In spherical surfaces with smaller radii, the normal velocity of the flow field near the wall was higher, resulting in increased film thickness and a longer film long axis. From Figure 19c, it can be observed that as the spherical surface radius increased, the RSD values for film thickness were 65.23%, 62.17%, and 57.05%, respectively. Film uniformity improved with increasing radius. This was because, with an increasing radius, the curvature of the surface decreased, and the geometric features of the surface approached a plane, thereby enhancing the uniformity of the film thickness.

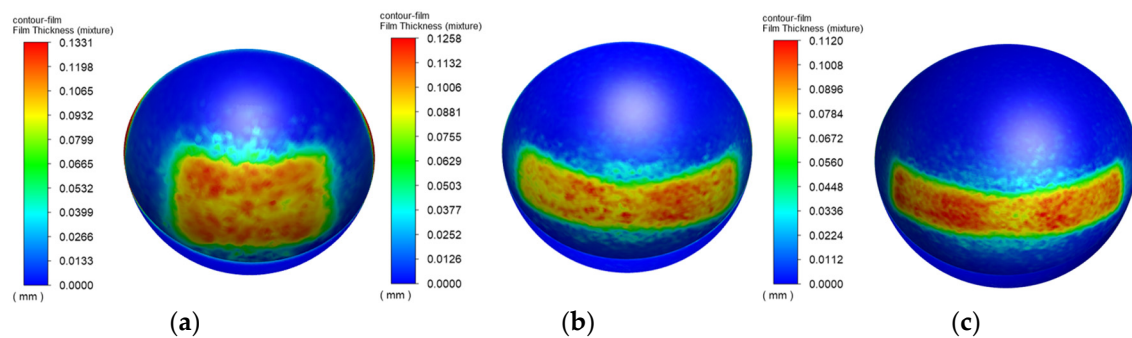


Figure 18. Film thickness contours of dynamic spraying on inner spherical surfaces. (a) $r = 200$ mm; (b) $r = 300$ mm; (c) $r = 400$ mm.

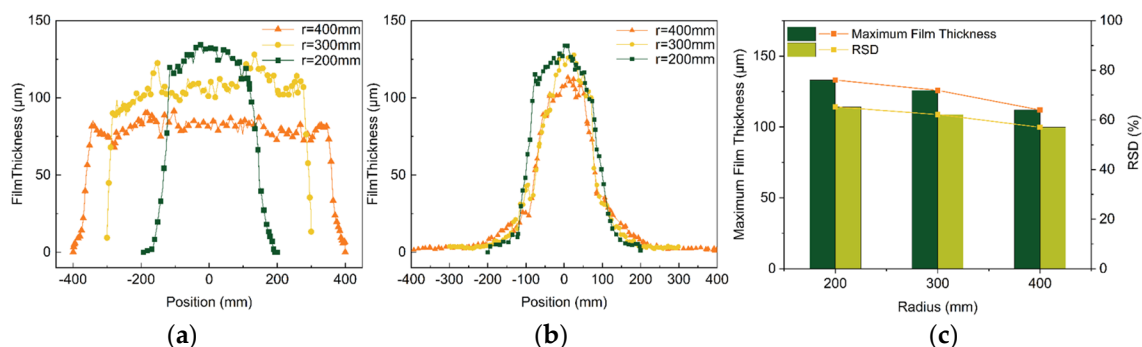


Figure 19. Film thickness curves of dynamic spraying on inner spherical surfaces. (a) Direction of motion; (b) direction of the long axis; (c) maximum film thickness and RSD values.

The dynamic spraying film formation cloud maps for the outer walls of spherical surfaces with radii of 200 mm, 300 mm, and 400 mm are shown in Figure 20. The film formation distribution trends were quite consistent and similar to those observed during static spraying on spherical surfaces, with good film uniformity. The film thickness curves along the spray gun movement direction and the long-axis direction for the outer wall at

each radius are plotted in Figure 21. It is evident that the film thickness distribution along the spray gun movement direction was stable. As the radius increased, the outer wall film thickness also increased, with maximum film thicknesses reaching 110.1 μm , 115.2 μm , and 131.7 μm , respectively. The distribution curves for the film long axis showed that, with increasing radius, the length of the film long axis also increased. The RSD values for the film thickness on the outer wall for the 200 mm, 300 mm, and 400 mm spherical surfaces were 56.74%, 54.95%, and 51.14%, respectively. As the radius increased, film uniformity improved. The reason for this is that with an increasing spherical surface radius, the normal velocity of the flow field near the wall increased while the tangential velocity decreased. This resulted in improved film formation efficiency and thicker films. Additionally, as the surface curvature decreased and approached a planar geometric characteristic, the uniformity of film thickness also improved.

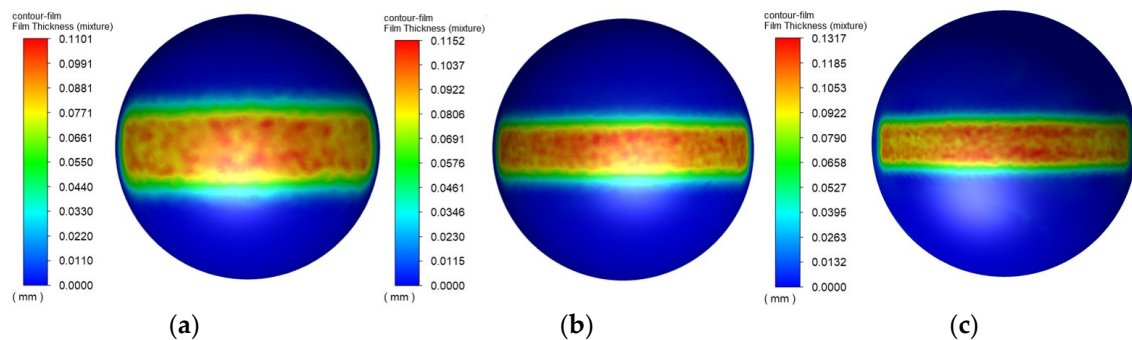


Figure 20. Film thickness contours of dynamic spraying on outer spherical surfaces. (a) $r = 200$ mm; (b) $r = 300$ mm; (c) $r = 400$ mm.

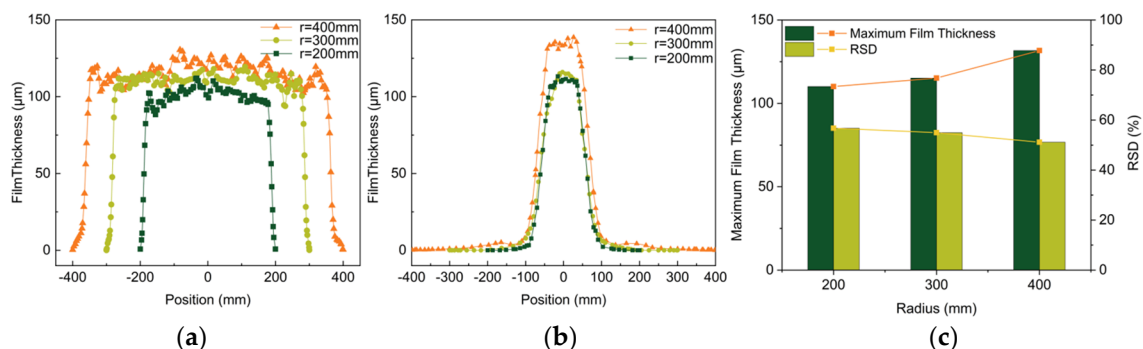


Figure 21. Film thickness curves of dynamic spraying on outer spherical surfaces. (a) direction of motion; (b) direction of the long axis; (c) maximum film thickness and RSD values.

4.3. Experimental Validation

To validate the numerical simulation results for film formation on spherical surfaces, the J06–1 chlorinated rubber anti-corrosion primer was chosen for spraying on the spherical workpieces with radii of 200 mm, 300 mm, and 400 mm.

The film formation shapes for different radii were generally consistent. Here, we present the coating film for a 300 mm-radius spherical surface, sprayed along the 0° latitude, as shown in Figure 22. It can be observed that the film distribution was uniform, with a dense and well-adhered film at the center, while the edges of the film showed a significant amount of irregularly distributed discrete droplets. Comparing the experimental results to Figures 18b and 20b, the numerical simulation results align closely with the experimental film formation.

Since the numerical simulation results were based on wet film thickness, wet film thickness needed to be converted to dry film thickness according to the solid component of the coating. The converted dry film thickness simulation data were then compared with the experimental data. Here, we present the comparison of simulation and experimental

results for a spherical surface with a radius of 300 mm, sprayed along the 0° latitude, as shown in Figure 23. Overall, the numerical simulation results showed a high degree of agreement with the experimental results in terms of film thickness. In the spray gun movement direction, the film thickness distribution trends were consistent, although the experimental film thickness was slightly higher than the one in the simulation due to calculation errors. In the direction of the film's long axis, the experimental maximum film thickness was slightly lower than that of the simulation, but the distribution along the film's long axis was wider than in the simulation. This discrepancy was primarily due to the fact that, in actual experiments, the film exhibited some leveling before drying, and during the drying process, the film experienced slight flow due to surface tension and gravity.



Figure 22. Film formation experiments of spraying on spherical surfaces. (a) Inner surface; (b) outer surface.

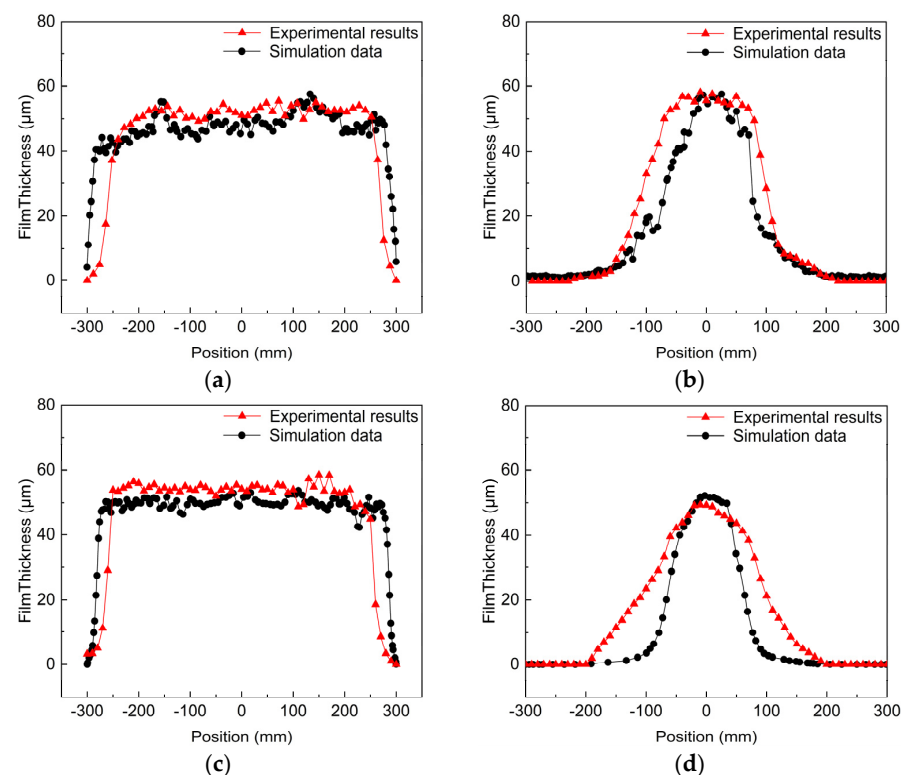


Figure 23. Comparison of film thickness curves between experimental results and simulation data. (a) Movement direction of inner surface; (b) long-axis direction of inner surface; (c) movement direction of outer surface; (d) long-axis direction of outer surface.

5. Conclusions

Based on the established airless spray film formation model, this paper systematically investigated the spray flow field characteristics and film deposition properties of static and dynamic spraying conditions on the inner and outer walls of spherical surfaces. The numerical simulation results were validated through spray experiments. The main conclusions are as follows:

- (1) A model combining the Eulerian multiphase model, realizable $k-\varepsilon$ turbulence model, and Eulerian Wall Film model was developed for the film formation process of airless spraying. Numerical simulations were conducted for airless spraying on spherical surfaces. Experimental results by spraying a kind of chlorinated rubber anti-corrosion primer showed good agreement compared to the simulation data, demonstrating that the established model and simulation methods are reasonable and feasible for studying coating characteristics on spherical surfaces.
- (2) The characteristics of airless spray flow fields and film formation on the inner and outer walls of spherical surfaces were studied. For inner wall spraying, as the spherical surface radius increased, the decrease in normal velocity and the increase in tangential velocity of the near-wall flow field became more pronounced, leading to a reduction in film thickness with an increasing radius. Conversely, for outer wall spraying, the trend was the opposite.
- (3) The film formation characteristics of dynamic spraying along different trajectories on spherical surfaces were examined. With increasing spray latitude, the difference in film velocity between high and low latitudes enlarged, causing the film on the major axis to deviate more from symmetrical distribution toward higher latitudes. The maximum film thickness increased for both inner and outer walls, while film uniformity decreased. Therefore, for actual spraying on spherical surfaces, spraying along the 0° latitude line is recommended to meet thickness and uniformity requirements.
- (4) The film formation characteristics of dynamic spraying on spherical surfaces with different radii were studied. For inner wall spraying, as the radius increased, the maximum film thickness decreased, the length of the film's major axis slightly decreased, but film uniformity improved. For outer wall spraying, as the radius increased, the maximum film thickness increased, the length of the film's major axis slightly increased, and film uniformity also improved.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/coatings14101299/s1>, Figure S1: Fluid regions of static spraying on spherical surfaces. (a) inner surface and $r = 200$ mm; (b) inner surface and $r = 300$ mm; (c) inner surface and $r = 400$ mm; (d) outer surface and $r = 200$ mm; (e) outer surface and $r = 300$ mm; (f) outer surface and $r = 400$ mm; Figure S2: Meshes of static spraying on spherical surfaces. (a) inner surface; (b) outer surface; Figure S3: Fluid regions of dynamic spraying on spherical surfaces. (a) inner surface; (b) outer surface; Figure S4: Meshes of dynamic spraying on spherical surfaces. (a) inner surface; (b) outer surface; Figure S5: Airless spraying machine and supporting equipment. (a) airless spraying machine; (b) air compressor; (c) automatic spray gun; (d) automatic spraying device; Table S1: Physical and chemical parameters of paints.

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