Analysis and Research on the Working Parameters of Colloidal Spraying for the Thermal Insulation Layer of Rocket Tank

Haiyang Xue¹, Haibo Xu¹,*, Yingkun Qian²

¹School of Mechanical Engineering, Xi’an Jiaotong University, Xi’an 710049, China
²Ke-rui Institute, Shanghai Aerospace Equipments Manufacturer Co. Ltd, Shanghai 201100, China

Email: hbxu@mail.xjtu.edu.cn

Abstract. In this paper, the working parameters of DW-1 type colloid spray coating for rocket tank insulation are analysed and studied, and the optimal working parameters are determined. Firstly, a flow field simulation analysis model of thermal insulation layer DW-1 colloid spray is established, the spray flow field simulation of different spraying working parameters is performed. Then the relationship between the flow field characteristics such as spray speed and atomization uniformity and the spraying working parameters are initially determined. After that, an analytical model of droplet impact is established to study the influence of spraying speed on the impact dynamics and spreading quality of the droplet, and the optimal working parameters of colloidal spraying are determined.

1. Introduction
The rocket tank is the core component used to store the propellant fuel inside the launch vehicle, and it also plays an important role in the connection and support of the front and rear structures of the rocket. The thermal insulation layer is an important measure to ensure the reliability of the work of the rocket tank. Spray coating using the high-viscosity DW-1 type colloid of the thermal insulation layer is a common method of thermal insulation layer forming. In fact, most of the aerospace accidents caused by the failure of the thermal insulation layer are caused by problems in the coating of the insulation layer. Therefore, the use of appropriate colloid spraying working parameters to obtain better spray coating results is of great significance for ensuring the safety and stability of rocket tanks and launch vehicles.

For the high viscosity DW-1 type colloid of the thermal insulation layer of the rocket tank, it is necessary to obtain a good spray coating effect. In this paper, the flow field simulation analysis of thermal insulation layer DW-1 type colloid spraying is performed. By analysing the flow field characteristics such as spray speed and atomization uniformity, the relationship between colloid spray effect and spray working parameters is studied, and the dynamic characteristics of droplet impact spreading are numerically simulated. After comprehensive analysis, the optimal spraying working parameters of the colloidal spraying system are obtained.
2. Flow Field Simulation of Colloid Spraying and Analysis of Spraying Effect

This section we will use the computational fluid dynamics (CFD) method to simulate the spraying flow field, analyse the spraying effect, and initially determine the range of spraying working parameters.

2.1. Spray system parameter setting

**Material parameters.** The insulation layer colloid used in this paper is a DW-1 type colloid containing a butanone solution. The main parameters of the DW-1 type colloid are shown in table 1 [1, [2]:

| Density (kg·m⁻³) | Viscosity (mPa·s) | Surface tension (N·m⁻¹) |
|------------------|-------------------|-------------------------|
| 901              | 950               | 0.069                   |

**Physical parameters.** In the spraying system used in this article, a high-pressure airless spray gun is selected as the spray tool, and a wear-resistant nozzle is used in combination with a high-pressure airless spray gun. The models and parameters of the nozzles used in the study are shown in table 2.

| The types of nozzle | Diameter (mm) |
|---------------------|---------------|
| 413                 | 0.330         |
| 523                 | 0.584         |
| 633                 | 0.838         |

Figure 1 depicts the spray flow field of a fan nozzle and its physical model. The main parameters related to the spraying effect, such as the spray angle \( \alpha \), spray distance \( S \), spray length \( L \), spray width \( W \), etc. In this paper, a fan nozzle with an atomizing angle \( \alpha \) of 60° is used to achieve higher spraying efficiency.

![Figure 1. Physical model of fan-shaped flow field.](image)

For the high-viscosity colloid automatic spray coating system of the thermal insulation layer, the working pressure of the plunger type pump is generally within 30MPa. During the research, the spray pressures \( P_{in} \) are 5MPa, 10 MPa, 15 MPa, 20 MPa, 25 MPa, and 30 MPa for comparison and analysis.

2.2. Flow field simulation of colloid spraying

2.2.1 Computing domain and grid division. A 500mm×1000mm plane calculation domain with the X axis as the axis of symmetry is established, and the nozzle is located at the origin. The structural unit is used to divide the grid. The minimum size is 0.25mm, the total number of nodes is 49,087, the number of grid units is 48,551, and the grid near the axis is properly encrypted.
2.2.2. **Boundary conditions and model settings.** In the model, the ambient temperature is set to 298.15K, the gravity is along the -Y direction, the ambient pressure is 101,325Pa, and the air density is 1.225kg·m$^{-3}$. The turbulence governing equation uses a standard \( \kappa - \varepsilon \) two-equation model. The discrete term model (DPM) is enabled, and its governing equation is the equation \((1)\). A new spray model needs to be established under the DPM model, and the spray atomization type is selected as the plane fan atomization model.

\[
m_k \frac{dv_k}{dt} = (\sum F)_k
\]

As in equation \((1)\): \( v_k \) is the speed of the droplet's movement; \( m_k \) is the mass of the droplet's movement; \( (\sum F)_k \) is the sum of all forces on the droplet.

Set the boundary conditions of the model: The X axis is set to the axis type boundary, the interior area is the interior type, the surrounding wall is the wall boundary, the discrete phase reflection type of the wall is escape, and the other boundary conditions remain the default settings.

Finally, the spray fluid material is set, and the parameters are the DW-1 colloid parameters containing butanone in table 1.

2.3. **Study on the relationship between spraying speed and spraying working parameters**

With a certain spraying distance \( S \), the two most important working parameters in the spraying system are spraying pressure \( P \) and nozzle diameter \( d \) [3, 4]. The proper spraying speed is conducive to the adhesion and spreading of colloidal materials, so the spraying speed has an important effect on the colloidal spraying effect [5]. Based on the three nozzle diameters and six spray pressures described above, the CFD simulation of the spray flow field under different spraying parameters of each group is solved. Plot the change curves of spraying speeds \( v_0 \) and \( v_1 \) under different spraying working parameters, as shown in figure 2, where the spraying speed at the nozzle outlet is \( v_0 \) and the spraying speed at 1 meter is \( v_1 \).

![Figure 2. Variation curves of spraying speed under different spraying working parameters.](image)

It can be seen from figure 2 that as the spray pressure increases, both the spray speeds gradually increase, \( v_1 \) is greatly reduced than \( v_0 \), and \( v_1 \) decreases more when the spray pressure is higher, because as the spray pressure increases, the spray coverage area of the flow field expands, and the area of air resistance on the flow field also increases, which accelerates the dissipation of fluid kinetic energy. At the same spray pressure, the larger the nozzle diameter, the greater the spray speeds.

For the nozzle with a diameter of 0.838mm, the entire system is always in a high-speed spray state, which easily causes colloids to splash and bounce against the surface of the rocket tank, so it is not suitable for spraying. In addition, for nozzles with a diameter of 0.330 mm, the width of the spray width at 5MPa and 10MPa starts to decay significantly at a distance of less than 1 meter, and the effective spray distance is short, so it is not suitable for colloid spraying.

For the nozzle with a diameter of 0.330 mm, when the spray pressure is controlled in the range of 15-20 MPa, the spray speed \( v_1 \) is basically maintained between 13.3-15.6 m·s$^{-1}$, and the entire system...
is in a low-speed spray working state; for a 0.584 mm diameter nozzle, when the spraying pressure is controlled at 15-20 MPa, the variation range of spraying speed $v_1$ is 28.9-35.1 m·s$^{-1}$, and the system is in a relatively moderate working state of spraying speed.

2.4. Relationship between atomization uniformity and spraying working parameters

The uniformity of atomization is an important factor affecting the colloid spraying effect. The more uniform the distribution of the material in the spray area, the better the uniformity of the adhesive layer after spraying. Based on the solution results of spraying flow field, the relationship between atomization uniformity and spraying working parameters is studied. In this chapter, the Sauter Mean Diameter is selected as the indicator of the atomization uniformity. Sauter's average diameter is recorded as $D_{32}$ or SMD particle diameter.

Based on the CFD simulation results of three diameter nozzles at different pressures of 5-30MPa, the maximum value Max, minimum value Min, and SMD average value of the atomized droplet size in the spray flow field are calculated, and the atomization under different spraying parameters is plotted in figure 3. The variation curve of the droplet size is shown in figure 3. It can be seen from the figure that the spray pressure has a greater effect on the particle size of the atomized droplets. For the same nozzle diameter, the SMD particle size decreases with increasing spray pressure. Under the same spraying pressure, the smaller the nozzle diameter, the smaller the SMD particle size and the maximum and minimum particle diameters of the atomized droplets.

![Figure 3. Variation curve of atomized droplet size under different spraying working parameters.](image)

In order to control the spray speed of the flow field at a relatively moderate or low speed, and to achieve a better spray atomization uniformity, in order to obtain a better colloid spraying effect, a suitable spraying working parameter range can be initially determined, as shown in the table 3.

| Nozzle diameter (mm) | Spraying pressure (MPa) | Spraying speed (m·s$^{-1}$) | Atomized droplet size (mm) |
|---------------------|-------------------------|-----------------------------|---------------------------|
| 0.330               | 15-20                   | 13.3-15.6                   | 0.360-0.382               |
| 0.584               | 15-20                   | 28.9-35.1                   | 0.478-0.534               |

3. Research on Droplet Impact Spreading Dynamics and Optimal Spraying Working Parameters

3.1 Establishment of the droplet ejection impact model

In this section, a CFD analysis model of droplet impact is established, the dynamic characteristics of droplet impact spreading under different ejection speeds are analyzed, and the influence of the variation of ejection speed on the quality of the droplet spread forming is further determined, so as to further determine the optimal colloid spraying working parameters range. As shown in figure 4, a 5mm×5mm CFD simulation calculation domain is established. A DW-1 type colloidal droplet is
established at a height of 1mm from the bottom, and the initial diameter $D_0$ of the colloidal droplet is set to 0.6 mm according to the research results in the previous section.

![Droplet impact model](image)

**Figure 4.** Droplet impact model.

![Dynamic changes of droplet spreading coefficients at different spray speeds](image)

**Figure 5.** Dynamic changes of droplet spreading coefficients at different spray speeds.

Rectangular structured cells are used for mesh division. The mesh near the bottom region is properly encrypted. The model consists of 62,500 mesh cells. Air is the basic phase and DW-1 type colloid is the second phase. The bottom of the model is the non-slip wall boundary condition, and the wall material is defined as aluminum alloy; the top and the boundary on both sides are atmospheric boundary conditions. The numerical simulation in this section uses the Volume of Fluid (VOF) model.

### 3.2. Research on droplet impact dynamics and spread forming process

For DW-1 type colloid droplets in the thermal insulation layer, the ejection speed has a great influence on the dynamic process of impact. In this paper, four different spray speeds of $v_1$, $v_2$, $v_3$, and $v_4$ are selected as 13.3 m·s$^{-1}$, 15.6 m·s$^{-1}$, 28.9 m·s$^{-1}$, and 35.1 m·s$^{-1}$, respectively, and the numerical simulation of the dynamic process of the impact of the droplet under different spray speeds is carried out. Select the main feature moments from each group of simulation results, as shown in figure 5.

![The dynamic process of droplet impact and spread under different spray speeds](image)

**Figure 6.** The dynamic process of droplet impact and spread under different spray speeds.

It can be found from figure 5 that as the spray speed increases, the droplets will gain greater impact kinetic energy, and the spreading speed will become faster and faster, that is, the maximum spreading
state will be reached faster, but the speed is too large. At the same time, there will be splashes and lifts at the edges, the final shrinking and gathering effect of the droplets will become more and more obvious, and the flatness of the spread will also be affected [6].

3.3. Research on the quality of spread spreading
The ratio of dynamic diameter to initial diameter is the spreading coefficient. The change of the spreading coefficient reflects the dynamic characteristics of the spreading of the droplet. The larger the spreading coefficient, the better the overall spreading quality of the colloid droplets. Based on the simulation results of droplet impact spreading at different jet speeds in this section, the dynamic change of the droplet spreading coefficient with time is shown in the graph in figure 6.

It can be seen from figure 6 that after the droplet spreading coefficient reaches the maximum value, it decreases slightly and then stabilizes. The greater the spray speed, the more pronounced the tendency of the droplet to retract. With the increase of the spraying speed, the maximum spreading coefficient of the droplets gradually decreases, and the time to reach the maximum spreading coefficient is relatively shortened, but the overall spreading degree of the droplets is getting lower and lower, and the spreading quality is also worsening.

In general, when the spraying speed $v_1$ is 13.3 m·s$^{-1}$ and the spraying speed $v_2$ is 15.6 m·s$^{-1}$, the spreading degree of the atomized droplets after hitting the wall is higher, and the spreading quality of the droplets is higher than that of $v_3$ and $v_4$.

Based on the research results of the impact and spreading characteristics of the droplets in this section, when the spray speed of 0.330mm nozzle diameter in the range of 15-20 MPa spray pressure is relatively more suitable for colloid spraying. Finally, the optimal spraying working parameter range of the thermal insulation layer colloid is further determined, as shown in table 4.

| Nozzle diameter(mm) | Spraying pressure (MPa) | Spraying speed (m·s$^{-1}$) | Atomized droplet size (mm) |
|---------------------|-------------------------|----------------------------|---------------------------|
| 0.330               | 15-20                   | 13.3-15.6                  | 0.360-0.382               |

4. Conclusions
The research in this paper has obtained the following research results:

A CFD simulation model for DW-1 type colloid spraying of adiabatic layers was established, and the flow field simulation results were analyzed. Based on the CFD simulation results of the spray flow field, the spray velocity of the flow field was studied separately. Based on the relationship between atomization uniformity and spraying working parameters, a suitable spraying working parameter range is initially determined after analysis: when the nozzle diameter is between 0.330-0.584 mm and the spraying pressure is within the range of 15-20 MPa, the spraying speed can be set to $v_1$ controlled at 13.3-35.1 m·s$^{-1}$, while the SMD particle size of the atomized droplets is less than 0.6 mm.

A spray impact analysis model for atomized droplets was established, and the DW-1 type droplet impact spreading dynamics at different spraying speeds were numerically simulated, and the influence of spraying speed on the droplet spreading coefficient and spreading quality was analysed. It is found that when the spraying speed is relatively low, the spreading quality after the impact of the droplet is better. Optimal spraying working parameters were obtained.

Based on the analysis of the characteristics of the flow field and the research on the impact of the droplets, the optimal spraying parameters were obtained: the nozzle diameter is 0.330 mm, and the spraying pressure is in the range of 15-20 MPa.

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