The Influence of Shaping Air Pressure of Pneumatic Spray Gun

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Abstract. The shaping air pressure is a very important parameter in the application of pneumatic spray gun, and studying its influence on spray flow field and film thickness distribution has practical values. In this paper, Euler-Lagrangian method is adopted to describe the two-phase spray flow of pneumatic painting process, and the air flow fields, spray patterns and dynamic film thickness distributions were obtained with the help of the computational fluid dynamics code—ANSYS Fluent. Results show that with the increase of the shaping air pressure, the air phase flow field spreads in the plane perpendicular to the shaping air hole plane, the spray pattern becomes narrower and flatter, and the width of the dynamic film increases with the reduced maximum value of the film thickness. But the film thickness distribution seems to change little with the shaping air pressure decreasing from 0.6bar to 0.9bar.

1. Introduction
Robotic painting technology is widely applied in the manufacture of automobile, plane, furniture and many other products [1-3]. In order to optimize paint process, ideal painting parameters are needed, such as paint flow rate, atomization air pressure, shaping air pressure, painting distance, which are crucial to painting quality. Among these, shaping air jetting out from the shaping air holes on the horn-like structures of pneumatic paint guns affects the shape of spray pattern and the paint thickness distribution on workpiece: the cross section of the spray cone would turn elliptical with the opening of the shaping air hole during painting process, and major and minor axes of the elliptical cross section would be enlarged and reduced, respectively, with the increase of shaping air pressure. Therefore, the shaping air pressure is an important parameter that should be taken into consideration when planning the path of painting robot.

With the development of computer and computational fluid dynamics(CFD), a large number of researchers have studied the painting process through CFD methods. Hicks et al. [4], Fogliati et al. [5], Ye et al. [6-7], Toljic et al. [8] and Osman et al. [9] have researched the spray flow field of painting the flat surface using the painting mode established by the Euler-Lagrangian method. This method intends to describe the two-phase paint spray flow in two frames, with the air flow described in Euler frame and the motion of paint droplets described in Lagrangian frame. Chen Yan et al. [10] researched spray flow field of painting process on flat surface using the Euler-Euler method, which is a more general method of describing two-phase flows, both the phases described in Eulerian frame and with similar governing equations. However, few of them investigate the effects of shaping air pressure through CFD simulation.

Therefore, the paper aims to study the effects of shaping air pressure based on CFD simulation. A paint deposition model is established based on Euler—Lagrangian method in CFD theory. Simulations
for the cases with different shaping air pressures are carried out. The effects of shaping air pressure on the air flow field and paint thickness distribution are obtained and analysed.

2. Governing equations for paint deposition process

The flow field of paint deposition process can be regarded as a two-phase flow where the atomized liquids are transported under the action of high-speed air phase to the workpiece. Euler-Lagrangian method is adopted to describe the two-phase flow of painting process.

2.1. Basic governing equations for air phase

The description of the gas phase is obtained by solving the continuity and momentum equations coupled with a suitable closure model for turbulence.

Continuity equation for the air phase is

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$$

where, \(\rho\) is the gas density and \(u\) the gas velocity.

Momentum equation for the air phase is

$$\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho uu) = -\nabla p + \nabla \cdot (\tau) + \rho g$$

in which, \(p\) the pressure, \(\tau\) viscous stress tensor, \(g\) the gravitational acceleration.

The equations (1) and (2) is closed by standard \(k-\varepsilon\) turbulence model:

$$\frac{\partial (k)}{\partial t} + \nabla \cdot (\rho ku) = \nabla \cdot \left( \left( \frac{\mu + \frac{\mu_t}{\sigma_k}}{\rho} \right) \nabla k \right) + G_k - \rho \varepsilon$$

$$\frac{\partial (\varepsilon)}{\partial t} + \nabla \cdot (\rho \varepsilon u) = \nabla \cdot \left( \left( \frac{\mu + \frac{\mu_t}{\sigma_\varepsilon}}{\rho} \right) \nabla \varepsilon \right) + C_{1\varepsilon} \frac{\varepsilon}{k} G_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k}$$

2.2. Governing equations for the liquid phase

The liquid phase is treated by the Lagrangian approach, where the trajectory of the droplet can be calculated by solving the equation of motion for a single droplet according to equation (5).

$$\frac{du_d}{dt} = f_d (u - u_p) + \frac{g(p - \rho)}{\rho_p}$$

in which, \(f_d\) is the unit mass drag force with a coefficient \(f_d = 18 \mu \epsilon_\text{Re} \), \(C_{1\varepsilon} \rho \frac{\varepsilon^2}{k} \), \(u_p\) the droplet velocity, \(u\) the instantaneous air velocity that can be calculated as the sum of the local mean velocity and a fluctuating velocity corresponding to the local turbulence degree, by using a stochastic tracking model.

2.3. Paint impingement and sticking model

When the paint liquid phase from the spray flow field impinge and stick onto the workpiece, its mass and momentum are removed from the spray flow, and added as source terms to the governing equations for the film on workpiece.

The conservation of mass for the film is:

$$\frac{\partial h}{\partial t} + \nabla \cdot (h \cdot V) = \frac{\dot{m}}{\rho_i}$$

$$\dot{m} = \alpha_s \rho_i V_{ds} A$$

where, \(\rho_i\) is the liquid density, \(h\) the film height, \(V\) the mean film velocity, \(\dot{m}\) the mass source, where \(\alpha_s\) is the volume fraction of the paint, \(\rho_i\) is the paint phase density, \(V_{ds}\) is the paint phase velocity normal to the wall surface, and \(A\) is the wall surface area.
The conservation of momentum for the film is:

\[
\frac{\partial hV}{\partial t} + \nabla \cdot (hVV) = -\frac{hV_lP_l}{\rho_l} + \frac{3}{2}\frac{\tau_h}{h} - \frac{3V_l}{h}V + \dot{q}_l
\]

(8)

\[
\dot{q}_l = m_dV_d
\]

(9)

The terms on the left-hand side of equation (7) represent transient and convection effects, respectively. On the right hand side, the first term includes the effects of gas-flow pressure, the gravity component normal to the wall surface (known as spreading), and surface tension; the second and third terms represent the net viscous shear force on the gas-film and film-wall interfaces, based on the quadratic film velocity profile representation; and the last term is the effect of the momentum source. In equation (8), the \(\dot{q}_l\) is the momentum source and \(V_d\) is the velocity vector of the paint liquid.

3. Simulation setup

The geometry of the pneumatic atomizer adopted in this study is shown as Figure 1. The paint hole with diameter 1.1 mm is coaxially surrounded with an annular air orifice which is an annular ring with outer diameter 2 mm and inner diameter 1.6 mm. On each side of the annular air orifice are two assisting air holes with diameter 0.6 mm. On each of the horn-like structures, there are two shaping air holes, which can jet shaping air so that spray cone with elliptic cross-section can be formed for painting larger workpieces.

![Figure 1. 3-D model of the spray gun](image1.png)

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

The simulation cases in this study were carried out for painting a 300 mm×500 mm flat plate. For all the simulation cases, the axis of the atomizer was perpendicular to the target wall, and the paint hole was set at a distance of 180 mm from the wall. The calculation domain was built up as shown in Figure 2 and was meshed with 500,000 unstructured grids. 71 droplet injection sources were set uniformly in a 1.1 mm diameter-circular plane 2 mm downstream the paint hole. Atomization hole was set as the pressure inlet hole, the pressure of which was 1.2 bar. The shaping air pressures corresponding to the four cases in this study were set to 0 bar, 0.3 bar, 0.6 bar, 0.9 bar respectively. The simulation was carried out on the platform of ANSYS Fluent, where the model was discretized by the 2nd order upwind scheme and the discretized equations were solved by the SIMPLE algorithm. The time step was \(\Delta t = 1 \times 10^{-4}\) s.

4. Simulation results and analysis

Figure 3 shows the contours of the air velocities of the four cases with different values of shaping air pressures. Only the flow fields in XZ-plane (i.e. the plane perpendicular to the shaping air hole plane) are presented, because they are larger and more obvious to measure than that in YZ-plane due to the effect of shaping air. The highest value of the air phase is around 512 m/s at the exit of the air nozzle, but the air velocity contours are depicted in the range of 0–50 m/s in order to provide reasonable shapes of the entire flow fields.
The spray patterns of the paint films on the flat plate obtained under different shaping air pressures are shown in Figure 4; these can also be called static film growth rate (μm/s), for the spray gun did not move in the simulation.

As is shown, with the increase of the shaping air pressure, the air phase flow field spreads in XZ-plane, and the spray pattern becomes narrower being flattened in X direction and extended in Y direction.

In practical painting process, the spray gun is usually moved along the direction of the minor axis of spray pattern (i.e. Y-axis direction) to achieve high painting efficiency. Therefore, in order to better illustrate the influence of shaping air pressure, the dynamic film distributions are acquired as shown as Figure 5 by integrating the fitted static film growth rate along the Y axis for the movement of the spray gun at a linear speed of 180 mm/s.

It can be seen that as the shaping air increases from 0 bar to 0.9 bar, the width of the film increases from 100 mm to about 264 mm, and the maximum value of the film thickness decreases from around 50 μm to around 18 μm. It is also worth noting that the film thickness distribution seems to change little with the shaping air pressure decreasing from 0.6 bar to 0.9 bar.
Figure 5. Dynamic film thickness distributions obtained under three different shaping air pressures

5. Conclusions
In order to analyse the influence of shaping air pressure, Euler-Lagrangian method has been used to build a model to describe the paint spray flow field based on CFD theory. The cases of painting a flat plate with four different shaping air pressures were simulated based on the model. Results were achieved on the commercial codes—ANSYS Fluent.

With the increase of the shaping air pressure, the air phase flow field spreads in XZ-plane, and the spray pattern becomes narrower being flattened in X direction and extended in Y direction. As the shaping air increases from 0 bar to 0.9 bar, the width of the dynamic film increases, and the maximum value of the film thickness decreases. But the film thickness distribution seems to change little with the shaping air pressure decreasing from 0.6 bar to 0.9 bar.

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