Numerical Simulation of Air Spray using the Eulerian multiphase model

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Keywords: Air Spray Flow; Eulerian Multiphase Model; Liquid Droplet

Abstract. This work establishes an air spray model using the Eulerian multiphase model, and analyzes the spray cone shape and characteristic of paint droplets in the cone by performing computational simulations. Results show that the cross section of spray cone is elliptical. The distribution of big droplet phase is narrow, while the small one covers all the spray cone section. The transverse spread capability of droplet phases is poor, and velocity of big droplet phase is slightly larger than small droplet phase along the short axis of elliptical-shaped section. However, the small droplet phase has a significantly lager transverse velocity, and spreads further than big droplet phase along the long axis.

Introduction

Researches of spray simulation by computational fluid dynamics (CFD) are helpful to analysis spray process, which are of significance to planning spraying trajectory and calculating film thickness. Plenty works have been done about simulations of spray flow with a pneumatic atomizer. The spray models demand complicated techniques for coupling the dynamics of paint droplets and gas carrier. So far, strategies of multiphase simulation fall into two basic methods, namely the Euler-Lagrangian method and Euler-Eulerian method.

Over recent years the Discrete Phase Model (DPM) within the Euler–Lagrangian framework has dominated in simulating the spray process [1] [2]. In this method, the air phase is treated as a continuum, described by solving Navier-Stokes equations using Eulerian formulation. And the paint droplets are considered to be a discrete phase, of which motion and transport is tracked using the Lagrangian formulation. This method is sensitive to the grid resolution in the near nozzle and target wall region. And the computational time increases by exponential growth, with increasing droplets. So it is rather difficult to describe huge number of droplets flow and deposition in the spray.

Above difficulties could be overcome by using the Euler–Eulerian method. This method treats the gas phase and droplet phase as interpenetrating continua, and each phase are treated from the Eulerian point of view. Detailed spatial distribution of velocity and volume fraction could be obtained. A unified numerical solution method could be used for each phase. Thus, the model has a lower computation, which is acceptable to solve an industrial problem. The method is first addressed by Harlow in multiphase flow simulation [3]. And it has been applied for spray simulation with improved models by Vujanović and Chen et al [4] [5].

In this paper, Eulerian multiphase model is used to simulate air spray. The gas-droplet multiphase spray model is presented. The model shows a capability to predict spray cone shape, and the distribution and movement characteristic of paint droplets in the cone.

Multiphase Spray Model

The spraying process can be considered as multiphase flow including air and paint droplets. Gas and droplet phases are treated to be separate, yet interacting, which are calculated under Eulerian coordinates. The volume fraction α_k represents the space occupied by each phase, and the set of conservation equations is solved for each phase, individually. Eq. (1) shows the volume fraction condition. The mass, momentum and energy conversation equations for phase k are shown in Eq. (2)

- (4). The terms on the left hand side of the conservation equations represent the transient change and convective transport of the phase flow properties. The terms $\mathbf{M}_{kl}$ and H_{kl} are the momentum and energy exchange terms between phases. And no mass exchange occurs. For description of turbulent spray behavior, the standard k-ε model is employed.

$$\sum_{k=1}^{n} \alpha_k = 1 \tag{1}$$

$$\frac{\partial \alpha_k \rho_k}{\partial t} + \nabla \cdot (\alpha_k \rho_k \mathbf{v}_k) = 0 \tag{2}$$

$$\frac{\partial \alpha_k \rho_k \mathbf{v}_k}{\partial t} + \nabla \cdot (\alpha_k \rho_k \mathbf{v}_k \mathbf{v}_k) = -\alpha_k \nabla p + \nabla \cdot \alpha_k (\tau_k + \tau_k^t) + \sum_{l=1, l \neq k}^{n} \mathbf{M}_{kl} \tag{3}$$

$$\frac{\partial \alpha_k \rho_k h_k}{\partial t} + \nabla \cdot (\alpha_k \rho_k \mathbf{v}_k h_k) = \alpha_k \frac{\partial P_k}{\partial t} + \alpha_k \tau_k : \nabla \mathbf{v}_k - \nabla \cdot \alpha_k \mathbf{q}_k + \sum_{l=1, l \neq k}^{n} \mathrm{H}_{kl} \tag{4}$$

Simulation Setup

The prototype of the atomizer used in simulation is a DeVilbiss automatic air paint gun. The primary features are the central liquid paint orifice, the atomizing air orifice, the cleaning air orifices and the shaping air orifices. The fluid control domain adopts a 200 mm×300 mm×200 mm hexahedron. The air cap is perpendicular to the target wall and at a distance of 180mm from the wall. The domain is meshed in unstructured grid. Additionally, grid fining is used in the core region to improve computational accuracy, and coarsening is adopted in the exterior region to limit the total number of mesh.

Three phases are defined for the spray simulation. The first phase is a gas phase consisting of air, while other phases are droplet phases representing paint droplets. The second phase is a big diameter droplets phase (30 μm), and the third phase is a small diameter droplet phase (10 μm). A liquid with viscosity of 0.03843 kg/(m·s) and density of 1200 kg/m^3 is used as paint. Velocity inlet have been prescribed as boundary condition at the liquid paint orifice: a velocity magnitude of 5 m/s, with volume fractions of 0.05 and 0.15 for the second and third phase separately were set. And pressure inlets are defined at other orifices with 140 kPa atomization pressure.

Spray Cone Shape

Droplet phases, emanating from the liquid paint orifice at low velocity, are accelerated, driven by high velocity atomizing air. The droplet phases and the gas phase are mixed sufficiently, generating the spray. The spray is compressed in one direction and spread out in the other direction by the impingement of shaping air flow, creating an elliptical cross section, shown in Figure 1. In the coordinate system, Z is the axial coordinate of the spray cone, X the short axis coordinate along the minor width of section, and Y the long axis coordinate along the maximum width.

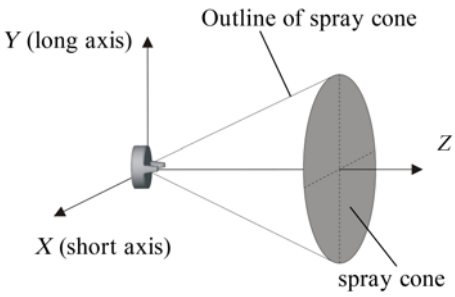


Fig.1 Sketch map of spray cone

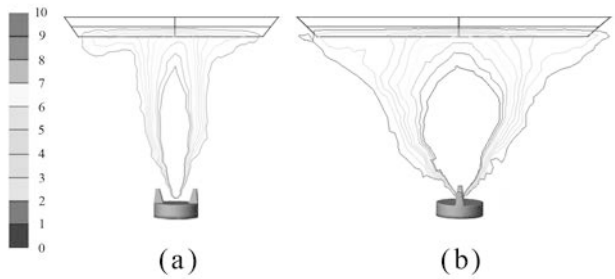


Fig.2 Liquid phase velocities in sections

Figure 2 presents the velocity distribution of the small diameter droplet phase on the longitudinal section of spray cone. The velocity of the droplet phase on XZ plane is shown in Figure 2(a), and

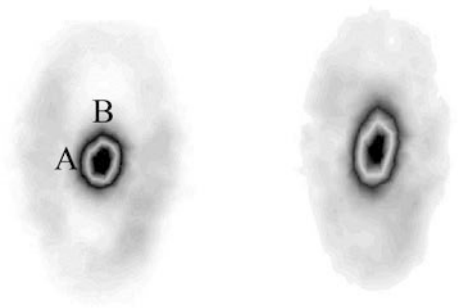
velocity on *YZ* plane shown in Figure 2(b). Velocity of droplet phase dropped quickly when it approached the wall and liquid film is formed on the wall. Part of the droplet phase is driven away by the airflow, while some droplet phase rebounded after impinging.

Characteristic of Droplet Phases

Small droplets were preferentially compressed towards *X* direction and transported towards the *Y* direction by shaping air, due to their smaller inertia, more easily than large droplets. Figure 3 shows distributions of droplet phases at a distance of 15cm from the air cup (3cm from the wall). The distributions in section are elliptical, and vaporific droplet phases around the spray cone are rebounded droplet phases. The distribution of big droplet phase is narrow. Region A is at the edge of the short axis, while region B at the interior, as can be seen in Figure 3(a). The distribution of small droplet phase is wide and covers all the spray cone section, as shown in Figure 3(b).

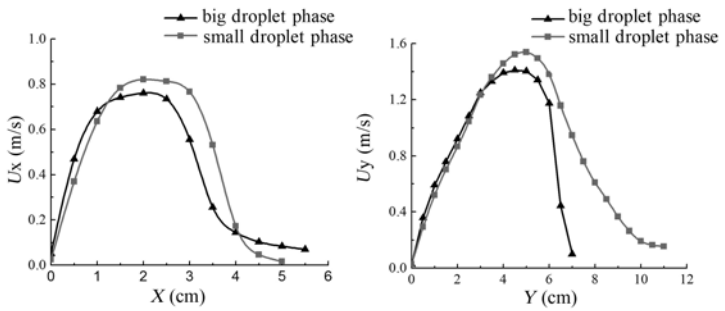
Figure 4 shows the transverse velocities of droplet phases. *U*x and *U*y are velocities on *X* and *Y* direction separately, representing the spread capability in the short axis and long axis direction respectively. Since the velocities of droplet phases at the center are perpendicular to the wall, the transverse velocities are nearly zero. The transverse velocities rise by increasing the distance from the center. In the middle region, the transverse velocities are stable; on the edge, they decrease sharply.

The transverse velocity of small droplet phase decreases faster than big droplet phase on *X* direction. When *X* is above 4 cm, the velocity of small droplet phase is almost zero, while big droplet phase is about 0.1m/s, as depicted in Figure 4(a). The velocity of droplet phases on *Y* direction is higher than that on *X* direction. The velocity of big droplet phase decreases rapidly at 6 cm, and keeps zero beyond 7 cm. The small droplet phase has a transverse velocity on entire spray cone, and keeps a velocity of 0.2 m/s beyond 10 cm, as can be seen in Figure 4(b).



(a) (b)

Fig.3 Volume contour of droplet phases



(a) (b)

Fig.4 Transverse velocity of droplet phases

It can be gotten that there are mainly big droplet phase and a little small droplet phase with poor transverse velocity, at the edge region of the elliptical cone section on the *X* direction. The transverse spread capability of the big droplets on the *Y* direction is poor, and there exists only small droplet phase beyond 7cm. The small droplet phase at the edge of the long axis still has a transverse velocity and tendency to extend further.

Experiment

The film on a flat plate in practical painting process is shown in Figure 5. In practical process, paint droplets in the spray cone are teared into uniform and tiny droplets by high pressure airflow, however droplets at edges are not teared. Therefore, there are tiny droplets at the center region, big droplets at the edge of the short axis, and small droplets at the edge of the long axis and other edges. Big droplets at the edge of short axis have a low transverse velocity and poor diffusion ability; large amount of small droplets at the edge of the long axis are easy to be driven away by the airflow, and spread away, as shown in Figure 6.

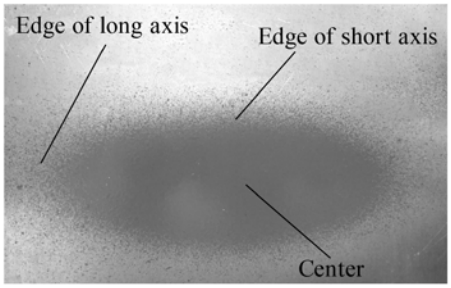


Fig.5 Paint film on a flat plate

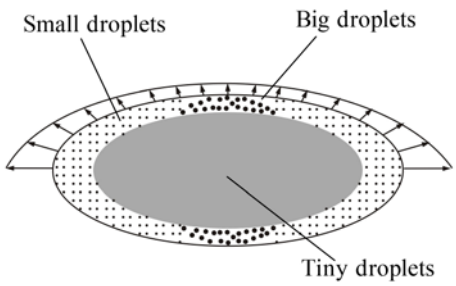


Fig.6 Schematic of droplets distribution

Therefore, the film at center region is uniform, and there exists some diffused film at the edges. There is little dispersed film at the edge of short axis, while plenty of dispersed film at the edge of long axis and other edges (Figure 5).

Conclusion

The cross section of simulated spray cone is elliptical. The distribution of big droplet phase is narrow. Small droplet phase is widely distributed and covers all the section. The transverse spread capability of big droplet phase is slightly larger than small droplet phase along the short axis of elliptical section. However, small droplet phase spreads significantly further than big droplet phase along the long axis. The experiment phenomenon that there is little dispersed film at the edge of short axis and plenty of dispersed film at the edge of long axis and other edges is explained.

Acknowledgements

This project is supported by National Natural Science Foundation of China (Grant No. 51475469).

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