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NUMERICAL STUDIES OF SPRAYS IMPACTING NORMALLY ON AN INFINITE PLATE

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The transportation process of industrial impacting sprays onto an infinite target plate has been studied numerically using the concept of inertial impaction with a 3-D transient CFD code. The effect of turbulent dispersion on the structure of sprays is investigated. Three patterns of impacting sprays, namely weak, transition and strong sprays respectively with respect to the dimensionless stopping distance are analyzed. The mechanism of spray transportation onto the target plate is also studied. An inertial impaction parameter K for impacting sprays is defined in terms of the momentum conservation to reveal the relation between spray transportation and aerodynamic conditions. Results indicate that the transfer efficiency of impacting sprays onto the plate is a function of the impaction parameter and the transfer efficiency increases greatly with the increase of impaction parameter.

Keywords: Spray, Impaction, Modeling, Plate

1. INTRODUCTION

Impacting sprays onto the infinite target plate have been widely used in industrial processes such as painting, coating, drying, cooling and fuel injecting, etc. Researchers have been working experimentally in these areas for a long time. Due to the rapid development in computational fluid dynamics in recent years, computer codes are gradually becoming an effective means for the simulation of spraying processes.

The transportation processes of impacting sprays are extremely complex and a lot of works have been done so far. Some of them focused on the spray dynamics (Zhou and Yao, 1992; Li, et al., 1995). Other researchers' works are mainly limited in the description of the structure of sprays and the interaction between sprays and surrounding flows (Domnick, et al. 1997). Only a few people (Hicks and Senser, 1995; Ding and Chyu, 1997) paid attention to the transportation of impacting sprays onto the target plate and presented their results about the transfer efficiency and deposition of sprays. Hicks and Senser emphasized that the dependency of transfer efficiency on droplet diameter is significant. In fact, other physical conditions, such as spray injection velocity, spray flow mass rate and impacting distance, etc., are also important in the transportation processes.

The inertial impaction phenomena of uniform particles, mainly the aerosol, on surfaces of objects, such as cylinders, spheres, rectangular strips and discs, have been extensively examined by various researchers theoretically and experimentally (Langmuir and Blodgett, 1946; Hahner et at., 1994; and Hung and Yao, 1997). In these studies, a potential flow field around the object was assumed. For impacting sprays onto an infinite target plate, however, the conventional concepts of impaction parameter and transfer efficiency can not be applied easily because the velocities of sprays, the surrounding flows and the size of the target objects could not be determined directly.

In this paper an effort has been made to find out the interrelation of impaction parameter and spray characteristics. In order to obtain a better knowledge of the transportation process, the effect of turbulent dispersion on particle movement is investigated. Three patterns of sprays, namely the weak, transition and strong sprays respectively with respect to the dimensionless stopping are analyzed. And the inertial impaction parameter and transfer efficiency for impacting sprays onto the infinite target plate are redefined and correlated in terms of the momentum conservation.

This study is intended as a first step of the exploration of impacting spray behaviors using numerical methods. Therefore, some detailed mechanisms are not included at this stage. In this study we assume that sprays are sparse, therefore no coalescence occurs in the domain. Also we assume all droplets deposit on the target plate. Although some droplets do bounce back, for the time being ignoring the bounce gives us the basic idea of the deposition amount. Furthermore, water is chosen as the liquid of sprays and the evaporation of droplets is neglected. Future studies may address the effects of coalescence, bounce and even evaporation of droplets to give more realistic estimations on the transportation of impacting sprays.

2. NUMERICAL METHOD

2.1 Governing Equations

The transportation of the gas phase is simulated by solving the transient time-averaged Navier-Stokes equations in connection with the standard k-ε turbulence model in computation.

Finite difference approximations are employed to discretize the transportation equations on a non-staggered grid mesh system. A third-order upwind scheme plus adaptive second-order and fourth-order dissipation terms are used to approximate the convective terms. A pressure based predictor/multi-corrector solution procedure is employed to enhance velocity-pressure coupling and mass-conserved flow field solutions at the end of every time step. A time-centered Crank-Nicholson time-marching scheme is accepted for the temporal discretization for transient flow simulations. Wall functions are used for velocity components and the turbulence source terms on the surface of the target plate. Details of the numerical method have been widely (Wang and Chen, 1990; Chen, et al., 1992).

The discrete phase is solved by the Lagrangian approach. The trajectories of droplets are calculated by solving the droplet momentum equation

$$\frac{dU_{pi}}{dt} = \frac{U_i + u_i' - U_{pi}}{\tau} + \frac{F_{bi}}{m_p} \tag{1}$$

where the magnitude of relaxation time τ is determined by

$$\tau^{-1} = \frac{3}{8}\frac{\rho_a}{r_p \rho_p} C_D \left| U_i + u_i' - U_{pi} \right| \tag{2}$$

The drag coefficient used is given by (Amsden et al., 1985) where the Reynolds number of a droplet is based on the droplet diameter and the slip velocity between the droplet and the surrounding air.

Numerical modeling of turbulent dispersion in conjunction with the Lagrangian droplet tracking approach was first proposed by Dukowicz (1980). Based on a stochastic method, the droplet turbulence was modeled by arbitrarily assuming gas turbulence kinetic energy and particle-eddy interaction time. Shuen et al. (1983) later used the k-ε model to estimate gas turbulent kinetic energy and eddy lifetime. The present study basically follows the latter approach. The effect of turbulence on the droplet transport is modeled by adding a fluctuation velocity u' to the mean gas velocity U while tracking droplets through a continuous succession of turbulent eddies. Assuming isotropic turbulence, each component of u' is randomly chosen from a Gaussian distribution with standard deviation $\sqrt{2k/3}$. Note k is the specific turbulent kinetic energy of the gas phase within a computational cell where the droplet is located.

2.2 Computational Conditions

The spraying system comprises of a spray nozzle and a target plate with the size of 600x600 mm at a distance of 300 mm downstream of the nozzle. The boundaries in both X and Z directions are open and used as outlets. The top is set to be the inlet. The computational domain covers the whole plate from the nozzle. For our case, the size of the plate is large enough to demonstrate overspray. A grid system of 33x29x33 is used in this study. It has been proved to be sufficiently fine for our purpose on a trial basis.

Since the discrete phase is solved using a Lagrangian formulation, the boundary conditions are described as initial conditions, and the variables are initial positions, diameters and injection frequency of droplets. For convenience, water is chosen as the liquid of sprays in the study. Droplets are generated with diameter ranging from 10 to 200μm, initial velocities from 5 to 80 m/s, injection angles of 0°, 30° and 45°, and a frequency of 100 droplet groups for each time step. The mass flow rate settings of liquid droplets are 3.35 and 6.7 g/s. The flow field is transient with an initial velocity of 0 m/s. Due to the limitation of the computer storage and speed, droplet groups in the domain usually are restricted less than 50,000.

With 50,000 droplet groups and 33x29x33 grids in the computational domain, the calculation time is approximately 5 hours on a Pentium Pro 200 PC.

3. ANALYSES AND RESULTS

3.1 Spray Patterns

When a droplet is projected into stagnant air, it would travel for a distance before brought to rest by air friction under Stokes law. This distance is the so-called stopping distance. With the assumption of Stokes flow, the stopping distance is

$$\lambda = \frac{\rho_p d_p^2 U_p}{18\mu_a} \tag{3}$$

For a uniform impacting spray containing a great number of droplets, when the initial velocities, sizes of droplets, and the mass flow rate and momentum of the spray, are relatively small, it behaves like an air jet and not be able to remain its original cone shape due to the momentum exchange between droplets and the surrounding air. On the one hand, the air around droplets begins to move forwards and the air near the nozzle and spray is entrained into the spray, which pushes droplets to move inwards, as shown in Fig.1. On the other hand, the turbulent dispersion, i.e. the turbulent exchange between air and sprays makes droplets to spread out. To demonstrate the effect of turbulent dispersion on the structure of the spray, the turbulent dispersion function in the code is simply switched off. A result for a spray without turbulent dispersion is presented in Fig.2. It is obvious that without dispersion all droplets are pushed inwards near the centerline downstream of the nozzle by the entrained air. Further calculation shows that sprays of different injection angles would demonstrate the same way as in Fig.2 without turbulent dispersion. In other words, the spray structure mostly depends on the turbulent exchange but not on the injection angle in case the momentum of sprays is not large. Therefore, there is no significant difference between sprays with different injection angles, for instance 0° and 45°, as illustrated in Fig.3. It is reasonable to assume that a spray behaves like an air jet in structure when the momentum is relatively small in magnitude in later analyses.

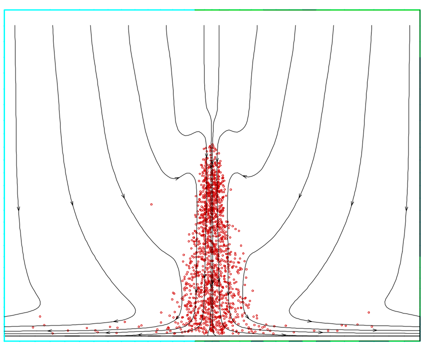


Fig.1 Spray and streamlines in the flow field.

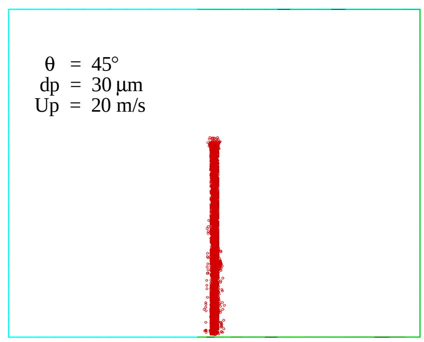
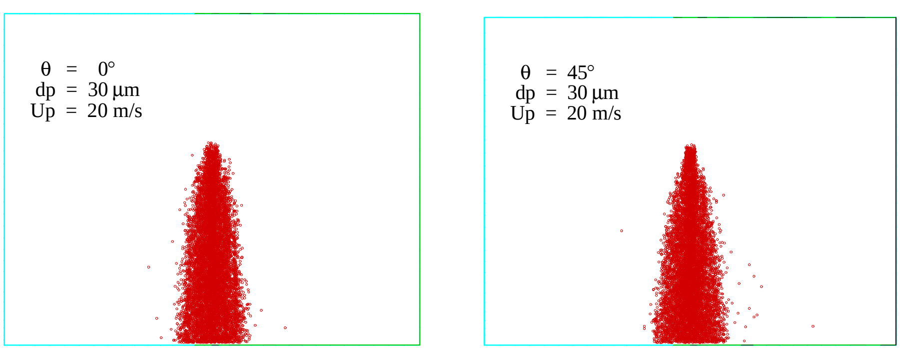


Fig.2 Spray without turbulent dispersion.



(a) 0° (b) 45°

Fig.3 Sprays with different injection angles.

As sizes and velocities of droplets increase, the momentum of droplets becomes larger, and droplets have more inertia to keep in their original trajectories. The spray could remain its shape for a longer distance before droplets change their trajectories to follow the movement of the air flow due to the exchange of momentum between air and the spray. If the momentum of droplets is large enough, the spray would be able to remain its shape until droplets reach the target plate. The dimensionless stopping distance, the ratio of droplet stopping distance to impacting distance (λ/l), is introduced to describe the spray patterns. The sprays of three patterns, namely the weak, transition and strong inertia sprays will be considered

Considering the weak spray as an axially symmetric air jet, its profile can be approximated by the expression for an air jet which was given by Abramovich (1963). The strong spray is assumed to be a solid cone in shape. The transition spray is simply treated as a combination of a strong spray at the beginning and a weak spray afterwards. Therefore, sizes of impacting sprays for above three patterns can be approximately described by equation (4). As discussed later, our study is mainly concentrated on weak and transition sprays. The results from equation (4) are close to the corresponding numerical predictions, which indicates that the equation (4) is acceptable for impacting sprays.

$$r = \begin{cases} 0.22l & \dfrac{\lambda}{l} < 1 \\ l(\dfrac{\lambda}{l} - 1)\tan\left(\dfrac{\theta}{2}\right) + 0.22l(2 - \dfrac{\lambda}{l}) & 1 \le \dfrac{\lambda}{l} < 2 \\ l\tan\left(\dfrac{\theta}{2}\right) & \dfrac{\lambda}{l} \ge 2 \end{cases} \tag{4}$$

The radius of a real spray can be determined by equation (5).

$$r = \max\left(0.22l, l\tan\left(\frac{\theta}{2}\right)\right) \tag{5}$$

3.2 Transportation of Droplets towards the Target Plate

For the weak and transition sprays, while droplets are injected into the stagnant air, surrounding air begins to move to follow the movement of droplets and droplets gradually slow down because of the momentum exchange between droplets and air. Finally, droplets and air stream come up to the same velocity.

Assuming that no external forces act on the spray, the total momentum of air and spray flow is conserved downstream of the spray. Neglecting the momentum of air flow at the exit of the nozzle, then the entrained air mass flow rate can be found. Considering the spray as an air jet, when droplets move far downstream of the nozzle, the entrained air mass flow rate from the surrounding should be much greater than that of the jet (Beer and Chigier, 1983), i.e. the spray mass flow rate. Therefore, the droplet momentum can be neglected. Finally, the flow mean velocity $\overline{U}$ is determined by

$$\overline{U} = \frac{1}{\sqrt{\pi}r}\sqrt{\frac{\dot{m}_p U_{pin}}{\rho_a}} \qquad (6)$$

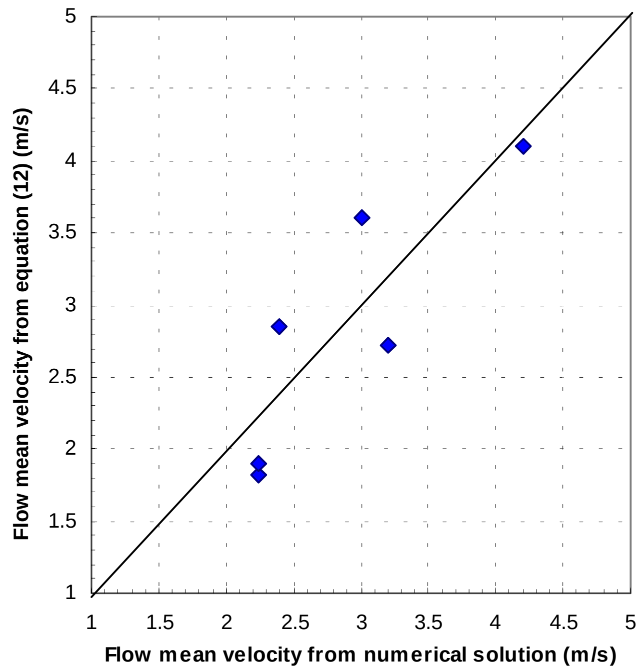


Fig.4 Estimated and numerically computed mean velocities.

Mean velocities estimated by equation (6) and numerically computed are shown in Fig.4 for comparison.

If a target plate is set downstream of the nozzle, the situation would be different. However, the flow mean velocity $\overline{U}$ from equation (6) and the spray radius from equation (4) and (5) still can be accepted as the characteristic velocity and size. The inertia impaction parameter is then defined as the ratio of the stopping distance based on the flow mean velocity to the width of the spray at the cross section of the target plate as if the plate were removed away

$$K = \frac{1}{18}\left(\frac{2r\rho_a\overline{U}}{\mu_a}\right)\left(\frac{\rho_p}{\rho_a}\right)\left(\frac{d_p}{2r}\right)^2 = \frac{1}{9\sqrt{\pi}}\left(\frac{\sqrt{\dot{m}_p U_{pin}\rho_a}}{\mu_a}\right)\left(\frac{\rho_p}{\rho_a}\right)\left(\frac{d_p}{2r}\right)^2$$

(7)

From equation (7), the dimensionless impaction parameter K can also be interpreted as a product of Reynolds number based on the spray width at the cross section of the target plate, the density ratio of the droplet to the surrounding air, and the squared ratio of droplet size to the spray width at the cross section of the target plate.

The transfer efficiency η of the impacting spray on the target plate is defined as the ratio of the amount of droplets actually deposited onto the target plate within the projected area of the spray to the amount which would pass through this area if the target plate is removed.The projected area of a spray onto the target plate can be obtained from equation (4) and (5).

4. Results and Discussion

Spraying processes for both uniform and log normal distributions are simulated. The droplets are injected into the air with diameters from 10 to 200 μm, the velocity from 5 to 80 m/s, the mass flow rates of 3.35 and 6.7 g/s, and the injection angles of 30 and 45 degree.

The predicted transfer efficiency of impacting sprays onto the target plate is plotted against the inertial impaction parameter K in Fig.5. It shows that all the points almost fall in the same curve. When the value of K is small all droplets move with small inertia and overspray occurs due to the turbulent dispersion. As the impaction parameter K becomes larger, the transfer efficiency increases gradually. When K is greater than 0.3 which is responding to the pattern very close to the strong spray, the transfer efficiency is almost unity. That means almost all droplets under this circumstance impact against and are deposited on the target plate. For industrial applications of impacting sprays, such as painting, cooling and drying, etc., it is important to select a suitable impaction parameter K.

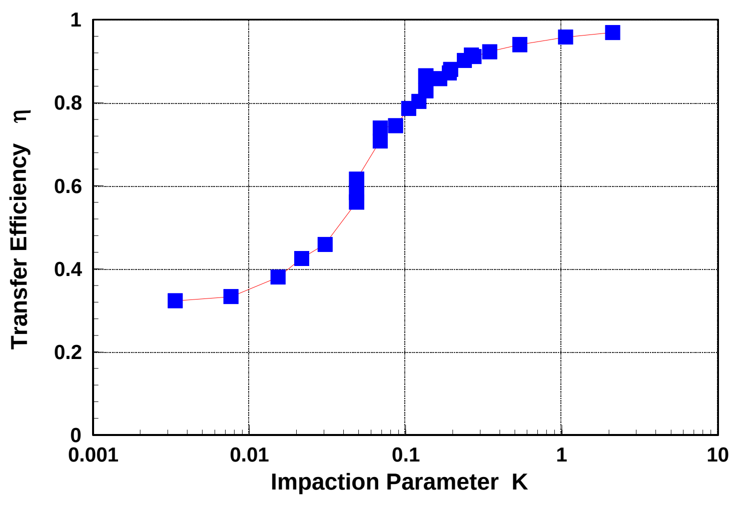


Fig.5 Spray transfer efficiency η against impaction parameter K (uniform distribution).

5. CONCLUSIONS

The transportation process of industrial impacting sprays onto the target plate has been investigated numerically using the concept of inertial impaction with a 3-D transient CFD code in this study. Three patterns of spray, namely the weak, transition and strong sprays respectively with respect to the dimensionless stopping distance of $\lambda/l<1$, $1\leq\lambda/l<2$ and $\lambda/l \geq 2$, are analyzed. An inertial impaction parameter K for impacting sprays onto the target plate is defined. Results indicate that the transfer efficiency of impacting sprays to the plate is a function of the impaction parameter.

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NOMENCLATURE

C_D	drag coefficient	U_p	droplet velocity
d_p	droplet diameter	U_{pin}	initial droplet velocity
F_{bi}	body force	$\overline{U}$	flow mean velocity
K	inertial impaction parameter	u'	turbulent fluctuation velocity
k	turbulent kinetic energy	η	transfer efficiency
l	impacting distance	λ	stopping distance
$\dot{m}_P$	mass flow rate of liquid	μ_a	viscosity of surrounding air
Re_p	droplet Reynolds number	θ	spray cone angle, total
r	spray radius	ρ_a	air density
r_p	droplet radius	ρ_p	droplet density
U	air flow velocity	τ	droplet relaxation time