# Computational Modeling of Gas-Particle Two-Phase Jet
# by a 3-D Vortex Method

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## Summary

The grid free computational model of gas-particle two-phase jet flow using 3-D vortex method is presented. The calculated results using the present method are compared with the previous experimental and the calculated results using DNS. The interaction between the particle and gas-phase is considered using Lagrangian method. It is found that the present computational model of gas-particle two-phase jet flow using 3-D vortex method is very useful for the prediction of the physical properties of the two-phase jet flow and for saving the computational time.

## Introduction

The vortex methods are widely used to simulate the 3-D turbulent flow as one of the powerful tool for CFD. The advantages of the vortex method are the grid free in the flow field and the use of the Lagrangian scheme. Therefore the algorithm is very simple compared with the computation method using Euler's equations and the numerical solutions are obtained without the iteration at the every time step. There is a few paper concerning to the analysis of the 3-D gas-particle two-phase flow using the vortex method. The computational modeling of gas-particle two-phase flow has not been established now. Recently the gas-particle two-phase round jet is analyzed using 3-D vortex method with the two-way coupling[1]. The interaction between the particle and gas-phase is considered and the grids in the space are generated to calculate the interaction effect in the vorticity transport equation. This calculation method is not completely Lagrangian method. It is predicted that the computational time using this method is longer than using the complete grid free method.

In the present study, the complete grid free computational model of gas-particle two-phase jet flow using 3-D vortex method is presented. When the two-way method is used to calculate the interaction between the particle and gas-phase, MPS(moving particle semi-implicit) method[2] is employed as one of the Lagrangian scheme without the grids in the flow field. The present computational modeling of gas-particle two-phase jet is the complete Lagrangian method and the time reduction for computation is predicted. The comparison of the results using the present model with the previous experimental and

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calculated results[3] shows that our computational modeling is very useful and available to solve the gas-particle two-phase jet.

## Numerical simulation

The assumptions are as follows:1.The gas phase is incompressible. 2.The density of the particles is far higher than that of the gas-phase. 3.The shape of the particle is a sphere and the diameters of all particles are same. 4.The mass concentration of the particle is low (0.6). 5. The collision between the particles is ignored.

The computational model for the gas-particle two-phase round jet in the present study is shown in Fig.1. The center axis of the jet is $z$ axis and the perpendicular axes to the $z$ axis are $x$ and $y$ axes. The origin is the center point of the exit plane and the sources are distributed on the $x$-$y$ plane at the distance $L(=1.5R)$ upstream from the exit to give a flow. The number of the sources is 160 and $R$ is the radius of the nozzle. Furthermore the wall surface of the nozzle is divided by a number of the source panels to express the wall of the nozzle. The total number of the triangle panel is 640 including the source disk.

The vorticity transport equation for incompressible flow is given by Eq.(1).

$$\frac{D\boldsymbol{\omega}}{Dt} = (\omega \bullet \nabla)\boldsymbol{u}_g + \nu\nabla^2\boldsymbol{\omega} - \frac{1}{\rho_g}\nabla \times \boldsymbol{F}_D \tag{1}$$

where $\boldsymbol{\omega}$ is the vorticity vector, $D/Dt$ is the substantive derivative, $\boldsymbol{F}_D$ is the force of the gas-phase per unit volume, acted by the particle, $t$ is time, vis kinematic viscosity of the gas-phase, $\rho$ is the density and $\boldsymbol{u}$ is the velocity vector, and the subscripts $g$ and $p$ show the physical properties of the gas and particle respectively.

As the density of the particle is large compared with that of the gas from the assumption 2 the forces acting on the particle are mainly the fluid drag and the gravity. The equation of the motion for the particle is given by Eq.(2).

$$M\frac{d\boldsymbol{u}_p}{dt} = \boldsymbol{f}_D + M\boldsymbol{g} \tag{2}$$

where $\boldsymbol{f}_D$ is the fluid drag acting on the particle, $g$ is the gravity acceleration and $M$ is the mass of the particle. Two-way method is used to describe the interaction between particles and gas as shown in Eqs.(1) and (2).

The blob method[4] is employed in the present calculation as one of the vortex model . When the vortex blob $i$ at $r_i$ is supposed to have the core radius $\sigma_i$, the vorticity $\boldsymbol{\omega}_i$ and the volume $dv_i$, the vorticity at $r$ induced by the blob $i$ is expressed as Eq.(3)[5].

$$\boldsymbol{\omega}(r) = \frac{1}{\sigma_i^3} p(\frac{|\boldsymbol{r} - \boldsymbol{r}_i|}{\sigma_i})\boldsymbol{\omega}_i dv_i \tag{3}$$
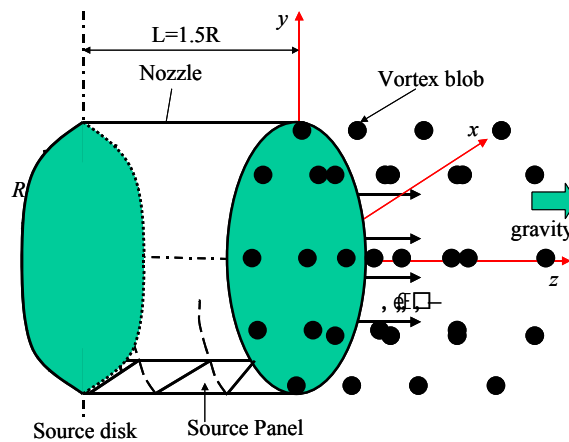
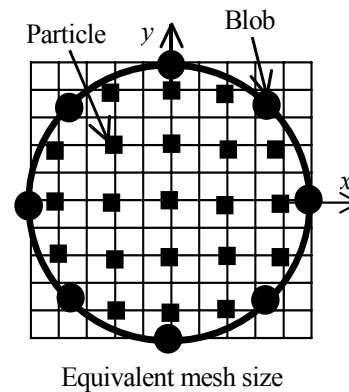Fig.1 Computational model                    Fig.2 Positions of particle and blob

where the function $p(\chi)$ is the core distribution function and the function $p(\chi)$ presented by Winckelmans-Leonard[6] is employed in the present calculation.

The velocity $\boldsymbol{u}$ at $\boldsymbol{r}$ is calculated from the Biot-Savart equation given by[5]:

$$\boldsymbol{u}(\boldsymbol{r}) = \frac{1}{4\pi}\sum_i \frac{\omega_i \times (\boldsymbol{r}-\boldsymbol{r}_i)}{|\boldsymbol{r}-\boldsymbol{r}_i|^3} q(\chi)dv_i + \boldsymbol{u}_{pt} \tag{4}$$

where $q(\chi) = 4\pi\int_0^\chi t^2 p(t)dt$ and the velocity $\boldsymbol{u}_{pt}$ shows the velocity of potential flow induced by the source distribution on the surface of the nozzle in the present study. The time rate of the vorticity change can be calculated by Eq.(1). The first term which shows the stretch of the vorticity on the right-hand side of Eq.(1) can be calculated using Eqs.(3) and (4), the second term which stands for viscosity diffusion can be calculated using core spreading method[7] and the third term which shows the influence by the particles can be calculated using the MPS method[2]. The first derivative of the quantity at the position $\boldsymbol{r}_i$ can be obtained without the grids using the following equation for the present method.

$$\left.\frac{\partial\phi}{\partial x}\right|_i \cong \frac{3}{\sum\limits_{j\neq i} w(r_j)}\sum_{j\neq i}\frac{\phi_j-\phi_i}{r_j^2}\Delta x_j w(r_j) \tag{5}$$

where $\varphi$ is the arbitrary scalar quantity like the $x$ component $F_{Dx}$ for the force $F_D$ and $r_j$ is the distance between the $\boldsymbol{r}_i$ and $\boldsymbol{r}_j$, and $w(r_j)$ is the weighting function. From above computational modeling the simulation can be performed completely without generating the grids in the flow fields.

Air jet flow with the particles of the average diameter 58 μm is demonstrated with the initial speed $W_0$ of 14.9m/s from the round nozzle of the diameter 8mm to compare with the previous experimental and calculated results[3]. The positions of the introduced particles are shown in Fig.2 at $z=0$ and 21 particles are introduced every time step.
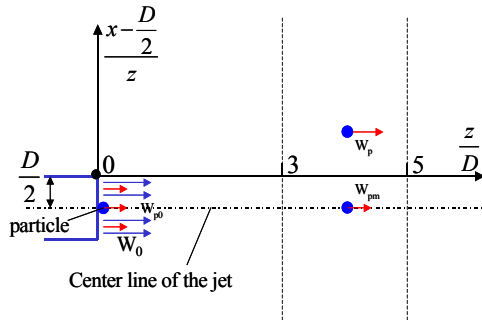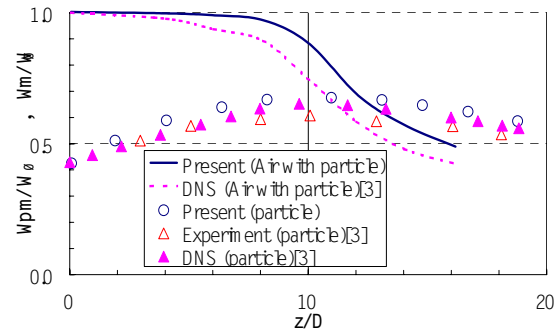
Fig.3 Symbols                     Fig.4 Axial velocity components

The mass ratio of the particle(=the particle mass introduced per unit time/the air mass supplied per unit time) is 0.6 and the initial velocity of the particle $W_{p0}$ is $0.43W_0$[3]. The eight vortex elements are introduced at the radius $R$ and $z=0.061R$ for same interval in the peripheral direction. All of the vortex elements are moved by Euler method. The time interval of the present calculation $\Delta t$ is 0.00015sec.

### Simulated results and discussion

The illustration of the symbols used in the simulated results is shown in Fig.3. The exit diameter is $D$ and $D=2R$. The time averaged axial velocity components on the center axis are shown in Fig.4. The time averaged axial velocity components for the particle on the center axis is $W_{pm}$ and those for the gas-phase on the center axis is $W_m$. The values are averaged between 0.03sec and 0.033sec during the fully developed jet flow. The values of the particles in the space of the radius 0.5mm at the center axis are also averaged. The velocity $W_{pm}$ increases gradually near $z/D=12$ and it decreases after $z/D=12$. Those results are in good agreement with the previous experimental data[3] and calculated results[3] by DNS. The particles are accelerated by the gas-phase till $z/D=12$ because the velocity of the fluid is faster than that of the particles. The particles can not follow the gas between $z/D=6$ and 12 and the velocity of the particles increase in spite of decreasing of the fluid velocity. After $z/D=12$ the velocity of the particles begin to decrease with the fluid because of the inertia of the particles. The velocity $W_m$ is decreasing gradually from $z/D=8$ and this tendency is quite similar to the results obtained using DNS.

The axial velocity components of the velocity $W_p$ for the particle are shown in Fig.5 for the initial region of $z/D$ 10. The velocity components are distributed in the radial direction. The values of the particles existing in the space of the radius 0.5mm are averaged. The results of the present calculation give good agreement with the value that had been obtained by experiments[3] and numerical simulation[3]. Especially the present results are found to be in good agreement with the experimental results compared with the results by DNS for $z/D=8$ as shown in Fig.5.
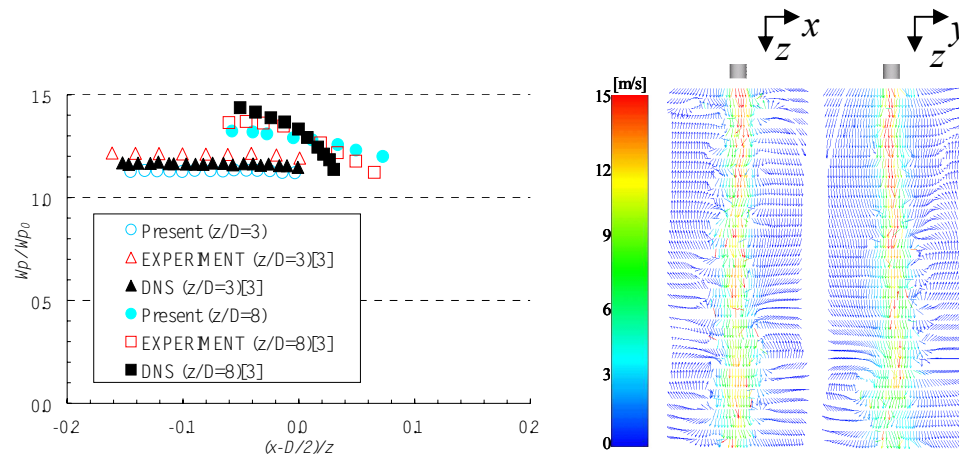
Fig.5 Axial velocity components of the particles    Fig.6 Velocity distributions (t=0.03sec)

The velocity distributions of the gas-phase are shown in Fig.6 at $t$=0.03sec and the distributions of the particles are shown in Fig.7 at $t$=0.0075,0.015, 0.0225 and 0.03sec. Fig.7 shows the view from perpendicular to $x$-$z$ plane. Reynolds number(=$2RW_0/\nu$) is about 8000.  The particles near the exit region of the jet seem to be a straight-line motion because the initial speed $W_{p0}$=0.43$W_0$ is given at the nozzle exit. After $t$=0.0225 the particles are mixed with turbulent flow structure and the motion of the particles becomes complex.

The vorticity distributions on the cross section at $z$=const. are shown in Fig.8 at $t$=0.0225sec. The absolute values of the vorticity are shown in Fig.8. The vorticity structure of the jet is found clearly and the magnitude of the vorticity is small near the center axis of the jet.

In the present study the simulations are also conducted to calculate the interaction between the gas-phase and particle using Euler's method with generation of the grid after using MPS method. The computational time of our grid free modeling can be reduced to 75% compared with Euler's method with the grids.

## Conclusions

In the present study the gas-particle two-phase jet flow is simulated using 3-D vortex method. The interaction between the particle and gas-phase is considered and Lagrangian scheme is used completely by applying MPS method. On the basis of the results obtained in the present investigation, the following conclusions can be drawn.

(1) It is successful that the gas-particle two-phase jet flow is simulated using the grid free computational model by 3-D vortex method.
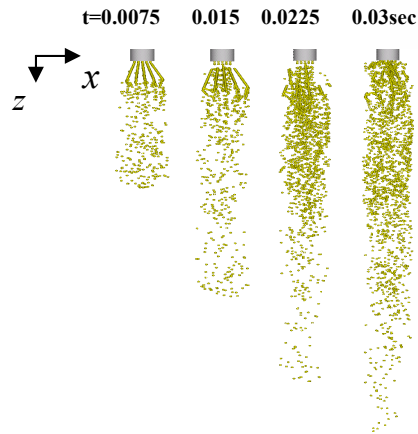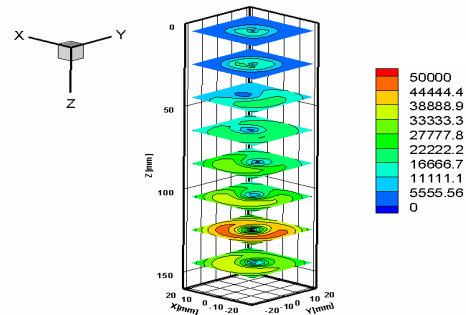
Fig.7 Distributions of particles     Fig.8 Absolute values of vorticity (t=0.0225sec)

(2)In comparison with the Euler's scheme, the algorithm of the present scheme is very simple and the computational time can be reduced to 75%.

## References

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