7th International Conference on Modelling and Simulation in Nuclear Science and Engineering (7ICMSNSE)

Ottawa Marriott Hotel, Ottawa, Ontario, Canada, October 18-21, 2015

7ICMSNSE-6

Particle Motion in Sudden contraction&Sudden Expansion Structures

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Abstract

In dilute fluid-solid two phase flow, particle motion in sudden contraction and sudden expansion structure is studied. CFX is used to simulate both fluid field and particle motion. Four different turbulence models are compared with each other and k-e model is proved to be efficient to calculate this situation. Four different particle injection regions are set to observe particle motion. The influence of particle diameter and virtual mass force are studied, separately.

Keywords: Solid-fluid Two Phase Flow, Sudden Contraction&Sudden Expansion, Particle Motion

Introduction

In the secondary side of steam generator (SG), there are several impurities consisted in water, including insoluble particles. Particles deposit in steam generator and the sedimentation can worsen the heat transfer in the secondary side. Most deposition is observed near the supporting plate. Therefore, the mechanism of particle deposition, especially force analysis, is critical for particle analysis in steam generator. On the one hand, steam generator has a complex structure which makes observing particle motion difficult. On the other hand, the most complex region in SG is the supporting plate. Hence, the supporting plate of steam generator was simplified into sudden contraction and sudden expansion structure to make the analysis clear. Moreover, the contraction ratio of the simulation, 0.2, is the same as it in the supporting plate structure in steam generator.

Forces acting on moving particles consist of the following ones:

Gravity

Gravity is significant for particle motion in fluid. Particle gravity can be calculated by

$$G = \frac{4}{3}\pi r_p^3 \rho_p g \quad (0.1)$$

Where: r_P is particle radius; ρ_p is particle density; g is gravity acceleration.

Buoyancy

Buoyancy is proportional to the cube of particle radius. It can be calculated by

$$F_f = \frac{4}{3}\pi r_p^3 \rho_f g \qquad (0.2)$$

Where: ρ_f is fluid density.

Gravity and buoyancy are two of the most important forces for upwards and downwards particle motion in force analysis. The ratio of gravity to buoyancy is ρ_p / ρ_f, which is independent of particle radius.

Drag Force

Recently, most studies are focusing on drag force, because drag force plays an important role on particle deposition. In many cases, to discuss the dynamics of a particle in a fluid, the relationship between the Reynolds number and drag coefficient of the particle is vital for calculation of the particle's motion. So me have concentrated on experiments to obtain data that can characterize and explicate this relationship, while others have tried to correlate the experimental results into simple equations for ease of calculations. In 1710, Newton studied particle motion in incompressible viscous fluid and found force acting on particles is

$$F_d = 0.22\pi r_p^2 \rho_f V_p^2 \qquad (0.3)$$

Where: r_p is particle radius; ρ_f is fluid density; V_p is particle velocity. Drag coefficient is expressed as $C_D = 0.44(500 < Re < 2\times10^5)$, where Re is Reynolds number of particles. In 1850, Stokes studied sphere particles in uniform fluid and obtained the equation of particle force:

$$F_d = 2\pi\mu r_p \left(V_f - V_p\right) + 4\pi\mu r_p \left(V_f - V_p\right) \qquad (0.4)$$

Where: μ is the kinematic viscosity of fluid; r_p is particle radius; V_f and V_p are velocity of fluid and particle separately. According to equation （2.4）, drag coefficient is obtained as $C_{Ds} = \frac{24}{Re}（Re < 1）$. Schiller and Naumann also obtained the relationship between drag coefficient and Reynolds number expressed as $C_D = 0.44$, when $Re < 1$; $C_D = \frac{24}{Re}(1 + 0.15 Re^{0.687})$,when $1 < Re < 1000$. Clift obtained the relationship between drag coefficient and Reynolds number in different Reynolds number range from 0 to 1000000 in 1978. In 2003, Brown and Lawler found the relationship between drag force and Reynolds number as $C_D = \frac{24}{\mathrm{Re}}(1+0.15\,\mathrm{Re}^{0.681}) + \frac{0.407}{1+8710\,\mathrm{Re}^{-1}}$, when $\mathrm{Re} < 2\times10^5$. Some results that show the relationship between drag coefficient and Reynolds number are shown in figure 1:

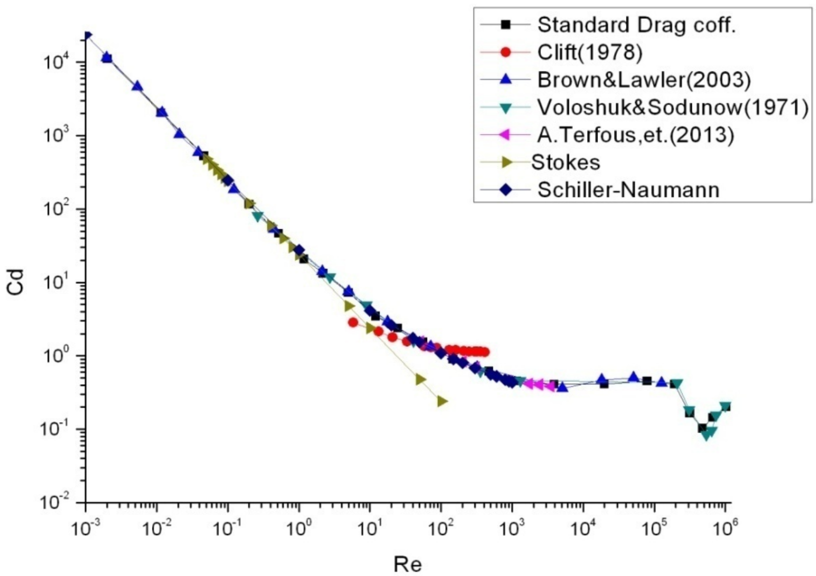

Figure 1 Drag coefficient

In Figure 1, the black square shows the standard drag coefficient obtained by a large number of experiments. As shown in Figure 1, the data obtained by Schiller and Naumann can be used to calculate particle drag force for it is in accord with standard drag coefficient data.

Virtual Mass Force

Virtual mass force is the reaction that is generated by particle pushing fluid forward when accelerating. Hence, virtual mass force must be taken into consideration when there is large acceleration.

Basset Force

Because fluid cannot accelerate synchronous with particle, Basset force is generated. It varies as time goes by and should be considered when the fluid is viscous.

Fluid Nonuniform Force

Fluid nonuniform force is caused by the nonuniformity of fluid, such as pressure gradient and velocity gradient consisting of Magnus force and Saffman force. For particle used in this calculation is small, it is assumed that there is no pressure gradient or velocity gradient around particles.

Recently, most researches have been done to find out the influence of virtual mass force and Basset force. In most cases, the unsteady terms are not negligible. They may be ignored when the particles are much denser than the fluid (E. Dodemand et al. 1995). M. van Aartrijk and H.J.H. Clercx used direct numerical simulations to study the role of Basset force on light particles (particle density is of the same order as that of the surrounding fluid). They came to the conclusion that the smallest scales of the flow are the most important for the strength of the forces that act on a particle and the history term has to be calculated over a time interval of at least one Kolmogorov time. It is also found that almost all forces have magnitudes comparable to that of the Stokes drag (M. van Aartrijk et al. 2009). Wang Yao studied spherical particles in liquid steel and found out for big-size particles ($D > 50\mu m$), the Basset force, virtual mass force and Stokes force work together to influence the movement, collision and removal of the particles (Wang Yao et al. 2013).

Numerical Scheme

Calculation domain

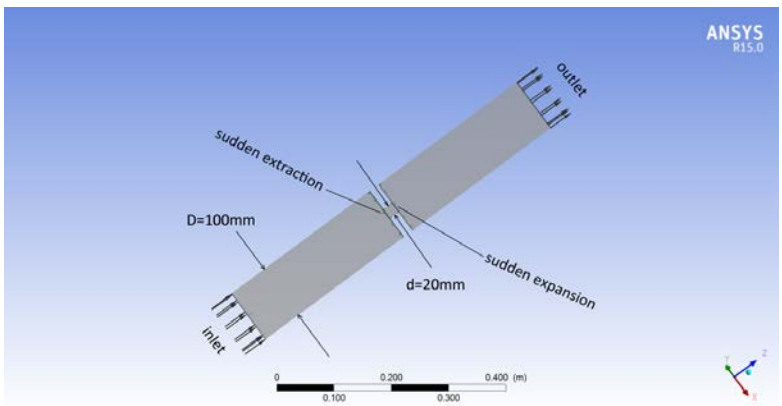

Figure 2 Calculation domain

As shown in Figure 2, the calculation domain includes both contraction part and expansion part. The main diameter of the model is 100mm, and the diameter of contraction part is 20mm.

Fluid moving through the channels is water under 0.2MPa, 298.16K. Particle phase is Fe_3O_4, because Fe_3O_4 is the most common particle in the secondary side of SG. The density of water and Fe_3O_4 is set to $988.11139 kg/m^3$ and $9180 kg/m^3$ separately. Gravity and buoyancy is taken into consideration. Reynolds number used in this simulation is 100, which make the inlet velocity 0.5536m/s. The mass flow rate of particle is 5×10^{-9}.

Governing equations

The fluid is assumed incompressible with uniform density ρ, and dynamic viscosity μ. The flow in the domain is governed by the momentum and mass conservation equation:

$$\begin{cases} \rho \dfrac{\partial U}{\partial t} + \rho U \nabla U = -\nabla P + \mu \nabla^2 U + \rho G + \rho F \\ \nabla \cdot U = 0 \end{cases}$$

Where U is the velocity vector, t is time, P is pressure, and G and F denote the gravity and applied force per unit volume, respectively. For the present study, F is chosen to be 0 such that it is assumed the continuous phase is unaffected by the presence of the dispersed phase. This choice is made as the present study seeks to understand the complexities of surface-force influence on particle motion without the additional complication of coupling the particle momentum back to the fluid.

Because the ratio of the mass flow rate of particles to the mass flow rate of fluid is small, particles are considered to be one-way coupled to the continuous fluid, which means that particles have a negligible influence on the fluid flow.

Boundary conditions

Inlet velocity is 0.5536m/s for both fluid and particles. Outlet average pressure is set to 0 and four particle injection regions are set to obtain the particle track file. The coordinate of the four injection regions are (0,0,0) (10,20,0) (-30,0,0) (30,-30,0), respectively. (The unit is mm)

Turbulence model and influence

For sudden contraction and sudden expansion structure, the flow condition is complex. Turbulence models may have a huge impact on flow calculation. There are 14 turbulence models in CFX. Four models are chosen to analysis the influence of turbulence model. They are k-Epsilon, SST, BSL Reynolds Stress, and SSG Reynolds Stress. In order to evaluate the influence of turbulence model, pressure change on the central line is used to evaluate the influence of each model. The results are shown as follow.

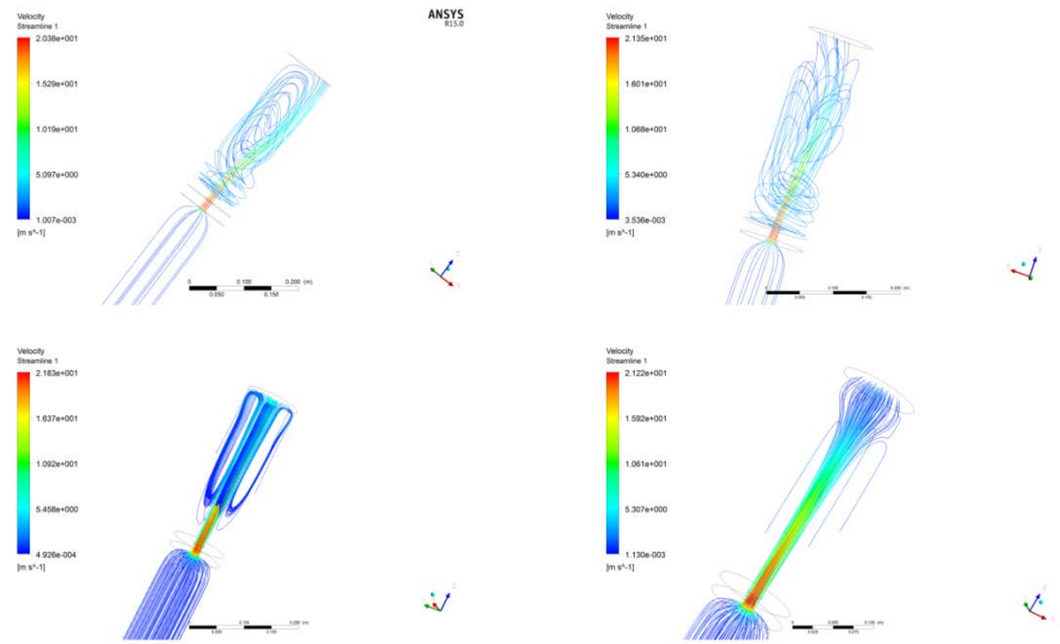

Figure 3 Fluid Streamline Using Different Turbulence Model

Figure 3 shows the fluid streamline using k-e, SST, SSG, BSL model from top to bottom, left to right, respectively. As is shown, both k-e model and SST model can obtain circulation right above the expansion structure, while SSG and BSL model obtain the circulation part near the outlet. For SST model also uses k-e equations to obtain the fluid field, but sets a limit on viscosity of boundary layer. While BSL model uses k-w equations and SSG model does not use the eddy viscosity hypothesis, but solve an equation for the transport of Reynolds stresses in the fluid.

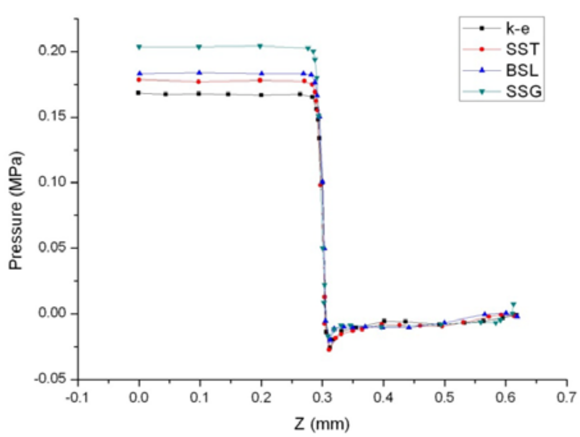

Figure 4 Pressure Change on Central Line

Figure 4 shows fluid pressure change on central line using different turbulence model. It can be seen that the pressure change trend is similar to each other and the pressure after the sudden contraction part is almost the same. So k-e model is chosen to calculate the fluid field because it can obtain the same accuracy but costs less time.

Results and discussion

Flow field

As it can be seen from Figure 4, there is a sudden pressure drop at sudden contraction structure. It can also be obtained by the energy conservation equation that when fluid flows through a narrow channel, velocity increases because flow rate stays the same. As velocity increases, pressure drops down. At the sudden contraction part, velocity reaches to near 20m/s. At such high speed, flow situation becomes complex and there is deflection after the expansion part. When the speed is high enough, recirculation appears.

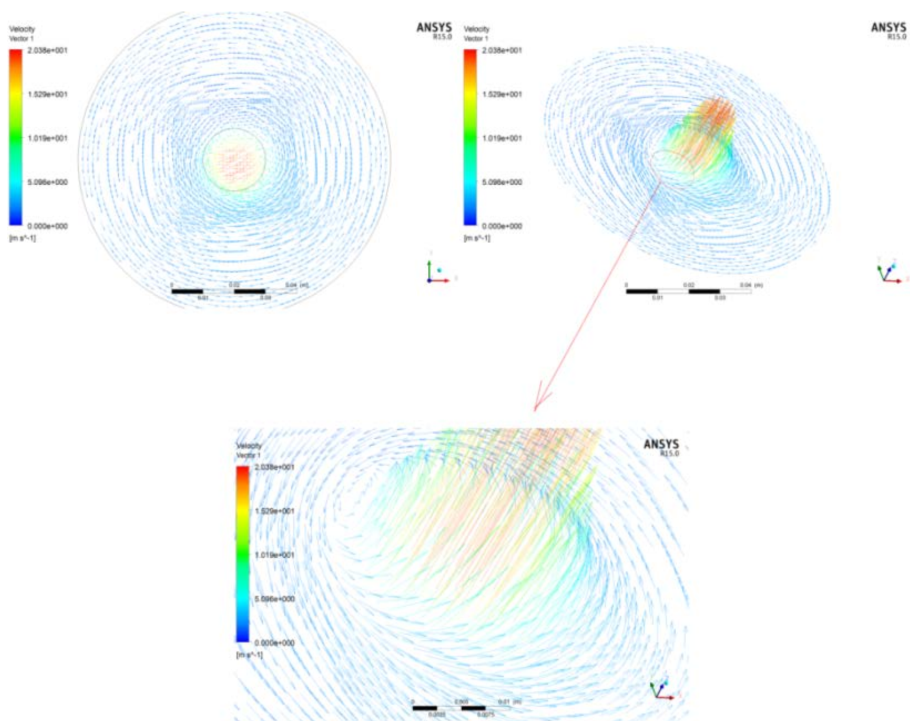

Figure 5 Velocity Vector z=0.35mm

Figure 5 shows velocity vector at height of 0.35mm. After the expansion part, fluid flows anticlockwise. Meanwhile, fluid flows upwards at center. The clockwise motion is more obvious when it is closer to the expansion part. So it is easy to get vortex at the expansion structure. When there is recirculation and vortex, there are more chances that particles will stay.

Particle Motion

Take particles of $10\mu m$ diameters as an example.

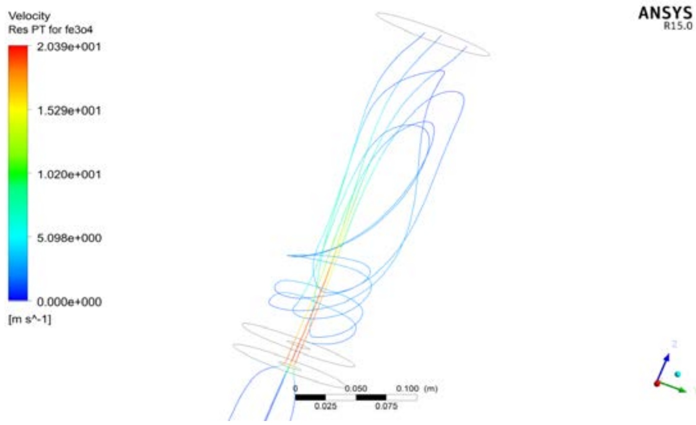

Figure 6 Particle Streamline d=10um

Figure 6 shows particle streamline at four different injection regions. Some particles flow with the main stream and leave the domain eventually, while some particles are affected by the recirculation and turbulence. They flow back in the domain and get trapped by the horizontal wall after expansion structure. The direction that particle moves is the same as fluid does. Compared with fluid streamline, it can be seen that most particles moves following the fluid.

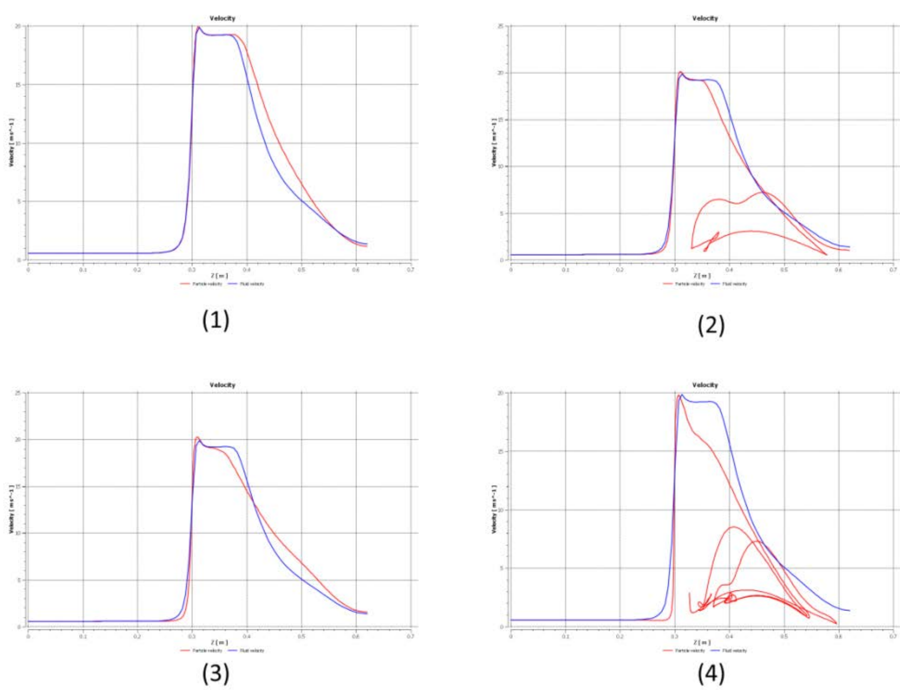

Figure 7 Particle Velocity

Figure 7 presents particle velocity at four different regions compared with fluid velocity on central line. The coordinate of each particle is (0,0,0) (10,20,0) (-30,0,0) (30,-30,0), respectively. It can be seen that number 1 to number 3 leave the domain while number 4 stays in the domain and keeps moving around before attaching to the wall. There is a sudden particle velocity drop after the expansion part, and the further particle from the central line, the sharper the drop is. The maximum velocity of particle is 20.28m/s, a little lower than the maximum fluid velocity, 20.37m/s, because of viscosity.

Influence of Particle Diameter

Different diameters of particles have different relative importance of the forces. For example, big particles have large gravity. Meanwhile, they have large buoyancy and drag force. The particle motion depends on the ratio of these forces. And the large inertial force makes it hard for particles to change their states.

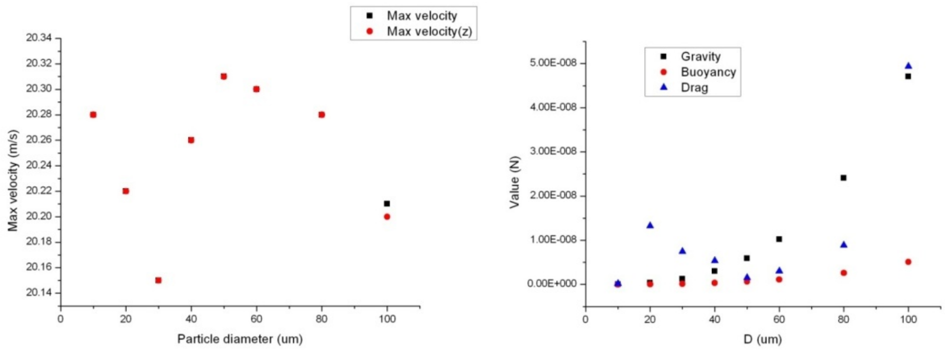

Figure 8 Maximum Velocity of Particles and Force Comparison

The left picture in Figure 8 shows maximum velocity of different sizes of particles. The figure presents that except for 10um particles, the relation between maximum velocity and diameter is parabolic. The top of the parabolic curve is when particle diameter is 50um in this simulation. The maximum vertical velocity is almost the same as the maximum velocity. It means that in this simulation, the highest speed is reached at the vertical direction. Compared to fluid maximum velocity (20.37m/s), it is assumed that the higher velocity is, the easier that particles could leave the domain. From Figure 8, it can be obtained that particles of diameters less than or equal to 10um, or of diameters around 50um could easily get out of the domain in this condition.

From the right picture in Figure 8, it can be seen that for particles of diameters equal to 10um or around 50um, buoyancy plus drag force reaches a balance with gravity. For particles of diameters between 10um and 50um, drag force is too large, which makes it easy for particles to follow fluid. When fluid flows back, so do particles. For particles of diameters between 50um and 100um, gravity is too large. When buoyancy and drag force are not enough to lift the particles, they drop.

Influence of virtual mass force

In this calculation, virtual mass coefficient is set to 0.5, which means it equals to the fluid mass of half volume of the particle.

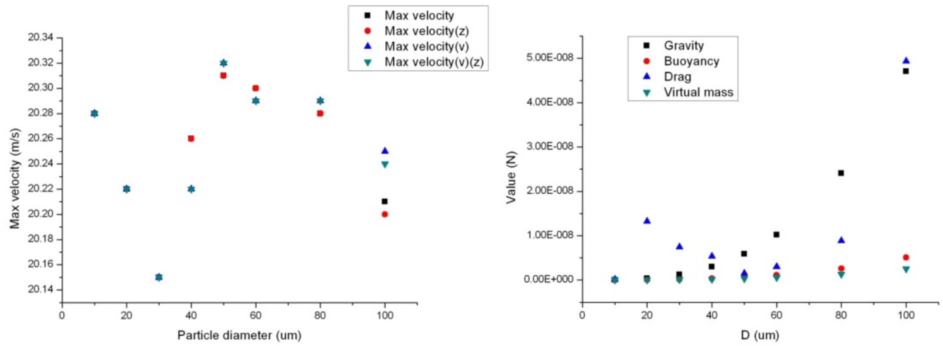

Figure 9 Maximum velocity (with virtual mass) and Force Comparison

The left picture in Figure 9 shows the maximum velocity of different sizes particles when virtual mass force is taken into consideration and its comparison with those when virtual mass force is not calculated. Even though the trend of maximum velocity is similar to each other, it still can be seen that when particle diameter is 40um, virtual mass seems to become significant on particle motion in this calculation. Virtual mass force is related to the volume of particle, so whether virtual mass force should be considered depends on the ratio of gravity and virtual mass.

The right picture in Figure 9 presents each force on different sizes of particles when virtual mass force is considered in this simulation. It can be seen that when particle diameter is below 40um, drag force is the leading force affecting particle motion. Other forces are much smaller than drag force. In this condition, drag force alone influences particle motion and other forces can be neglected. But when the particle diameter reaches 40um, gravity, virtual mass force and drag force is of the same order. Under this circumstance, virtual mass force cannot be neglected any more. However, when particle diameter continues to grow, gravity becomes significant and virtual mass force becomes negligible. To evaluate the role of every force, calculation is made as follow.

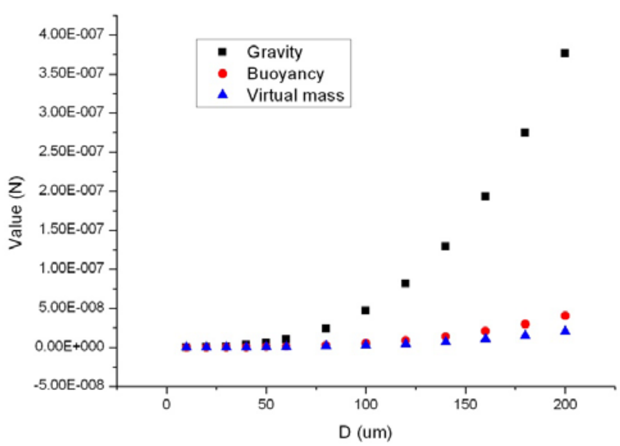

Figure 10 Forces on different sizes of particles

Figure 10 shows gravity, buoyancy and virtual mass force on different sizes of particles, respectively. (The calculation of drag force is not processed because drag force is related to the relative velocity of fluid and particle.) As the diameter increases, the gravity of particle increases exponentially, while buoyancy and virtual mass have little change. It can be obtained that with the growth of particle diameter, the effect of gravity is getting stronger. Even buoyancy and virtual mass force increase, they don't play an important role in particles motion. For small particles, virtual mass force is as important as gravity and buoyancy. In this simulation, the calculation that considers virtual mass force can present particle motion more accurately. That is to say in sudden contraction and sudden expansion structure, virtual mass force should be taken into consideration for small particles.

Conclusion

It can be concluded from the simulation that:

After sudden contraction and sudden expansion structure, fluid field becomes complex. Pressure suffers a sudden drop while speed reaches 40 times that of the inlet. There are both vortex and recirculation right above the expansion part.

Particles moving in the fluid are strongly affected by fluid motion. Small particles under a certain limit of diameter can move with the fluid. Some bigger particles will change its movement based on the portion of each force.

Gravity increases exponentially with diameters while buoyancy and virtual mass force only have a little change. However, for small particles, gravity, virtual mass force and drag force is of the same order. It turned out that for small particles, virtual mass force cannot be neglected.

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