Chapter 7

Conclusions

7.1 Summary

The process of a solid sphere normally colliding with a solid wall in an liquid environment is investigated through experiments and numerical simulations in the current study. The goal of this study is to develop an accurate and robust collision model that can be used in future simulations of liquid-solid flows.

Experiments of a sphere moving under gravity and colliding with a bottom wall in a mixture of glycerol and water are performed using an electronic-magnetic release system to drop a steel sphere from zero velocity without rotation. The fall and rebound of the sphere is recorded by a high speed videography system and the trajectory of the sphere is obtained from the video using an image process technique.

A higher frame rate for the recording camera is employed in the experiments so that sufficient position points are obtained especially when the sphere is about to collide with the wall. A velocity decrease prior to contact is observed by fitting the position points with a high order polynomial. This observation confirms that the velocity decrease prior to contact found in the pendulum-wall collision experiments performed by Joseph *et al.* (2001) also exits when a sphere falls under gravity to a wall. The existence of the wall influences the hydrodynamic forces that are exerted on the sphere; these forces exceed the gravitational force with diminishing gap between the sphere and the wall, which results in a deceleration on the sphere before it collides with the wall.

The effect of the viscous liquid on the motion of the particle during a collision process is further investigated by calculating the coefficient of restitution of the collisions. The coefficient of restitution, e, defined as the ratio of the rebound to impact velocity, provides a measure of the energy dissipated during a collision process. When presented as a function of impact Stokes number, St, the obtained coefficient of restitution shows a monotonic decrease as the Stokes number decreases, indicating an increase in dissipation of the particle kinetic energy with greater viscous effect. At a critical Stokes number, all the kinetic energy is dissipated and there is no rebound; correspondingly, the coefficient of restitution is zero. A dependence between e and St has been reported in the previous literature. The current experiments confirms the dependence by presenting more data for Stokes numbers ranging from 5 to 100 in which the coefficient of restitution changes remarkably with varying Stokes numbers.

The complexity of the flow field around the sphere affects the nature of the rebound. An accurate description of the evolution of the surrounding flow field facilitates the understanding of an immersed particle collision process.

A fast immersed boundary projection method is modified and applied in cylindrical coordinates to solve the incompressible Navier-Stokes equations for an axisymmetric flow. The hydrodynamic force exerted on a sphere moving in the liquid can be calculated from the simulation. After coupling with the equation of motion of the sphere, both the evolution of the flow field and the sphere dynamics can be simulated accurately and with high efficiency.

A contact model is proposed to simulate the normal collision between a solid sphere and a wall in a liquid environment. Based on the analytical formulas reported in the literature that evaluate the effect of the presence of the wall on the Stokes drag force, the added mass and the history force, the contact model computes the hydrodynamic forces on the particle when it is too close to the wall as an amendment for the hydrodynamic force calculated from the simulation. The model also includes an elastic force to account for the elastic deformation of the solids, which stores some of the impact energy of the particle and allows the particle to rebound. By including this contact model, the process of a particle settling and rebounding from a wall in a viscous liquid is simulated. The calculated rebound motion is examined with the measured trajectory from the current experiments; this comparison is used to calibrate an important dimensionless parameter, δ_{ss}, for the contact model.

The numerical simulation captures the trajectory of the sphere with multiple bounces and facilitates the calculation of the vorticity dynamics associated with the particle moving downwards and upwards, which has not been investigated in prior studies. Moreover, the velocity decrease before contact, observed in the experiments, is reproduced in the simulation. The hydrodynamic forces on the sphere calculated from the contact model increases dramatically with diminishing gap between the sphere and the wall. The sphere starts to decelerate as the result of the presence of the wall before it collides with the wall.

When applied to a wider range of impact Stokes number, the coefficient of restitution calculated from the simulation increases as a function of the Stokes number, and shows good agreement with the experimental results found both in the current experiments and by other researchers. Thus, it is concluded that the contact model appropriately incorporates the different material properties including the solid elasticity, the liquid viscosity and the density ratio so that the simulation truly describes the normal immersed collision between a particle and a wall with different particle impact Stokes number as long as the surrounding flow field remains axisymmetric.

A head-on particle-particle collision happening in a liquid environment is simulated by employing a modified contact model. The geometry and movability of the target sphere are taken into account in the contact model by (i) replacing the gap between the impact sphere and a wall non-dimensionalized with the diameter of the sphere by the gap between the impact and target spheres non-dimensionalized with the reduced diameter of the two spheres; (ii) using the relative velocity between the two sphere instead of the velocity of the impact sphere; (iii) using a larger value of δ_{ss} as calibrated with the experimental results.

The numerical simulations of a particle-particle collision produce the unique behaviors of the two colliding spheres including the pre-contact target motion and after-contact group motion that were observed in other researchers' experiments. The effect of the surrounding liquid on these behaviors is investigated by using different values of the liquid viscosity in the simulations. It is found that a higher value of the viscosity keeps the impact sphere from contacting the target sphere and leads to a smaller group motion velocity as a result of viscous dissipation.

The effective coefficient of restitution of a particle-particle collision predicted by the simulations compares favorably with the results reported by other researchers. When correlated with the binary Stokes number, St_B, the effective coefficient of restitution shows a monotonic decrease with diminishing St_B that is analogous to the results of particle-wall collisions.

In summary, according to both the current experiments and the numerical simulations, the incompressible viscous liquid is found to play an important role in a collision process. In a particle-wall collision, the velocity of the impact sphere decreases as the result of the remarkably increasing hydrodynamic force as the sphere approaches the wall. In a particle-particle collision, the target sphere moves prior to contact as the result of the hydrodynamic force from the surrounding liquid so that the relative velocity between the two sphere decreases as the impact sphere approaches the target. When the liquid is very viscous, the two spheres finally move at identical velocity with a constant distance between them so that the relative velocity is zero and there is no contact between the two spheres. This group motion without contact is analogous to the case in which a sphere settling to a solid wall decelerates and rests on the wall. The liquid effect on a collision process is quantitatively investigated by correlating the coefficient of restitution with the impact Stokes number. Both the experimental and simulated results show a strong dependence of the coefficient of restitution on the Stokes number. A large liquid viscosity dissipates more kinetic energy of the colliding system and results in a lower rebound. The decrease of the coefficient of restitution is more pronounced for the Stokes numbers lower than 100. The similar trends found in the particle-wall and particle-particle collisions indicates that the contact mechanisms for the two kinds of collision are similar.

The good agreement between the simulated and experimental results demonstrates the proposed contact model reproduces the particle dynamic behaviors during a particle-wall collision process. It is concluded that the contact model appropriately incorporates the contact mechanism in a numerical simulation without solving the thin lubrication layer and the elastic deformation of the solid parts. Moreover, a modified contact model using reduced material properties, the relative velocity for the solid phase and a larger dimensionless parameter, δ_{ss}, reproduces the unique behaviors during inter-particle collision processes and the functional relation between the effective coefficient of restitution and the binary Stokes number. Thus, the proposed contact model can be generally applied to different collision processes after incorporating the geometry and movability effect of the target and calibrating the parameter δ_{ss}, which is considered as the additional part of an effective diameter for the impact sphere.

7.2 Future work

There are several directions for the further application of the numerical method and the proposed contact model.

The values adapted for the parameter, δ_{ss}, in the contact model for different kinds of collision are different. To find the dependence of δ_{ss} on the geometry and movability of the target by employing spheres with different sizes and densities could be enlightening for further revealing the contact mechanism for different immersed collisions processes.

The Navier-Stokes equations solved in the current numerical simulations include only the mass and momentum equations. The equation of energy conservation can be added in the system to account for the heat transfer problem related to a collision process. Using the simulation, the motion of the fluid could be input to the energy equation to investigate the effect of the impinging wake on the transport from a heated surface. Similarly the simulation could be used to investigate erosion caused by a particle impacting on erodible bed.

The current numerical simulation is limited to solve only an axisymmetric flow problem. A three-dimensional code could be developed to simulate oblique collision and impacts at higher Reynolds number. The contact model is expected to be able to describe the collisions with three dimensional flow effect. If it is the case, then a flow with more particles in the liquid can be simulated and the macroscopic properties, such as the effective viscosity, of the mixture can be obtained from the simulation.