PHASE TRANSFER IN A DROPLET-SOLID SPHERE COLLISION

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Abstract - Heat and mass transfer of evaporation by collisions between droplets and solid particles can be significantly different under different conditions and could be affected by many factors, such as, the diameter ratio of solid and droplet, the hydrodynamic characteristics of the droplet, temperature difference between solids and droplet, the geometry curvature, the bridge effect of two or three balls and off-center condition. However, the reported studies on the droplet impacting onto the solid sphere are very limited. Thus a systemic research is very important and meaningful.

This study presents the effect of impact of a droplet upon the solid sphere under different conditions and compare the experimental results with modeling to see whether it can be validated. Both experimental methods and analytical modeling approaches have been included in this study.

1. INTRODUCTION

Heat and mass transfer of evaporation by collisions between droplets and solid particles can be significantly different under different conditions and could be affected by many factors, such as, the diameter ratio of solid and droplet, the hydrodynamic characteristics of the droplet, temperature difference between solids and droplet, the geometry curvature, the bridge effect of two or three balls and off-center condition. However, the reported studies on the droplet impacting onto the solid sphere are very limited. Thus a systemic research is very important and meaningful.

The hydrodynamics of a liquid droplet impinging on a hot surface have been extensively investigated using theoretical, numerical and experimental method. In the previous study, most experimental studies have been performed using high-speed camera, which showed the deformation process of liquid droplets impacting on a hot flat surface.

The boil heat transfer regimes could be divided into four basic regimes, i.e. free convection regime, nucleate boiling regime, transition boiling regime and film boiling regime. The characteristics of these regimes are detailed and established in Nukiyama's famous experiment in 1934.

Numerical efforts in the collision phenomena could be well addressed the fluid dynamics of the droplet impinging process. Numerical calculations with new simulation codes for two incompressible and non-viscous fluids including surface tension effects are compared with experimental results. The vapor cushion between the droplet and hot wall was simulated with special boundary conditions. Many researchers contributed on the isothermal droplet collision processes (Harlow and Shannon, 1967; Tsurutani et al. 1990; Hatta et al. 1993; Fukai et al. 1993; Hatta et al. 1995).

Recently, very little systemic research has been reported on the liquid attachment upon a collision of droplet and solids under different operational conditions such as center-to-center collision and off-center collisions, the bridge effect of multiple particles, the curvature effect of particles and heat and mass transfer of collision at temperature above Leidenfrost point.

Experimental approaches are conducted in this study to investigate the liquid attachment of a droplet colliding on a solid sphere and heat and mass transfer when there is a temperature difference during the collision. The effects of the droplet size, droplet velocity and the off-center condition on the outcome of the collision are analyzed. Also, the geometry curvature and bridge effect of two and three balls are illustrated. Some analytical explanations are given.

2. EXPERIMENTAL APPROACHES

To investigate the effect of different key parameters, such as droplet velocity, droplet-solids size ratio, center-to-center distance and temperature difference between droplet and solid, on the liquid attachment, heat and mass transfer during droplet-solid collision, two sets of experimental system are established and a series of experiment conditions are investigated, which include center-to-center collision without heat transfer, center-to-center collision with heat transfer, small droplet on large solid (a liquid droplet impinging onto a hot copper wall surface), comparable size collision (a liquid droplet impacting onto a hot solid ball) , off-center collision without heat transfer, droplet impacting with two solid balls and droplet impacting with three solid balls.

2.1 Liquid attachment upon collision without heat transfer

The liquid attachment during a process of collision between droplet and solid without temperature difference is acquired by measuring the mass of droplet before and after collision as shown in Figure 1(a). A pipette with

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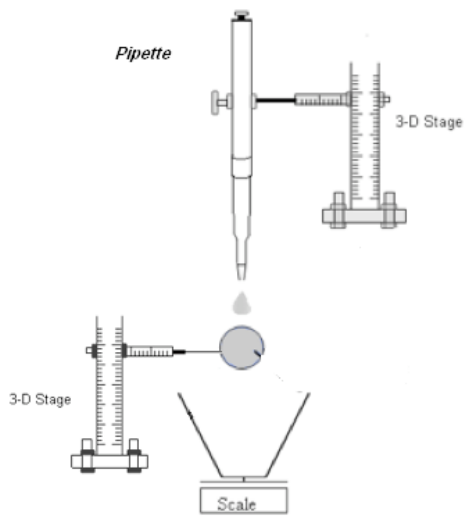
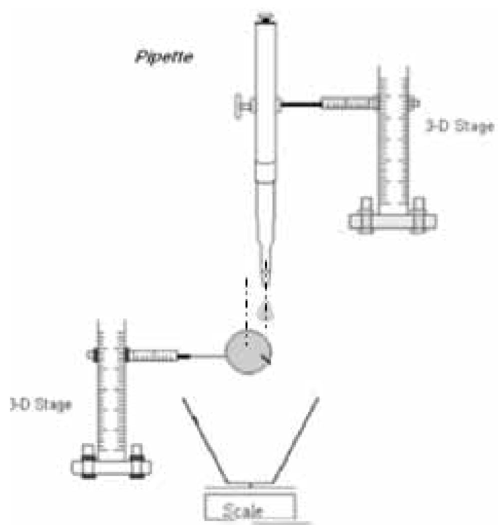
adjustable droplet size is adopted to create tiny droplet. The pipette and solid particles whose material is aluminum and with a diameter of 0.6mm are located vertically center-to-center with 3-D stages respectively. After dripping from pipette tip, the droplet is accelerated by forces of gravity and drag force from ambient air, and thus obtained a certain velocity before colliding with solid particle. The mass of droplet is calculated by the pipette-controlled droplet size and the mass after collision is measured by a Ohaus model E-400 scale under a plastic cup which is located under solid particle to collect droplet. The velocity of droplet upon collision was controlled by the adjusting the vertical distance between pipette tip and solid particle.

The pipette and solids then could be moved horizontally by adjusting the stages to make a off-center collision with a certain off-center distance to investigate the effect of off-center distance on the liquid attachment. The schematic diagram of off-center collision is shown in Figure 1(b).



(a) center-to-center collision



(b) off-center collision

Figure 1 schematic diagrams of collision without heat transfer.

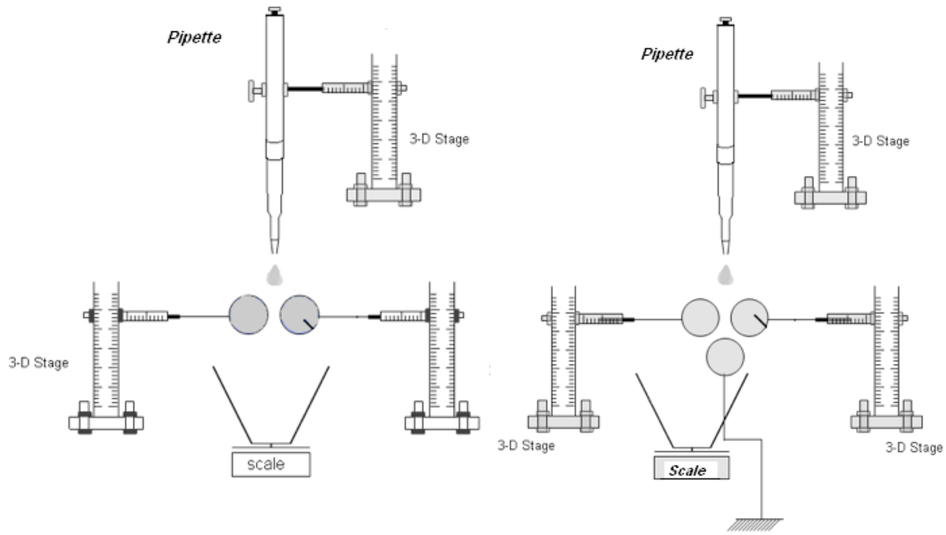
2.2 Bridge effect of droplet colliding with Multiple Solid Balls

The impact of the droplet on a solid sphere is quite different from that impinging on several solid spheres. To study the bridge effect of the droplet impinging on the solid surface, the collision of the water droplet is investigated in two or three balls. Schematic diagrams of the set-up are given in Figure 2(a) and 2(b) respectively. The system is very similar with collision with single solid except that more solids are located closely with each other by stages. The distances among solids could be adjusted to investigate bridge effect on liquid attachment under different conditions. Three different distances between two solid particles were investigated at different droplet velocities on two particles. Two different distances between three solid balls were studied at different droplet velocities on three particles. Similarly, the velocity was controlled by distance between pipette tip and particles.

2.3 Heat and mass transfer upon Center-to-center Collision with temperature difference

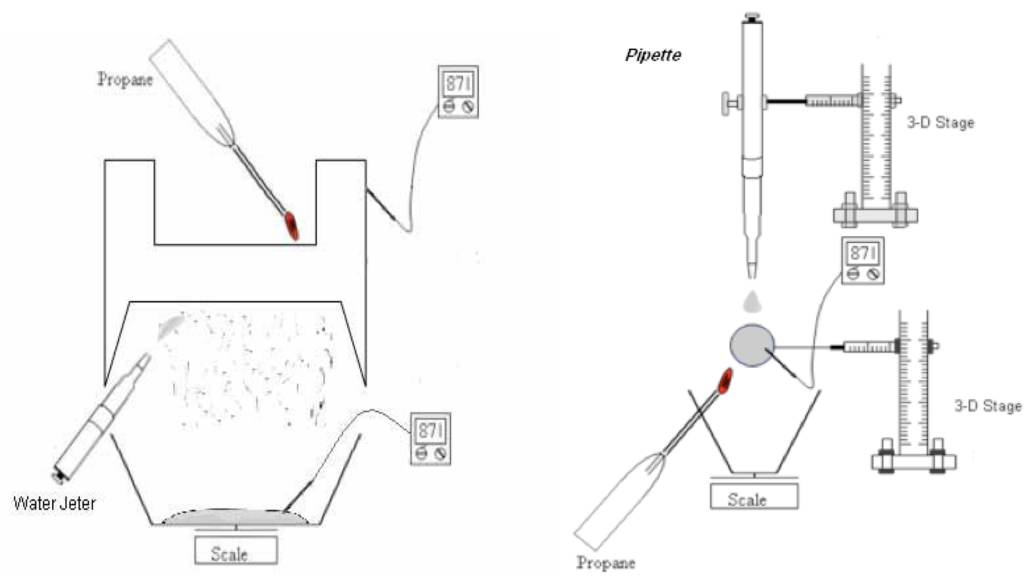
The heat and mass transfer during a collision between droplet and hot solid particle with large temperature difference is also investigated. Two sets of experiments are used according to the size ratio of droplet and solid. During a collision, when the particle size is much larger than droplet size, it could be treated as a droplet colliding on a plate surface. Thus, a system of hot droplet colliding on smooth inner surface of a big hot copper cylinder is designed (Figure 3 (a)). The copper cylinder could be heated up to a temperature of 500oc which is above Leidenfrost point of droplet with a propane flame. The tiny water droplet flow is injected with a pipette onto inner surface of cylinder with a velocity of 6 cm/s and is collected at bottom of cylinder with collection bins which is located at top of a scale to measure hot droplets after collision. The temperature of hot droplets and copper cylinder are measured with type K thermocouples.

The experiment of comparable size collision with heat transfer is measured by heating up the solid particles of experiment in section 2.1. The type K thermocouple is adopted to measure solid temperature before and after collision to calculate total heat transfer during collision. The schematic diagram is given in Figure 3(b).



(a) two particle collision (b) three particle collision

Figure 2 schematic diagram of bridge effect by multiple particles



(a) collision between small droplet and large particle (b) comparable size collision

Figure 3 schematic diagram of center-to-center collision with heat transfer.

3. RESULTS AND DISCUSSIONS

The experiments are conducted for the liquid attachment of droplet colliding with single particle center-to-center and off-center for different droplet size and velocity. The bridge effect of multiple particles on the liquid attachment is also studies with different particle-particle distance. The heat and mass transfer when a droplet collides with large particle and comparable size particle are also studied for different temperature difference between droplet and solid.

3.1 Liquid attachment of droplet colliding with solids without temperature difference

Firstly, the liquid attachment of center-to-center collision of droplet and particle is measured and analyzed. The off-center collision is then be investigated and compared with that of center-to-center collision. The liquid attachment of multiple particles is also compared with that of collision with single particle to investigate bridge effect.

3.1.1 Liquid attachment upon a center-to-center collision

When a droplet falls onto a solids particle center-to center, in general, it could be divided into three different conditions based on their sizes, i.e., small droplet on large solid, large droplet on small solid and comparable size collision. For a solid with certain size in a collision with droplet, there is a maximum attach-ability which should be about half volume of itself, if it is not trapped by the droplet. When the droplet size is over the maximum attach-ability of the solid, the amount of attachment would keep constant instead of increasing with the droplet size. While, when the droplet size is much less than the solid size, the droplet may completely attached to the solid until the size reach to a critical droplet size which is related to the Webber number of the droplet upon collision and could be solved by the mass and energy conservation of droplet deformation process during the collision. When droplet size is between critical size and maximum attach-ability of solids, the liquid attachment shall be proportional to the droplet size. The trend of liquid attachment on the droplet size is given in Figure 4.

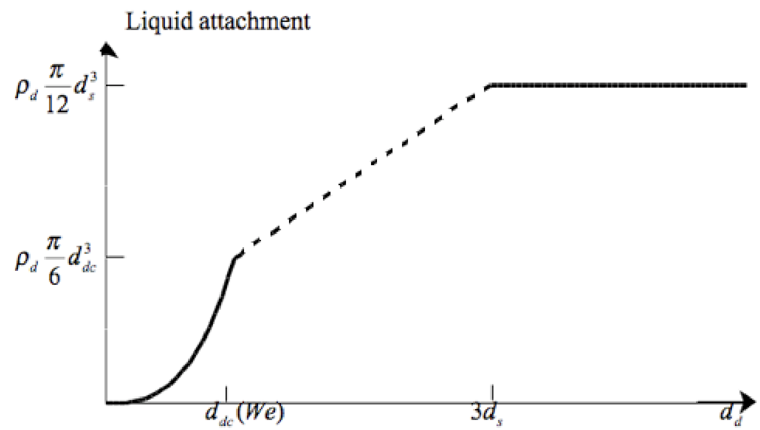


Figure 4 Liquid attachment v.s. droplet sizes

The experiment investigated the effect of Webber number of droplet upon collision on percentage of attached droplet mass with adjusting the impact velocity of droplet which is controlled by the height difference between pipette tip and solid particle. The droplet velocity is calculated by the momentum balance of droplet with effect of gravity and drag force of ambient air. Table 1 listed the velocities of droplets with two different sizes upon collision in the experiments.

The experimental results are showed in Figure 5. The attachment percentage at different impact velocities for two droplet sizes at the room temperature was studied. It is indicated that the variation trend of attachment percentage is similar for different droplet sizes when the impact velocity changes. As the impact velocity increases, the percentage of the attachment decreases. The theoretical results are shown in the figure with lines which are well matched with experimental data.

Table 1 Weber Number at Different Impacts Velocity and Droplet Sizes

Impact velocity (m/s) H (cm)	0.280 (0.4)	0.313 (0.5)	0.443 (1.0)	0.542 (1.5)	0.626 (2.0)	0.700 (2.5)
d_1 =0.284 (cm)	**3.1**	**3.9**	7.7	11.6	15.5	19.3
d_2 =0.337 (cm)	**3.7**	4.6	9.2	13.8	18.3	22.9

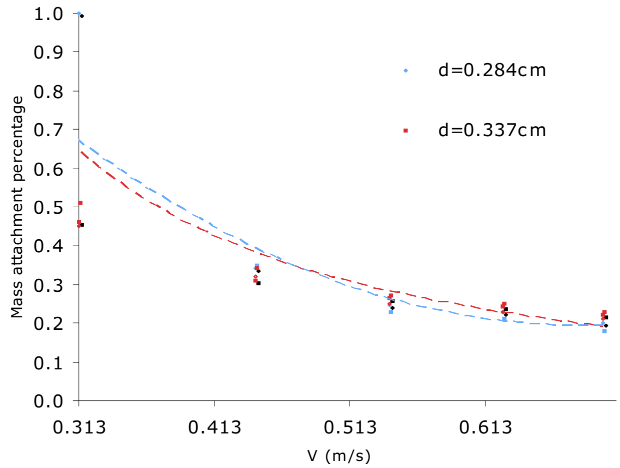


Figure 5 Liquid attachment percentage of center-to-center collision with a solid

4.1.2 Liquid attachment of off-Center Collision without Heat Transfer

When the droplet collide off-center with a solid, the attachment would be less than that under the center-to-center condition and its amount shall be dependent on the off-center distance (Δd). In the experiment, the attachment percentage at two different off-center distances (Δd_1 =2mm and Δd_2 =3mm) are measured and compared with that of center-to-center condition. Figure 6 shows a schematic diagram of relationship between liquid attachment and off-center distance.

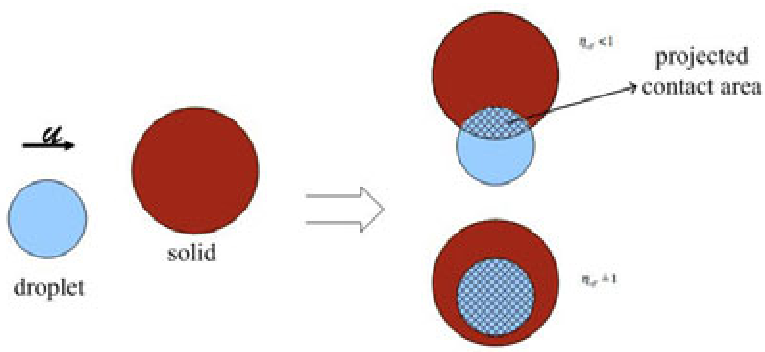


Figure 6 schematic diagram of off-center collision between droplet and solid

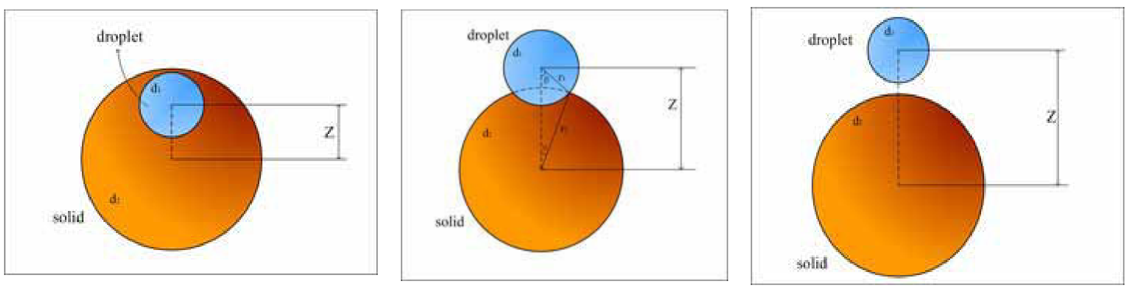
An off-center-collision efficiency could be defined to express the effect of off-center collision on liquid attachment, which is given by

$$\eta_{off} \equiv \frac{Liquid-attachment\,@\,off-center-collision}{Liquid-attachment\,@\,center-to-center-collision}$$

We could easily conclude that the off-center-collision is determined by offer-center distance of collision which could be estimated by the projected contacted area between droplet and solid during a collision, which is shown in Figure 7. Thus, the off-center-collision efficiency is obtained as:

$$
\begin{cases}
\text{if} \quad \dfrac{|d_1 - d_2|}{2} < Z < \dfrac{|d_1 + d_2|}{2}, & \eta_{off} < 1 \\
\text{if} \quad Z \le \dfrac{|d_1 - d_2|}{2}, & \eta_{off} = 1 \\
\text{if} \quad \dfrac{|d_1 + d_2|}{2} \le Z, & \eta_{off} = 0
\end{cases}
$$

Figure 8 listed the experimental results of liquid attachment percentage of different off-center distances. It can be seen that, the effect of the off-center to the balls for the droplet impacting process is significant. The attachment percentage drops much when the collision changes from center-to-center to off-center and the offer-center distance increases. It is also indicated when efficiency (η_{off}) is less than 1, the droplet couldn't be all attached in our experimental data range and the attachment of which is less than the center-to-center condition. Note that the lines in the figure are the theoretical results calculated by above analysis under same operational conditions with experiment, which are in good agreement with experimental results.



η_{off} =1 η_{off} <1 η_{off} =0

Figure 7 off-center efficiency under different offer-center

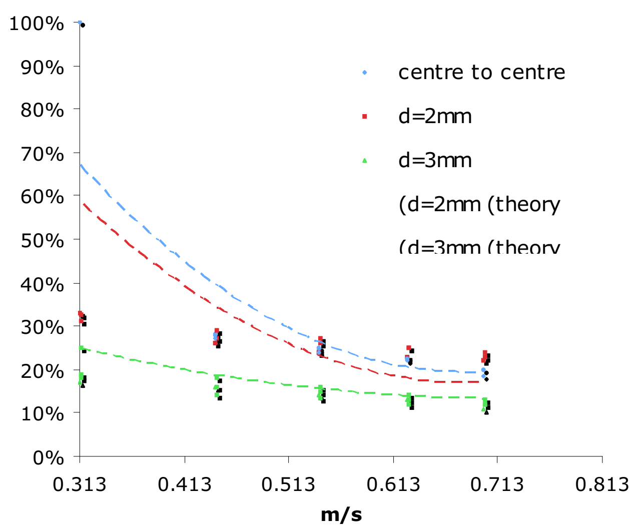


Figure 8 effect of off-center for attachment percentage

4.1.3 Bridge Effect of multiple solids during collision

When there are more than one solids located closely and the droplet collide with them simultaneously, more liquid tends to be held and stay on and between solids due to bridge effect of multiple solids. The amount would vary according to the amount of solids and the distances among the solids. In this study, the attachment percentage at three different distances under the configurations of two solid balls and three balls are measured. The results are compared with liquid attachment of single solid which is shown in Figure 9. It can be seen that, the bridge effect has a significant effect on the attachment percentage. When the solid number changes from one to two, the liquid attachment is nearly doubled and increases further when there are three solids.

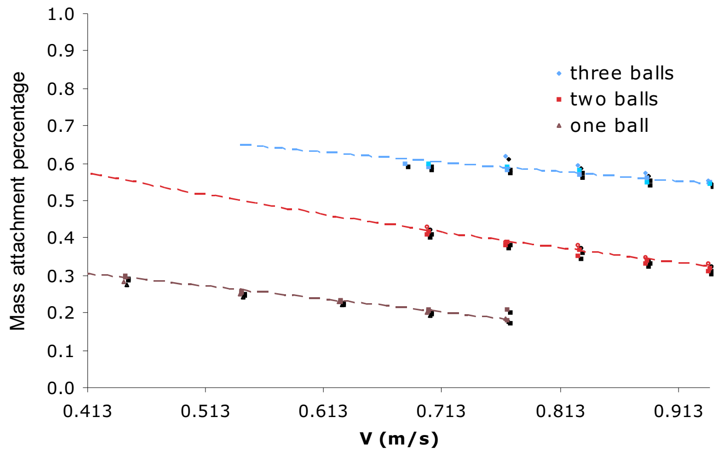


Figure 9 Bridge effect on liquid attachment

The liquid attachments under different distances among solids with two balls and three balls are shown in Figure 10 and 11 respectively. We could easily draw a conclusion that under both conditions, when the distance between solid balls increases, the percentage of the attachment decreases.

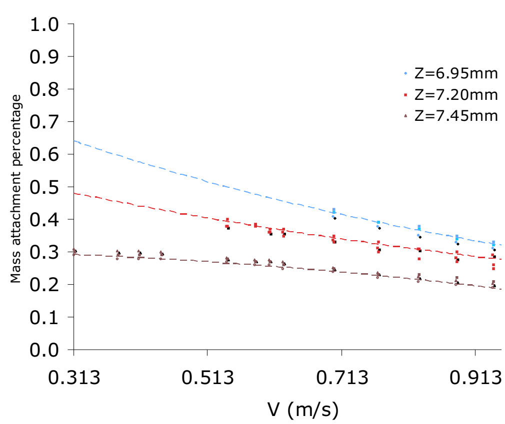


Figure 10 liquid attachment with different distance between two balls

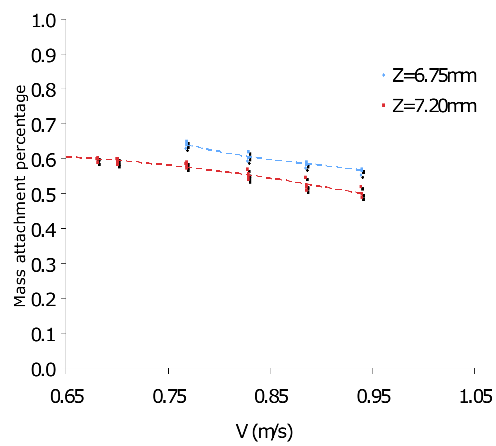


Figure 11 liquid attachment with different distance among three balls

4.2 Heat and mass transfer upon collision with temperature difference

When droplet collides with a hot solid, there is intensive heat transfer between droplet and solid. Part of heat transferred to the droplet is then conducted to the inner side of droplet and used to heat up the droplet. The other part of heat is rapidly absorbed by the surface of the droplet and is used to evaporate a portion of liquid on the droplet surface. Here, we define the percentage of heat used for evaporation as f=Qe/Q and percentage of evaporated droplet mass as fm=me/m. Two different experiments are conducted to measure heat and mass transfer upon collision with temperature difference when small droplet colliding on large solid and comparable size collision.

4.2.1 Small Droplet on Large Solid

In this section, the evaporation process of a liquid droplet impinging onto inner surface of a hot copper cylinder has been investigated and the evaporation amount at various surface temperatures was measured. Each value has been obtained as an average of 5 experimental results, under the same operative conditions.

Figure 12 gives the mass and energy evaporation percentage at different temperatures. From the figure, it could be easily found that at the lower temperature, the total heat transfer during collision is very high and gets to a peak value when temperature reaches to about 175oc. As the temperature increases further until the temperature reaches to Leidenfrost point, the rate of heat transfer decreases because of the transition boiling regime. In this regime, the direct contact between the liquid and the surface is decreasing due to the vapor, which has a lower thermal conductivity than of liquid, accumulated on the droplet surface.

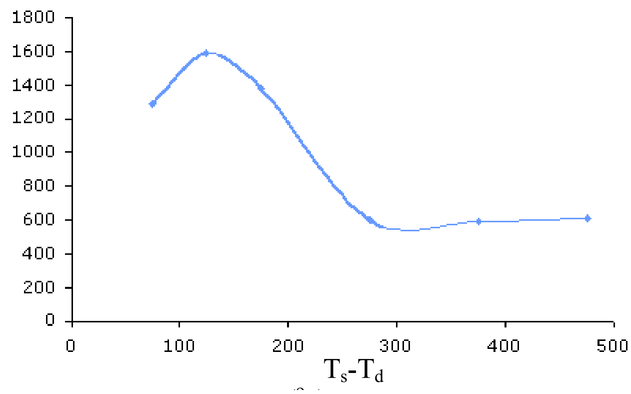


Figure 12 Total heat transfer during collision

Figure 13 shows the change of heat percentage for evaporation and evaporated mass percentage with temperature difference change. It seems that there have similar tendency with that of total heat transfer. When total heat transfer is higher, more heat percentage is used for evaporation. When heat transfer is lower, more heat tends to be conducted into inside of droplet for heating up.

4.2.2 Comparable Size Collision

The experimental results of heat and mass transfer upon comparable size collision is shown in Figure 14. From the figure, it could be easily found that at the lower temperature, the percentage of the evaporation mass is increasing and gets to a peak value when solid partice temperature increases to a value about 175oc. This could be explained as the heat transfer is in the nucleate boiling regime, the heat transfer rate tends to increase with temperature increases. As the temperature increases further, the heat transfer changes into transition boiling regime and the rate tends to decrease until the temperature reaches to Leidenfrost point.

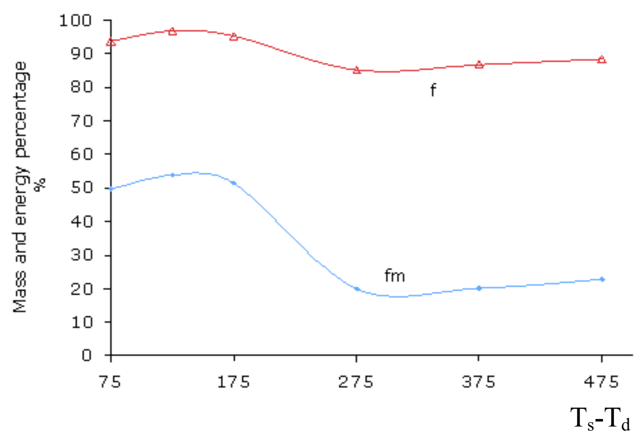


Figure 13 Evaporated mass and heat percentage for evaporation at different temperature

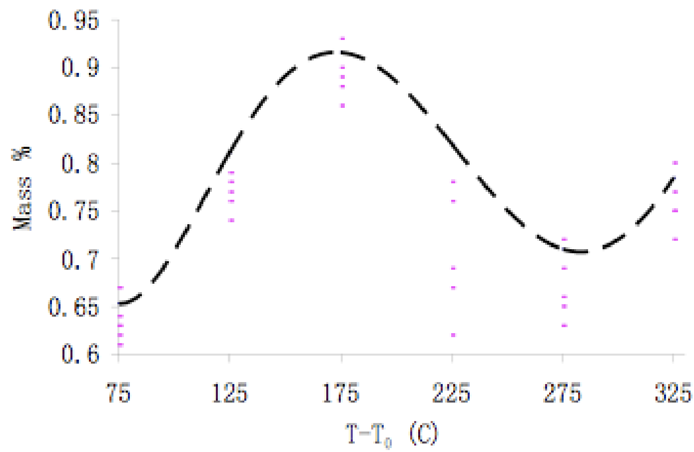


Figure 14 The percentage of evaporation mass at different temperatures.

4. Conclusion

A series of experimental systems are set up and a lots of experiments are conducted to investigate the heat and mass transfer process of droplet-solid collision under different conditions. The droplet velocity, size ratio between the droplet and solid, temperature difference on the heat and mass transfer during droplet-solid center-to-center collision, distance between multiple particles are changed to make parametric studies on the effects of these factors.

When the droplet collides velocity increases, the percentage of liquid attachment decreases. The off-center collision always has less liquid attachment compared with that of center-to-center collision and is proportional to projected contact area of collision. The bridge effect of multiple particles tends to increase liquid attachment during collision and decreases with increasing particle-particle distance.

The heat transfer and evaporated mass percentage changes when temperature difference between droplet and solid particle changes. Two different regimes were investigated by varying the tested surface temperature, a bubble boiling regime, for solid temperature larger than saturation temperature and lower than Leidenfrost temperature, a film boiling regime, for solid temperature larger than Leidenfrost temperature. A highest heat transfer rate is obtained at about 175oc and at the Leidenfrost temperature which is about 275oc, a lowest heat transfer rate is reached.