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ABSTRACT

PHASE TRANSFER
IN A COLLISION BETWEEN A DROPLET AND SOLID SPHERES

By
Zheng Shen

The hydrodynamics of a liquid droplet impinging on a particle is of direct relevance to many engineering applications. The mechanism of heat and mass transfer during the droplet solid collision is essential to the design and operation of many industrial systems. However, very limited systemic research is available to describe the droplet impact on hot solid spheres.

This paper aims to establish a systematic investigation of phase transfer due to the droplet-solid impact, by both experimental and modeling approaches. The targeted phase transfer includes the surface attachment, mass of vaporization, heat transfer to droplet and its partition between vaporization and droplet heat-up. Specific experiments were designed and performed to partially validate the model predictions on the droplet-solid phase transfer. A simple mechanistic model is proposed for the parametric study of droplet and solid sphere collision. Effects of the droplet size, velocity and the off-centre condition on the outcome of the collision are analyzed. In addition, the geometric effect, bridge effect of two and three balls and the effect of collision on heat transfer among droplet and solid sphere are also illustrated. The theoretical results agree reasonably with the experimental measurements.
PHASE TRANSFER
IN A COLLISION BETWEEN A DROPLET AND SOLID SPHERES

by
Zheng Shen

A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Mechanical Engineering

Department of Mechanical Engineering

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APPROVAL PAGE

PHASE TRANSFER
IN A COLLISION BETWEEN A DROPLET AND SOLID SPHERES

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Dedicated to the people I love and love me

Grandfather (沈薇)：我永远都是您眼里那个聪明伶俐，也长不大的小捣蛋。您也
永远是我最尊敬和爱戴的老人。

Father （郑晓洁）：恬然，豁达，无欲无求。言语不多的父亲却是我性格的塑造
者。我感谢您！

Mother （沈红）：我知道，您永远是那个为我牵挂，为我在被窝里默默掉泪的母亲。
我也知道，家永远都是那个家，我转身的时候，您就会在。

Boyfriend （叶睿智）：Until you’ve walked a mile in my shoes, just behind U.

路遥远，我们一起走。
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NOMENCLATURE

d \quad \text{Diameter (or distance function)}

E \quad \text{Energy}

f \quad \text{Ratio of } \frac{Q_r}{Q}, \text{ dimensionless, } f = \frac{Q_r}{Q}

f_m \quad \text{Ratio of } M_e \text{ to } M, \text{ dimensionless, } f_m = \frac{M_e}{M}

F \quad \text{Force}

l \quad \text{Maximum deformation}

L \quad \text{Latent heat}

M \quad \text{Momentum}

M_e \quad \text{Evaporation mass of liquid droplet}

p \quad \text{Pressure}

Q_r \quad \text{Heat change by the liquid droplet}

Q_h \quad \text{Heat change by the solid sphere}

R \quad \text{Radius}

Re \quad \text{Reynolds number}

S \quad \text{Area}

T \quad \text{Temperature}

t \quad \text{Time}

U \quad \text{Particle velocity}

u \quad \text{Velocity of droplet}

V \quad \text{Velocity (or Volume)}

We \quad \text{Weber number}

Z \quad \text{The distance between multiply solid balls}

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<td>$\mu$</td>
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<td>$\rho$</td>
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<td>$\sigma$</td>
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<td>$\eta$</td>
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1.1 Objective

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 objective of this thesis is to present the investigation of heat and mass transfer process during a droplet impacting on a solid sphere under different conditions. Both experimental methods and analytical modeling approaches have been included in this study. The experimental results are used to be compared with the model predictions to validate the model.

1.2 Backgrounds and Literature Survey

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 a high-speed camera, which showed the deformation process of liquid droplets impacting on a hot flat surface.

Nukiyama’s famous experiment in 1934 established the pool boiling curve. The entire boiling heat transfer curve is shown as Figure 1.1. He was the first who
experimentally identified different regimes of pool boiling and realized the boiling curve.

**Figure 1.1** The typical pool boiling curve [18].

**Figure 1.2** The typical boil heat transfer regimes [18].
The boil heat transfer regimes are better explained in Figure 1.2, which shows the four basic regimes, each described as follows:

1) Free convection regime: as water is not directly exposed to the atmosphere, it remains liquid even when it superheats above $T_s$ by as much as a few degrees. During this process, the heat transfer is constantly convection as hotter water rises and cooler water descends. There is no boiling (free convection up to point A).

2) Nucleate boiling regime between A and C: The first bubble forms at a nucleation site (point A). The production of vapor bubbles and columns is called nucleate boiling because of the formation and growth of the bubbles depending on crevices serving as nucleating sites. Maximum heat transfer coefficient occurs at point H between B and C. In this regime, when the temperature increases, the rate at which energy is transferred as heat to the water increases. Point C is the critical point (maximum heat flux).

3) Transition boiling regime between C and L: In this regime, when the temperature increases, the rate at which energy is transferred as heat to the water is reduced. In the transition regime, bubble columns become more and more crowded and a layer of vapor covers much of the surface. Since water vapor conducts energy more poorly than does liquid water, the transfer of energy to the water is diminished. The higher temperature, the less direct contact the water has with it and the worse the transfer of energy becomes. Point L is the leidenfrost point, where heat flux reaches minimum.

4) Film boiling regime is above the point L, where energy is slowly transferred to the liquid above the vapor by radiation and gradual conduction. As the temperature
increase, radiation across the vapor film to the liquid enhances the flux rate.

Wachters and Westerling (1966) studied the deformation process of a water droplet of 2.3 mm in diameter impacting on a gold surface heated to above the Leidenfrost temperature. They found that the dynamics of water droplets were much relevant to the droplet Weber number \( W_e = \frac{Dv^2 l}{\sigma} \). In \( W_e \leq 30 \) regime, depending upon the surface tension, the droplet rebounded off the heated surface without smash. In \( 30 < W_e < 80 \) regime, the droplet experienced similarly as the lower Weber number case \( (W_e \leq 30) \). In the rebounding process, the droplet split into a number of secondary droplets. On the occasion of \( W_e \geq 80 \) regime, upon impact, the splashing occurred because of the large kinetic energy, while the droplet broke into several small droplets. The previous studies also showed that the critical Weber number was spreading in the range of 50-90 in term of the experimental conditions, no matter the droplet broke up or not on the hot surface (Bolle and Moureau, 1976; Ueda, 1979; Akao et al. 1980; Hatta et al. 1995).

Chandra and Avedisian (1991) used flashing photography to measure the time of a subcooled n-heptane droplet impacting a stainless steel surface in the temperature range from room temperature to above the Leidenfrost temperature. They found that, within the temperature range of their experiments, all the impact characteristics were highly temperature interrelated. Also, within the experimental temperature range from \( 63^\circ C \) to \( 605^\circ C \), Xiong and Yuen (1991) measured the time history of a heptane droplet impacting on a stainless steel surface. Anders et al. (1993) studied the rebounding dynamics of ethanol droplets impinging on an oblique chromium-plated copper surface at \( 500^\circ C \).
The impact process of a 3.8 mm water droplet contacting on superheated surfaces experimentally investigated by Chen and Hsu (1995). They found that, the heat flux of the solid surface could reach to $10^7 \text{ W/m}^2$ at the initial phase of the droplet impact with a subcooling of 80°C. Also, the time duration of this high heat flux became significantly shorter, while the surface temperature rose from 150°C to 400°C.

Hatta et al. (1997) studied the collision phenomena of water droplets in size of 300-700 $\mu\text{m}$ in diameter impacting on a hot rough surface heated to 500°C. They found that, at low $W_e$ number, when the surface temperature was above the Leidenfrost temperature, the properties of water droplets were almost independent to the surface materials. But the kinetics of the surface did affect the droplet at higher $W_e$. With increasing Weber number, the irregularity was more remarkable in the later state and finally the droplet broke up. Also, comparing with the smooth surface case, on the rough surface, the critical Weber number became smaller to specify whether or not droplet is disintegrated.

Using static and high-speed photographic techniques, Bernardin et al. (1997) investigated the impinge phenomena of water droplets on a hot aluminum surface with temperature ranging from 100 to 280°C and Weber number of 20, 60, and 220. They found that neither the droplet velocity nor the impact frequency was much relevant to the temperature corresponding to the critical heat flux and the Leidenfrost point.

Wang et al. (2000) found that, the critical temperature of dry impact, which had no direct liquid-solid-contact during the impact, was much lower that the Leidenfrost temperature. Also, extensive studies of single droplet evaporation on a hot solid surface are found in the literature (Pedersen, 1970; Shoji et al. 1984; Inada et al. 1985; Makino
and Michiyoshi, 1987; Naber and Farrell, 1993; Wang, 1997). Karl and Frohn (2000) simulated the interactional process of small liquid droplets (100-200 μm) with hot walls in the Leidenfrost regime. They also investigated the lost momentum of the droplets, the droplet deformation, and the oncoming of droplet disintegration. A 180° contact angle and a free-slip boundary condition were applied on the solid surface.

The droplet residence time and the droplet deformation areas time are crucial to model the hydrokinetic and heat transfer behavior of the droplets. The droplet residence time is defined as the time lapsed between the droplet attaining of and detaching from the surface. Much information has been reported on this area. Wachters and Westerling (1966) used the first order period of a freely oscillational droplet to describe the residence time. Bolle and Moureau (1976) presented a theoretical model, which showed the droplet spreading film radius was interrelated to the contact time on two orders. Akao et al. (1980) and Senda et al. (1988) studied a film boiling regime relation to the residence time of the droplet. Also, Makino and Michiyoshi (1984) presented the contact period and deformation areas of water droplets. They found that the droplet spread out into a thin film before boiling for low velocity water droplets (0.3 m/s) with a diameter of 2.54 - 4.50 mm and the surface temperature ranged from 150 to 360°C. Also, they presented that the deformation area headed a linear relation to the contact time. Lee et al. (1985) studied that the duration of liquid contacts in transition boiling regime was of the order of 10 to 100 ms. Senda et al. (1988) found that the residence time for water droplets impacting on a heated surface (150°C ≤ T_w ≤ 400°C) was about half of the first-order period of a freely oscillational droplet.

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 nonviscous 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;
numerically in a low Weber number range, the deformation and rebounding processes of
a water droplet on a hot surface above the Leidenfrost temperature. They found that the
rebounding of droplet occurred owing to the surface tension effect and the numerical
results were found to be almost in good agreement with the experimental data. However,
it was impossible to analyze the droplet deformation process for higher Weber number
cases using numerical method because of the droplet breaking up on the surface during
the deformation. Karl, et al. (1996) studied numerically the interaction of the liquid
droplets and a hot wall, whose temperature was well above the Leidenfrost temperature.

Recently, very little systemic research has been reported on droplets impinging on
hot surfaces with finite dimensions, especially the size comparable to the droplet. Some
relevant work in this area was performed by Yao et al. (1988). They studied the behavior
of droplets impinging on thin rectangular strips, which were heated above the Leidenfrost
temperature. Also, they investigated that a combination of splashing and cutting were
showed when the droplet diameter and the strip thickness were comparable. Liu et al.
(1994) examined numerically the spreading behavior and consolidation of molted
droplets hitting on a waved target surface. Also, they showed that the droplet spread out
laterally and maintained a relatively good adhesive contact with the waved surface, when
the droplet impacted on a waved surface. Based on these studies, it could be expected that
the geometry and size of the impacted surface would play a significant role in the droplet
impinging phenomena.

1.3 Approaches

Both experimental methods and modeling approaches are included in this paper to
illustrate a work on the investigation of impact of a droplet on the solid sphere. 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.

Chapter 2 provides the background of the experimental studies on the droplet–
solid collision process. Some sets of experimental system are established and a series of
experiments are conducted. Each experiment is described and discussed in details in
Chapter 2.

In Chapter 3, the heat and mass transfer of droplet-solid collision are analyzed
under different conditions. A simple mechanistic model has been proposed for the
parametric study of droplet and solid sphere collision, which could be validated by
experimental results in Chapter 2.

In Chapter 4, the measured results from the experimental systems, which are
described in Chapter 2, are used to be compared with results coming from the models
described in Chapter 3. Some parametric are performed and discussed.

Finally, a summarized conclusion is given in Chapter 5. Based on the results and
progress of our experimental and modeling study, expectations for future research on
droplet-solid collision focusing on developing an analytical model are also discussed.
CHAPTER 2
EXPERIMENTAL METHODOLOGY

2.1 Introduction

To provide data base for modeling and parametric study, such as droplet velocity, size ratio between the droplet and solid, temperature difference on the heat and mass transfer during droplet-solid center-to-center collision, some sets of experimental system are established and a series of experiments are conducted. The experiments include:

- Center-to-center collision without heat transfer
- Center-to-center collision with heat transfer
- Off-center collision without heat transfer
- Droplet impacting with two solid balls
- Droplet impacting with three solid balls

They are described and discussed in details in each of the following sections.

2.2 Experiment Systems and Procedure

Two sets of experimental systems are set up for different types of droplet-solid collision. The first system is used for the experiments of droplet-solid sphere collision, whose major parts include high precision scale, 3-D stage, pipette, multimeter, type K thermocouple and type K thermocouple adaptor and the flame from a propane combustor is adopted to provide the heat source for the heat transfer experiments. The second system is designed for the investigation of small droplet impinging on the very large solid particle with intensive heat transfer. The major parts include scale, multimeter, propane,
self-designed copper cylinder, container and injector. In the experiments for droplet-solid sphere collision, the collected water was weighed per ten dipping. As the droplet size (12μl) was fixed, it is easier to get the relatively precise mass percentage of collected water, from which the attachment is also obtained.

2.2.1 Collision of a Droplet and a Solid without Heat Transfer

A schematic diagram of the experimental system of center-to-center collision without heat transfer is shown in Figure 2.1 (a), and that of off-center collision without heat transfer is shown in Figure 2.1 (b) and the photograph of the experimental system is shown in Figure 2.1 (c).

Figure 2.1 (a) The schematic diagram of center-to-center collision.
In the experiments of center-to-center and off-center collision without heat transfer, the ambient pressure (0.101 MPa), solid surface material (aluminium), solid
diameter (about 0.6 mm) and initial droplet size (12$\mu l$) were maintained to be constant throughout the experiments. The values of the weight of the container are recorded with the Ohaus model E-400 balance before and after the droplet impinging on the solids. The difference of these two values gives the fluid mass, which is not attached to the solids particle. Based on this, we then could determine the percentage of mass of droplet attached to the sphere. The special designed pipette could provide droplets with a fixed size. With adjusting the height of the pipette, the velocity of the droplet when impinging on the solid sphere is controlled. The detailed calculation of velocity from the height will be discussed in Chapter 4.

2.2.2 Center-to-center Collision with Heat Transfer

The two different experiments were conducted to examine the effects of small droplet on large solid and comparable size collision in center-to-center collision with heat transfer. Liquid droplets impacting onto a hot solid ball and a hot copper wall surface were investigated.

In order to investigate the heat and mass transfer of a small droplet impacting on a very large solid particle, which may be totally different from those of comparable-sized collision, the limiting case droplet impacting on the solid wall was studied. A series of experiments were performed at the hot copper surface temperature ranging from 150-500°C, which theoretically covers nucleate boiling regime, transition boiling regime and film boiling regime. The surface temperature was allowed, to reach a steady state before any measurements were started. When the desired temperature had been obtained, water was injected onto this heated copper cylinder interior surface.
A schematic diagram of the experimental system of a droplet impinging onto a hot copper surface is shown in Figure 2.2 (a) and the photograph of the experimental system is shown in Figure 2.2 (b). A multimeter shows the needed temperature of the copper cylinder (the tested surface) while a heating unit feeds heat to the copper cylinder. The surface was polished until the sheath of the thermocouple is almost bared. Water was injected at the velocity of 6cm/s onto this heated copper cylinder interior surface and a plastics cup is used to collect water. The water initially is at room temperature 25°C. A gravimeter measurement is used to measure the changes of weight in the system.
In this experiment, the water initially is at room temperature 25°C and the tested surface temperature ranging from 150-500°C, which theoretically covers nucleate boiling regime, transition boiling regime and film boiling regime. The average droplet diameter is about 1mm. The jet velocity of the water is about 6 m/s.

A schematic diagram of the experimental system of center-to-center collision with heat transfer is shown in Figure 2.3 (a) and the photograph of the experimental system is shown in Figure 2.3 (b).
Figure 2.3 (a) The schematic diagram of center-to-center collision with heat transfer.

Omega 10 channel Monogram Thermocouple Reader w/type T thermocouple adaptor was used to measure the temperature of the droplet. The type T thermocouple is adopted here, whose measuring range is from -200°C to +300°C. The BK-2703Multimeter has been modified with a type K thermocouple adaptor, whose measuring range is from -200°C to +850°C, to provide readings in two different units: degrees Celsius, or degrees Fahrenheit. As type K thermocouple is not as accurate as the Type T, it is used in high temperature, which is beyond the type T measure range. The Omega Type K thermocouple is used to attach to the aluminum sphere in order to determine its temperature.
In this experiment, the hot solid ball temperature ranging from 100-350°C, which theoretically covers all four regimes (free convection regime, nucleate boiling regime, transition boiling regime and film boiling regime).

### 2.2.3 Droplet Impacting with Multiple Solid Balls

The impact of the droplet on several solid spheres is quite different from that impinging on a solid sphere. 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.

A schematic diagram of the experimental system of the impact of a single droplet on two balls is shown in Figure 2.4 (a) and on three balls is shown in Figure 2.4 (b). The photograph of the experimental system is shown in Figure 2.4 (c). Three different distances between two solid balls were investigated at different impact velocities on two balls. Two different distances between three solid balls was studied at different impact velocities on three balls.
Figure 2.4 (a) The schematic diagram of the impact of a single droplet on two balls.

Figure 2.4 (b) The schematic diagram of the impact of a single droplet on three balls.
Figure 2.4 (c) The experimental system of the impact of a single droplet on multiply balls.
CHAPTER 3
ANALYSIS AND MODELING

To investigate the heat and mass transfer of droplet-solid collision under different conditions such as different droplet velocities, different size ratios between the droplet and solid, different collision mode (center-to-center or off-center), different temperature condition (with or without heat transfer), bridge effect, different kinds of models are developed. They could be validated by experimental results in Chapter 2 and be used to make parametric studies on the effects of different characteristics of collisions. In all of these models, the droplet is assumed to be spherical before the collision and the liquid is assumed to be incompressible. There are no droplet break-up upon collision and no vaporization effect on droplet movements.

3.1 Center-to-Center Collision Model without Heat Transfer
When a droplet falls onto a ball, in general, three different size ratios between droplet and solids are possible: small droplet on large solid, large droplet on small solid and comparable size collision. The dominant factors would be different under different size conditions. The heat and mass transfer process would also be significantly different. In this study, they have been depicted separately. Some basic assumptions are given: the droplet is assumed to be spherical before the collision and the liquid is assumed to be incompressible. There are no droplet break-up upon collision and no vaporization effect on droplet movements.
3.1.1 Small Droplet on Large Solid

When a small droplet impacts on the large solid surface, due to the incompressibility of the droplet, the total volume of droplet is approximately conserved. The maximum deformation (critical size of droplet) should be the diameter of the solid ($d_s$).

The impacting of small droplet on the large solid surface is showed in Figure 3.1

![Figure 3.1 The impacting of small droplet on the large solid surface.](image)

The mass conservation is expressed by

$$V_d = \frac{\pi}{6} d_d^3 = \frac{1}{2} \cdot \frac{\pi}{2} d_s^2$$  \hspace{1cm} (3.1)

The total energy of the system includes the surface energy and the kinetic energy. The whole system energy conservation is built by

$$E_T = E_s + E_k = \frac{1}{2} \cdot \rho_d \cdot \frac{\pi}{6} d_d^3 \cdot U^2 + \pi d_s^2 \cdot \sigma = [2 \cdot (\frac{\pi}{2} d_s^2) + \pi d_s \cdot l] \cdot \sigma = E_{\sigma_{\text{max}}}, \hspace{1cm} (3.2)$$

From (1) and (2), the following non-dimensional 3rd-order equation is obtained,

$$\frac{W}{12} \left( \frac{1}{3} \right) x^3 + x^2 - 1 = 0 \hspace{1cm} (3.3)$$

Where

$$x = \frac{d_d}{d_s} \hspace{1cm} (3.4)$$

$$W_e = \frac{\rho_d \cdot U^2 \cdot d_s}{\sigma} \hspace{1cm} (3.5)$$

The positive real root of the equation (3.5) provides the solution for the modeling.
Let \[ y = ax^3 + x^2 - 1 \] (3.6)

Where \[ a = \frac{W_e}{12} - \frac{1}{3} \] (3.7)

As \( W_e > 0 \), \[ a > -\frac{1}{3} \] (3.8)

It can be easily obtained, \( y(0) = -1 \) (3.9)

\[ y(1) = a \] (3.10)

When \( -\frac{1}{3} < a < 0 \),

\[ y(1) < 0 \] (3.11)

\[ y(x) < 0, \ 0 < x < 1 \] (3.12)

Let \( y = 0 \), when \( x = \frac{d_{dc}}{d_s}, \ x > 0 \),

That means, \[ y\left(\frac{d_{dc}}{d_s}\right) < y\left(\frac{d_{dc}}{d_s}\right) \] (3.13)

As, \[ \frac{dy}{dx} = 3ax^2 + 2x \] (3.14)

When \( 0 < x < -\frac{1}{3a} \), \( -\frac{1}{3} < a < 0 \),

\[ 0 < x < 1 \] (3.15)

\( y \) increases when \( x \) increases.

Thus, \[ d_d < d_{dc} \] (3.16)

For \( d_d < d_{dc} \), all liquid are attached. Substituted into (3.7), \( W_e \leq 4 \), always attached.

Let \[ a \geq 0 \] (3.17)
When \( a \geq 0 \), \( y(1) > 0 \) \hspace{1cm} (3.18)

Thus, there is a positive real root in \((0, 1)\). Substituted into (3.7), it is known that, \( W_e \geq 4 \), Equation (3.3) yields “critical size of droplet”.

\[ W_e \geq 4, \text{ Equation (3.3) yields “critical size of droplet”}. \]

\[ \text{Figure 3.2 Effect of } W_e \text{ and } d_{dc}. \]

Thus, when \( d_d \leq d_{dc} \), all liquid are attached. The attachment is the mass of the droplet,

\[ \text{That is, when } d_d \leq d_{dc}, \text{ mass attachment is } \frac{\pi}{6} \rho_d d_d^3. \]

\[ 3.1.2 \text{ Large Droplet on Small Solid} \]

When the large droplet impacts on the small solid, the maximum attach-ability is half of the volume of the small solid.
The impacting of large droplet on the small solid is showed in Figure 3.3.

Figure 3.3 The impacting of large droplet on the small solid.

Assume: \( l_u = 2d_s \)

Maximum attachment = carried mass = \( \frac{1}{2} \rho_d \cdot \left( \frac{\pi}{6} d_s^3 \right) \) \( (3.19) \)

For \( \frac{d_d}{d_s} \geq 3 \), only \( \left( \frac{\pi}{12} \rho_d d_s^3 \right) \) of liquid attached.

3.1.3 Comparable Size Collision

When the droplet impacts on the comparable size of solid, Assuming: \( (d_d < d_s < 3d_s) \)

The impacting of the droplet on the comparable size of solid is showed in Figure 3.4.

Figure 3.4 The impacting of the droplet on the comparable size of solid.
The liquid attachment is assumed to be linear of the comparable size of droplet-solid collision, which is showed in Equation (3.20).

For $d_d < d_s < 3d_s$,

$$\text{Liquid attachment} = \frac{\pi}{6} \rho_s d_s^3 + \left( \frac{d_c - d_d}{d_d} \right) \left( \frac{\pi}{12} \rho_s d_s^3 - \rho_d \frac{\pi}{6} d_d^3 \right).$$

(3.20)

### 3.1.4 Conclusion of Theoretical Analysis

The analytical model developed for center-to-center collision without heat transfer in this study is capable of illustrating the three different size ratios between droplet and solids are possible: small droplet on large solid, large droplet on small solid and comparable size collision.

When a small droplet impacts on the large solid surface, 

mass attachment $= \frac{\pi}{6} \rho_s d_s^3$. The maximum deformation (critical size of droplet) should be the diameter of the solid and $W_e > 4$ yields “critical size of droplet”, on the other hand, when $W_e \leq 4$, all liquid are attached. When the large droplet impacts on the small solid, the maximum attach-ability is half of the volume of the small solid. When the droplet impacts on the comparable size of solid, the liquid attachment is assumed to be linear (the dash line). The liquid attachment is showed in Figure 3.5.
3.2 Comparable Size Center-to-Center Collision Model with Heat Transfer

When a liquid droplet impinges onto a hot solid, it is quite different from those collisions in the room temperature without heat transfer. In order to investigate of the evaporation process, another model was set up.

The attachments in the droplet, solid sphere surface are modeled based on the heat conservation equations. The droplet is assumed to be spherical before the collision and the liquid is assumed to be incompressible. There are no droplet break-up upon collision and no vaporization effect on droplet movements. Also, there is no heat loss during the collision.

The schematic diagram of liquid droplet impacting with a hot solid sphere is showed in Figure 3.6.
Figure 3.6 The impacting of the droplet on the hot solid sphere.

The heat change of the system includes that, part of liquid droplet evaporates; the temperature of the rest goes high, while the temperature of the solid sphere goes down.

The heat conservation is expressed by

\[ Q_s = Q_h + Q_e \]  

(3.21)

In which, \( Q_h \) is the heat increased by the droplet left which has been heated up, \( Q_e \) is the heat increased by the liquid droplet evaporated and \( Q_s \) is the heat lost by the solid sphere.

Using the formula

\[ Q_h = M_s C_p (T_f - T_0) \]  

(3.22)

\[ Q_e = M_s [C_p (T_v - T_0) + L] \]  

(3.23)

\[ Q_s = M_s C_p (T_v - T_{0s}) \]  

(3.24)

In which, L means Latent heat of liquid droplet, \( T_0 \) is the initial temperature of liquid droplet, while \( T_{0s} \) is the initial temperature of the solid sphere. \( T_v \) is the vaporization temperature of water, \( T_f \) is the final temperature of the liquid droplet, while
$T_s$ is the final temperature of the solid. $M_e$ is the evaporation mass of liquid droplet. $M_h$ is the liquid left which has been heated up. $M_s$ is the mass of the solid.

From this model, the experimental data could be examined by testing $T_0$, $T_{0s}$, $T_i$, $T_s$, $M_s$ and the initial mass of the liquid droplet ($M_e + M_h$).

3.3 Off-Center Collision Model without Heat Transfer

In this section, the droplet-solid impacting off-center collision is discussed.

In order to simplify the model, the 2-D model is chosen instead of 3-D model. Thus, each includes two conditions—the size of the projected contact area is part or whole of the comparable smaller particle size. The droplet-solid impacting off-center collision is showed in Figure 3.7 (a) and Figure 3.7 (b).

Figure 3.7 (a) shows the small droplet impacts on the large solid, while the Figure 3.7 (b) shows the large droplet impacts on the small solid.

![Figure 3.7 (a)](image-url) The small droplet impacts on the large solid.
The large droplet impacts on the small solid.

The off-center-collision efficiency is defined as:

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

(3.25)

Also, it could be built as:

$$\eta_{\text{off}} \equiv \frac{\text{Projected - contact - area @ off - center - collision}}{\text{Projected - contact - area @ center - to - center - collision}}$$

(3.26)

Thus, the off-center-collision efficiency is obtained as:

$$\eta_{\text{off}} = \begin{cases} 1 & \text{if } \quad Z \leq \frac{|d_1 - d_s|}{2} \\ \frac{A_{\text{off}}}{\frac{\pi}{4} d_{\text{min}}^2} & \text{if } \quad \frac{|d_1 - d_s|}{2} < Z < \frac{|d_1 + d_s|}{2} \end{cases}$$

(3.27)

In which, $d_{\text{min}} = \min(d_1, d_s)$, $Z$ is the distance of the center of two particles (let “1” is droplet, “2” is solid).
Figure 3.8 (a) $\eta_{\text{eff}} < 1$.

Figure 3.8 (b) $\eta_{\text{eff}} = 1$.

Figure 3.8 (c) $\eta_{\text{eff}} = 0$. 
\[
\begin{align*}
\text{if } & \frac{|d_1 - d_2|}{2} < Z < \frac{|d_1 + d_2|}{2}, \quad \eta_{\text{eff}} < 1 \\
\text{if } & \quad Z \leq \frac{|d_1 - d_2|}{2}, \quad \eta_{\text{eff}} = 1 \\
\text{if } & \quad \frac{|d_1 + d_2|}{2} \leq Z, \quad \eta_{\text{eff}} = 0
\end{align*}
\] (3.28)

Now, the first condition would be discussed:

\[
r_1^2 = Z^2 + r_2^2 - 2Z \cdot r_2 \cos \alpha
\] (3.29)

According to the equation above, the following relation is obtained:

\[
\cos \alpha = \frac{Z^2 + r_2^2 - r_1^2}{2Z \cdot r_2}
\] (3.30)

Similarly,

\[
\cos \beta = \frac{Z^2 + r_1^2 - r_2^2}{2Z \cdot r_1}
\] (3.31)

\[
A_{\text{eff}} = \alpha r_2^2 - r_2^2 \sin \alpha \cos \alpha + \beta r_1^2 - r_1^2 - r_2^2 \sin \beta \cos \beta
\] (3.32)

Define:

\[
\gamma \equiv \frac{r_1}{r_2}, \quad \zeta \equiv \frac{Z}{r_2}
\]

Thus,

\[
\eta_{\text{eff}} = \begin{cases} 
1 & \text{if } 0 \leq \gamma \leq |\gamma - 1| \\
\frac{A_{\text{eff}}}{\pi r_{\text{min}}^2} & \text{if } |\gamma - 1| < Z < \gamma + 1
\end{cases}
\] (3.33)

In which, \( r_{\text{min}} = \min(r_1, r_2) \)

If \( r_1 \leq r_2 \), in other words, \( 0 \leq \gamma \leq 1 \)

\[
\frac{A_{\text{eff}}}{\pi r_2^2} = -\frac{1}{\pi \gamma}\left[\alpha - \sin \alpha \cos \alpha + \gamma^2 (\beta - \sin \beta \cos \beta)\right]
\] (3.34)

If \( r_1 > r_2 \), in other words, \( 1 < \gamma \)
Thus, the off-center-collision efficiency without heat transfer is related with the diameter of the droplet and solid and the distance of the center of two particles. It can be easily calculated by the Equation (3.34) or Equation (3.35).

\[
\frac{A_{\text{off}}}{\pi r^2} = \frac{1}{\pi} \left[ \alpha - \sin \alpha \cos \alpha + \gamma^2 (\beta - \sin \beta \cos \beta) \right]
\] (3.35)

where

\[
\cos \alpha = \frac{\xi^2 + 1 - \gamma^2}{2\xi}
\] (3.36)

\[
\cos \beta = \frac{\xi^2 + \gamma^2 - 1}{2\xi \cdot \gamma}
\] (3.37)

then,

\[
\eta_{\text{off}} = f(\xi, \gamma)
\] (3.38)

Thus, the off-center-collision efficiency without heat transfer is related with the diameter of the droplet and solid and the distance of the center of two particles. It can be easily calculated by the Equation (3.34) or Equation (3.35).

\[
m_{\text{off-center}} \% = \eta_{\text{off}} \cdot m_{\text{center-to-center}} \%
\] (3.39)

From this model, the off-center collision can be easily compared with center-to-center collision, which also can be examined by the experimental data.
CHAPTER 4
RESULTS AND DISCUSSION

To validate the theoretical analysis described in Chapter 3, the measured results from the experimental systems, which are described in Chapter 2, are used to be compared with results coming from the models. After that, some parametric studies such as 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 performed and discussed.

4.1 Center-to-Center Collision without Heat Transfer

The experiment was conducted to examine the effects of the collision velocity and the size ratio of droplet and particle in center-to-center collision without heat transfer. Six different impact velocities and two droplet sizes have been investigated.

4.1.1 Effect of Impact Velocity

For the study of the effect of impact velocity at the room temperate, six different impact velocities have been performed at the room temperature in the same droplet size. The velocity was controlled by the height of the droplet dripping from. The droplet size, the height dripping from the pipette to the solid ball (h), the impact velocity (v) and the Weber number ($W_e$) are shown in Table 4.1.
Table 4.1 Weber Number at Different Impacts Velocity and Droplet Sizes

<table>
<thead>
<tr>
<th>Impact velocity (m/s)</th>
<th>h (cm)</th>
<th>d_i =0.284 (cm)</th>
<th>d_2 =0.337 (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.280</td>
<td>3.1</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>(0.4)</td>
<td>3.9</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>0.313</td>
<td>7.7</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>(0.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.443</td>
<td>11.6</td>
<td>13.8</td>
</tr>
<tr>
<td></td>
<td>(1.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.542</td>
<td>15.5</td>
<td>18.3</td>
</tr>
<tr>
<td></td>
<td>(1.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.626</td>
<td>19.3</td>
<td>22.9</td>
</tr>
<tr>
<td></td>
<td>(2.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.700</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(2.5)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the experiment, the height dripping from the pipette to the solid ball is changed to get the different impact velocities.

As

$$m_d \frac{dU_d}{dt} = m_d g - F_D$$

(4.1)

In which, $F_D$ is the drag force, $m_d$ is the mass of the droplet and $U_d$ is the velocity of the droplet.

$$F_D = C_D \frac{\rho}{2} A U_d^2$$

(4.2)

Where $C_D$ is the drag coefficient, which is a function of $\text{Re}_t$ (the particle Reynolds number at the terminal velocity). A is the exposed frontal area of the particle to the direction of the incoming flow.

The relationship between $C_D$ and $\text{Re}_t$ for a sphere are given by Equation (4.3).

$$C_D = \begin{cases} 
\frac{24}{\text{Re}_t}, & \text{Re}_t < 2 \\
\frac{18.5}{\text{Re}_t^{0.8}}, & 2 < \text{Re}_t < 500 \\
0.44, & 500 < \text{Re}_t < 2 \times 10^5 
\end{cases}$$

(4.3)

The particle Reynolds number at the terminal velocity $\text{Re}_t$ can be expressed by
In which, $U_{pt}$ is the solid particle terminal velocity and $\mu$ denotes the viscosity of the air.

The particle terminal velocity $U_{pt}$ of a sphere is related to its diameter by

$$U_{pt} = \frac{d(\rho_p - \rho)g}{18\mu}, \quad \text{Re}_t < 2$$

$$U_{pt}^{1.4} = 0.072 \frac{d^{1.6}(\rho_p - \rho)g}{\rho^{0.4}\mu^{0.6}}, \quad 2<\text{Re}_t < 500$$

$$U_{pt}^2 = 3.03 \frac{d(\rho_p - \rho)g}{\rho}, \quad 500<\text{Re}_t < 2 \times 10^5$$

In which, $\rho$ and $\rho_p$ represent the densities of the air and the solid particle, respectively.

Therefore, the drag force $F_D$ can be obtained by Equation (4.2), (4.3), (4.4) and (4.5). Then the impact velocity is obtained by Equation (4.1).

In Table 4.1, it is seen that the impact velocity has an effect on the collision. The collision involving a larger impact velocity has a bigger Weber number.

It also needs to be noted that, the bold numbers in the Table show all the droplet are attached. These experimental results verify the model ($W_e \leq 4$, all attached), which is given in Chapter 3.1. The status of the entire droplet attachment captured by camera is showed in Figure 4.1.
4.1.2 Effect of Size Ratio of Droplet and Particle

In order to find the critical Weber number for the whole attachment, two droplet sizes are observed. In Table 4.1, it is seen that the droplet size has an effect on the collision. The collision involving a larger droplet size has a bigger Weber number.

The experimental results are showed in Figure 4.2. 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 in room temperature.

Note that the dash line is represented for the theory model for the attachment of one solid ball in Chapter 3.1.1. The experimental results were compared with the model. It is showed that the experimental data can show a good agreement with the model,
except when the low velocities. That maybe caused by the error in the experiments. The surface tension can affect a lot during the low velocity situation.

![Figure 4.2 The attachment percentage for one solid ball.](image)

### 4.2 Center-to-Center Collision with Heat Transfer

The experiment was conducted to examine the effects of small droplet on large solid and comparable size collision in center-to-center collision with heat transfer. The limiting case for small droplet on large solid collision is the wall surface, which will be discussed in next section.

#### 4.2.1 Small Droplet on Large Solid

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

From Equation (3.21), (3.22) and (3.23), the following are obtained:

\[ Q = Q_h + Q_e \]  

(4.1)
\[ Q_h = M_e C_p (T_1 - T_0) \]  
\[ Q_e = M_e [C_p (T_s - T_0) + L]\]

In which, \( L \) means Latent heat of water, \( T_0 \) is the room temperature (25°C), \( T_s \) is the vaporization temperature of water, \( M_e \) is the evaporation mass of water.

Based on these, the experiment results are as followings in Table 4.2 and Figure 4.3.

In which, \( f \) means \( f = Q_e / Q \)  
\( f_m \) means \( f_m = m_e / m \)

<table>
<thead>
<tr>
<th>T-T_0 (°C)</th>
<th>( f )</th>
<th>( Q ) (KJ/Kg)</th>
<th>( f_m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.95305</td>
<td>1380.34</td>
<td>0.5140</td>
</tr>
<tr>
<td>300</td>
<td>0.85146</td>
<td>596.11</td>
<td>0.1993</td>
</tr>
<tr>
<td>400</td>
<td>0.86691</td>
<td>590.00</td>
<td>0.2007</td>
</tr>
<tr>
<td>500</td>
<td>0.88507</td>
<td>610.68</td>
<td>0.2284</td>
</tr>
</tbody>
</table>
Figure 4.3 gives the curve of the mass and energy evaporation percentage at different temperatures. From the figure, it could be easily found that at the lower temperature, the factor $f = Q_e / Q$ is very high and gets to a peak value in our experiment range. As the temperature increases, the rate of heat transfer decreases because of the transition boiling regime. The direct contact between the liquid and the surface is decreasing, and the vapor has a lower thermal conductivity than of liquid. At the Leidenfrost temperature, the factor $f = Q_e / Q$ is very low and gets to a minimum value. The vaporization at Leidenfrost temperature is the least, which leads the $f$ is the minimum. That matches our experimental results.

From the figure, it could be easily found that at the lower temperature, heat transfer is very high and gets to a peak value in our experiment range. At the Leidenfrost temperature, heat transfer is very low and gets to a minimum. At the lower temperature,
factor $f_m$ is very high and gets to a peak value in our experiment range. At the Leidenfrost temperature, factor $f_m$ is very low and gets to a minimum.

\[ Q-T \]

**Figure 4.4** Heat transfer at different temperatures.

The same result can get from Figure 4.4. They give the curve of the heat transfer and factor \( f_m = \frac{m_e}{m} \) at different temperatures. From the figure, it could be easily found that at the lower temperature, heat transfer is very high and gets to a peak value in our experiment range. At the Leidenfrost temperature, heat transfer is very low and gets to a minimum.

### 4.2.2 Comparable Size Collision

The experimental results are showed in Figure 4.5. The investigation of the evaporation process of a liquid droplet impacting onto a hot solid ball has been studied.
Figure 4.5 The percentage of evaporation mass at different temperatures.

From the Figure 4.5, it could be easily found that at the lower temperature, the percentage of the evaporation mass is increasing and gets to a peak value in our experiment range. That is because, in this nucleate boiling regime, when the temperature increases, the rate at which energy is transferred as heat to the water increases. As the temperature increases, the rate of heat transfer decreases. That is because, in this transition boiling, the direct contact between the liquid and the surface is decreasing, and the vapor has a lower thermal conductivity than of liquid.

At the Leidenfrost temperature, the percentage of the evaporation mass is very low and gets to a minimum value. This is because when the temperature is just at or around the Leidenfrost temperature, the surface of a drop deposited on the solid ball almost immediately vaporizes. The gas pressure from this vapor layer prevents the rest of drop from touching the copper cylinder, which dramatically slows the vaporization of the drop. Thus, the vaporization at Leidenfrost temperature is the least, which leads the f is the minimum value. That matches our experimental results.
Note that the dash line is represented for the theory model for center-to-center collision model with heat transfer in Chapter 3.2. The experimental results were compared with the model, which could show the tendency of the model.

4.3 Off-Center Collision without Heat Transfer

The experimental results are showed in Figure 4.6. The attachment percentage at two different off-center distances on one solid ball at the room temperature was studied. \( \Delta d \) is the distance between the center of the droplet and solid (\( \Delta d_1 = 2 \text{mm} \) and \( \Delta d_2 = 3 \text{mm} \)).

![Figure 4.6](image)

**Figure 4.6** The effect of off-center for attachment percentage

It can be seen that, the effect of the off-center to the balls for the droplet impacting process is significant. When \( \Delta d_1 = 2 \text{mm} \), the attachment percentage is much larger than it did in \( \Delta d_2 = 3 \text{mm} \).
Comparing with the attachment percentage of center-to-center droplet impinging on one ball, it is showed that when the off-center-collision distance becomes larger, it can affect more. It is also indicated when efficiency ($\eta_{off}$) 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 dash line is represented for the theory model for the attachment of off-center collision in Chapter 3. The experimental results were compared with the model. The experimental data is found to be in a good agreement with the model, except when the low velocities. Also, that should be caused by some errors in the experiments, for example, the surface tension and wettability can affect a lot during the low velocity situation.

4.4 The Bridge Effect on Droplet Impacting with Two Solid Balls

The experimental results are showed in Figure 4.7. The attachment percentage at three different distances between two solid balls was investigated at different impact velocities. $Z$ is the distance between the centers of two solid spheres.

It can be seen that, the bridge effect has a significant effect on the attachment percentage. As the distance between two solid balls increases, the percentage of the attachment decreases in room temperature.
4.5 The Bridge Effect on Droplet Impacting with Three Solid Balls

The experimental results are showed in Figure 4.8. The attachment percentage at two different distances between three solid balls was studied at different impact velocities. $Z$ is the distance between the centers of two solid spheres.

It can be seen that, the distance between three solid balls increases, the percentage of the attachment decreases in room temperature.
4.6 The Geometry and Bridge Effect for Two and Three Solid Balls

The experimental results are showed in Figure 4.9. The attachment percentage at the same distance between the centers of two or three solid balls at the room temperature was studied. Z is the distance between the center of two solid spheres (Z=6.75mm).

It can be seen that, the effect of the geometry of two or three balls for the droplet impacting process is different. The geometry of three balls gives a large attachment percentage.

Comparing with the attachment percentage of one ball, it is also noted that the bridge effect is significant, the percentage of the attachment increases enormously in room temperature.
4.7 Discussions

A systematic study combining experimental measurements and analytical modeling has been performed to investigate the collision of phase transfer between a droplet-solid sphere. To investigate the effects of different parameters (droplet velocity, size ratio between the droplet and solid, temperature difference on the heat and mass transfer during droplet-solid center-to-center collision), sets of experiments are conducted to verify the analytical model, which have been discussed in details in this Chapter.

When $W_e \leq 4$, liquid always attaching, which was derived from the collision model, was verified by experimental results. When impacting velocity of the droplet increases, the percentage of the attachment decreases. The geometry of three balls gives a large attachment percentage, comparing with two balls. Also, the bridge effect is significant, the percentage of the attachment increases enormously in room temperature. As the distance between two solid balls increases, the percentage of the attachment
decreases. When the off-center-collision distance becomes larger, it can affect more. It is also indicated when efficiency is less than 1, the attachment of which is less than the center-to-center condition.

When it comes to collision with heat transfer, the case is quite different. Small droplet on large solid collision and comparable size collision has been investigated. At the lower temperature, heat transfer is very high and gets to a peak value in our experiment range. At the Leidenfrost temperature, heat transfer is very low and gets to a minimum value.
CHAPTER 5
SUMMARY AND CONCLUSION

A series of experimental systems are set up and 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.

Several models are proposed to make theoretical studies. The theoretical model for droplet-solid collision without heat transfer is firstly developed. In the model, the droplet size, velocities are the variables and the model yields the droplet mass attaching on the solid particle. The second model is a small droplet colliding with a very large particle with very high temperature difference between droplet and solid. The model gives the evaporated mass percentage of the droplet and heat transfer process during the collision.

These models are validated by the experimental results. Based on these models, some parametric studies are performed. The studies on the droplet-solid collision yield the conclusions that will be given as follows.

A droplet attachment model for the impact of a droplet on the solid ball or balls without heat transfer has also been set up, which includes the small droplet on large solid, large droplet on small solid, comparable size collision and off-center collision. When \( W_e \leq 4 \), liquid always attaching, which was derived from the collision model, was
verified by experimental results.

When impacting velocity the droplet increases, the percentage of the attachment decreases in room temperature. The effect of the geometry of two or three balls for the droplet impacting process is different. The geometry of three balls gives a large attachment percentage. Also, the bridge effect is significant, the percentage of the attachment increases enormously in room temperature. As the distance between two solid balls increases, the percentage of the attachment decreases in room temperature. When the off-center-collision distance becomes larger, it can affect more. It is also indicated when efficiency is less than 1, the attachment of which is less than the center-to-center condition.

When it comes to collision with heat transfer, the case is quite different. A water droplet impinging onto a hot solid sphere and a hot copper wall have been investigated. 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. At the lower temperature, heat transfer is very high and gets to a peak value in our experiment range. At the Leidenfrost temperature, heat transfer is very low and gets to a minimum value.

In the further study, study will be focused on developing an analytical model to describe the hydrodynamic and thermodynamic behavior of the evaporation process of water liquid droplets impinging onto a hot solid sphere at atmospheric pressure and discuss different materials with different characteristics such as surface tension, viscosity, evaporation temperature, heat conductivity and multi-component droplet.
REFERENCES


