Visualization Study on Dynamic Behaviors of Two Droplets Impinging onto Hot Plate

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Abstract A visualization study on the dynamic characteristics of two droplets impinging onto a hot plate was carried out. The sapphire plate was heated up to 300ºC by a brass casting heater. Two high speed cameras were used for side and bottom view visualization, and the frame rate was 20000 fps. De-ionized water droplet was made through a 31G injection needle and the droplet diameter (D) was 2.4 mm. The distances between two droplets were 1.5D and 2D. The Weber number was changed from 24.76 to 136.16 by changing the initial height of the droplet from 40 mm to 210 mm. Induced detachment of coalescing droplets on hot surfaces was observed in both cases. Dynamic behavior of the droplets after impingement was strongly depended on the surface temperature and the distance of two droplets. The rebounding height of droplets at the 1.5D case was lower than that of the 2D distance at the same Leidenfrost condition. As increasing distance of two droplets, both maximum spreading diameter and rebounding height were increased.
Keywords: Weber number, Leidenfrost phenomenon, Two droplet, Visualization

1 Introduction

The impingement of single droplet on a hot surface has been applied in various fields such as spray cooling, ink-jet printing, and the rewetting of nuclear reactors. After impingement, droplet atomization increases the ratio of the droplet volume makes heat transfer and vaporization quickly and improves the cooling efficiency. In the case of diesel combustion, enhance the efficiency and decrease harmful emissions can be achieved. An icing droplet after impingement is dangerous to the road safety and may occur trouble to engine and measuring equipment in the aviation industry. It is necessary to study the collision of droplet onto the heated plate to understand characteristics of impinging jet at microscopic observation. [1]

The dynamic behavior of droplet impingement are different depends on droplet size, velocity and temperature of hot surface such as stick, rebound, spread phenomenon. Fig 1 is the typical boiling curve. The critical heat flux point locates between the nucleate boiling regime and the transition boiling regime. At the Leidenfrost point, the lowest wall heat flux is occured.

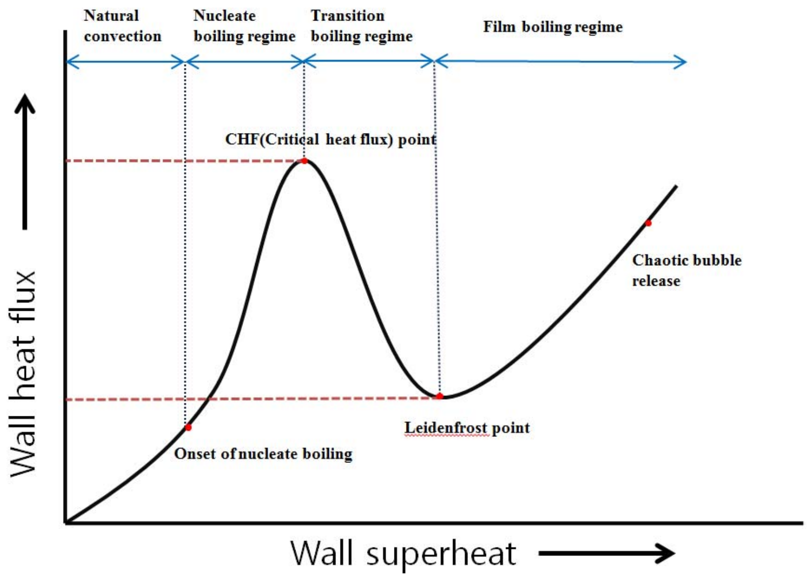

Fig 1 Boiling curve for water of 1 atm (Bernardin et al. [1999])

For example, for water droplets at atmospheric pressure and modest impinging velocities, the temperature above which wetting does not occur is approximately 220 ºC [2]. Because of the great difficulty in measuring the amount of heat removed by a single impinging droplet, the most experimental studies have been focused on the hydrodynamics of the phenomenon. The effect of the droplet size on the interaction has been studied thoroughly [3, 4]. As a general observation, the behaviour of the droplet was found to vary according to its initial size. Smaller droplets would bounce off the hot surface with a higher velocity whereas larger ones would stay close to the wall for a long period. The effect of the velocity of the droplet has been studied experimentally [5, 6]. Large droplet velocities would cause large droplet spreading and droplet breakup.

There have only been a small number of previous attempts to measure directly the heat extracted from an impinging droplet. Makino and Michiyoshi [3] found a correlation that the heat flux between the droplet and hot solid surface is only a function of the surface temperature. In order to measure the temperature a sheathed K-type thermocouple was used soldered on the central place of the surface that the droplets would impinge on. Inada et al. [7] examined the heat transfer during the impingement of 4 mm water droplets upon a hot platinum surface attached on the upper surface of a cylindrical copper block heated in the range of 180-420 ºC. The transient heat flux for cases beyond Leidenfrost was found to be in the range 10^5 – 10^7 W/m^2. Recently, Chatzikyriakou et al. [8] measured heat transfer between a hot surface and an impinging droplet by means of transient, high resolution infrared microscopy. They reported that the heat transferred by a 1.5 mm droplet was measured to be 0.19 J with the heat flux peaking at 3.5 MW/m^2 during 10 ms it spends the vicinity of the surface

Micro-explosion phenomenon has been observed when water in oil emulsion droplets impinged on the superheated plate [9]. Significant reduction in carbon monoxide, nitrogen oxides and particulates was observed in the exhaust gas from boilers or internal combustion engines when they use emulsified fuels due to micro-explosions of water droplets. Similar phenomenon has been found in water droplet impingement onto the superheated surface [10]. However, there is no attempt to measure the velocity field of droplet injections in the micro-explosion process. In the present study, we aim to visualize dynamic behaviour of impinging water droplets onto a hot surface at Leidenfrost condition. In addition, quantitative measurement of droplet velocity during micro-explosion was attempted. Transient measurement of heat transfer from the hot plate due to continuous droplet impingement and associated hydrodynamic behaviours was reported in this paper.

Table 1 Summary of previous researches

Dynamic behavior Visualization	Previous Researches	Lack of Researches
Droplet impinging onto Horizontal surface	- Surface roughness - Leidenfrost conditions - Energy balance, heat transfer eqution - High speed visualization - Dynamic behavior characteristic map - Numerical simulation	- High quality visualization of dynamic behavior - Wide range of Weber number/ Temperature - Detailed characteristic map
Droplet impinging onto Inclined surface	- Water, isopropanol,glycerin - Surface roughness - Leidenfrost conditions - Energy balance - High speed visualization - Numerical simulation	- Dynamic behavior characteristic map - Heat transfer equation
Two droplet impingement Onto smooth surface	- Water - Energy balance - Numerical simulation	- High speed visualization - Leidenfrost conditions
Droplet impinging onto Cooled surface	- Water - Surface roughness - Energy balance - Numerical simulation	- High speed visualization of dynamic behavior - Numerical simulation -30ºC to 30ºC

Experimental studies of impinging two droplets onto hot surface were reported a little. And visualization of two droplet collision onto hot surface was not presented yet. In the present study, we aim to do a study on the dynamic behaviour of impinging two droplets onto hot surfaces using high speed visualization technique. Both side and bottom views of the deforming and rebounding water droplet were used to obtain maximum spreading diameters and rebounding height which are characterization quantities of impact dynamics of impinging two droplet.

2 Experimental Method

Droplet impact dynamics on heated surfaces were studied experimentally using high speed visualization technique. Fig. 2 shows the schematic diagram of the experimental setup. The droplet was made through a 31G injection needle. The droplet formed at the needle's tip detaches as soon as the gravitational force overcomes the surface tension. The injection flow rate of de-ionized water was 50 μℓ/min and the droplet size was found to be 2 mm. By varying the needle's height, we controlled the droplet velocity before impacting the surface. Side-view and bottom-view images of the droplet were captured using two synchronous high speed cameras (Photron Fastcam SA1.1) with the frame rates 20,000 fps. A 250W halogen lamp was used for illumination. From the series of recorded images in each experiment, we obtained the impact velocity, the droplet diameter, and the maximum spreading diameter. Weber number (We) was estimated based on the measured droplet velocity, diameter, water density and the surface tension. In this experiment, dropping height was changed from 40, 120 and 210 mm above the surface so that We was varied from 24.7 to 136.2.

The test surface we used was a sapphire glass which stands for up to 1,000 ºC. Average surface roughness was about 5 nm. The plate was placed on top of a bronze heater block (200 mm x 200 mm. At the center of the heater, a 50 mm-diameter hole allowed for bottom-view observations. Thermocouples were imbedded in the heater and the temperature of the heater surface was controlled using a PID controller. Since sapphire has high thermal conductivity, the temperature difference between the heater and the test surface is only a few degrees and can be neglected in the high temperature range. Table 2 and 3 present specification of used equipments in this experiment and specification of the sapphire glass.

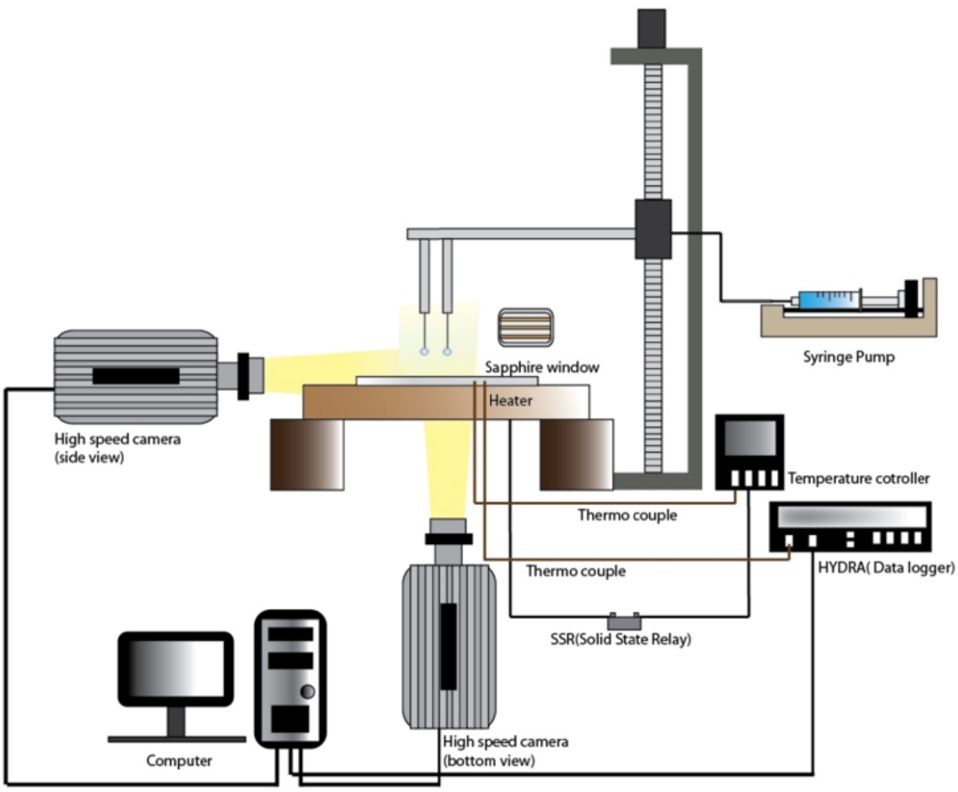

Fig. 2 Schematic diagram of the experimental setup(horizontal surface)

Table 2 Specification of the sapphire glass

Maximum useful temperature	~2000ºC
Specific heat	0.181 cal/gm (25 ºC)
Thermal conductivity	0.4 W/cm 23.1 W/mK parallel to optical axis(300K) 25.2 W/mK perpendicular to optical axis(300K)
	0.1 W/cm (1000 ºC)
Density	3.97 gm/cm^3 (25 ºC)
Roughness	Rz 0.1 (μm)

Table 3 Specification of used equipments

Instrument	Model
High speed camera	Photron Fastcam SA1.1
Camera Lens	Nikon AF 105mm F2.8
Light Source	Halogen lamp(500W)
Hot plate	Brass heter (200 x 200mm, t:25mm, 2kW)
Thermocouple	K type
Plate	Sapphire window (100 x 100mm, t:3mm)
Temperature controller	TZ4ST(Autonics)
SSR(Solid State Relay)	HSR 2D402Z(Input:2~32V d.c, Output : 90~264V a.c)
Data logger	HYDRA 2024A(Fluke)

The Weber number (We) was estimated based on Eq. 1 for the measured droplet velocity, v, diameter, D_0, water density, ρ, and surface tension, σ. The increase in the temperature of the water droplet can lead to a decrease in surface tension, so the Weber number can explain some of the kinetic energy when a water droplet impinges on the surface.

$$We = \frac{\rho v^2 D_0}{\sigma} \tag{1}$$

Before impact, the kinetic energy E_{kin} is $\pi\rho D^3 v^2/12$, and the surface energy $E_{surf,1}$ is $\pi D^2\sigma$. After impact, the kinetic energy is zero, and the surface energy $E_{surf,2}$ is $1/4\pi D^2\sigma$. A normalized Weber number (We*) is expressed by the ratio of the kinetic energy to the surface energy after impact, as defined by Eq. 2.

$$\mathrm{We}^* = \frac{\mathrm{E_{kin}}}{\mathrm{E_{surf,2}}} \tag{2}$$

Combining Eq. 1 and Eq. 2, Eq. 3 can be derived.

$$\mathrm{We}^* = \frac{\mathrm{We}}{48} \tag{3}$$

The droplet was attached at the end of the needle for a moment (less than 1 second) and the droplet detached from the tip due to the motion of syringe pump. Since we used DI water, it cannot absorb heat by radiation. Most of previous studies used the same method for dropping water droplets. At the lowest Weber number case, few droplets were released before visualization to avoid heat transfer from the needle which could be heated by radiation. We confirmed that every droplets before impingement did not contain any bubbles.

3 Experimental results and discussion

Fig.3 shows dynamic behavior of the two droplet impinging simultaneously onto 300ºC surface at Weber number 24.76, distance of two droplet was 1D(distance = diameter of droplet). After 3ms two droplets emerged one droplet and recoiled. 12ms later the droplet starts to rebound. Fig. 4 presents dynamic behavior of the two droplets impinging simultaneously onto 300ºC surface at Weber number 24.76 with the separation distance of 2D. Two droplets shows similar behavior with the 1D distance case but after 12ms there is a difference compared to that of 1D case. In the 1D case, impinging droplets are emerging and rebounding but in case of 2D distance, the droplets are rebounding and emerging. Rebounding height was different due to their emerging mechanism.

Fig. 5 and 6 show dynamic behavior of the two droplets impinging separately onto 300ºC surface at the same Weber number 24.76 for 1D and 2D distance cases, respectively. In case of 1D separation, the first impinging droplet onto hot surface is spreading while the second droplet is impacting onto the hot surface. After impingement, the two droplets are emerging and rebound with a single droplet. In case of 2D separation distance, the first droplet spreads onto the surface, while the second droplet is about to impact the surface. When the second droplet spreads onto the surface, the impinged first droplet is recoiling. After recoiling, both droplets are rebounding separately.

Fig 7 shows rebound coefficients of two droplets impingement with respect to time. Rebound coefficient is defined as h/H. At 300ºC surface, the maximum rebounding height of droplets in 2D distance case is almost double compare to that of 1D distance case. It can be explained that the mass of rebounding droplet after emerging two droplets in case of 1D distance is double compared to the mass of two rebounding droplets in case of 2D distance. However, simultaneous impacting two droplets with 2D distance also emerged together just before rebounding. In this case, the maximum height of rebounding is lower than that of separately impinging two droplets with 2D distance. The reason is that the loss of kinetic energy during coalescence due to the wide separation. It should be noted that the rebound height becomes higher when the time delay of second impact of droplet becomes larger.

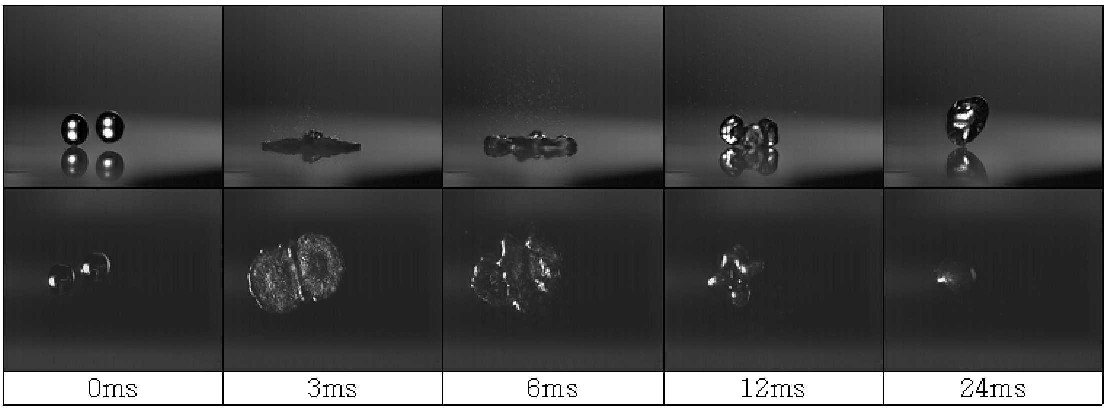

Fig. 3 Dynamic behavior of the two droplet impinging simultaneously onto 300ºC surface at Weber number 24.76 (40 mm) 1D

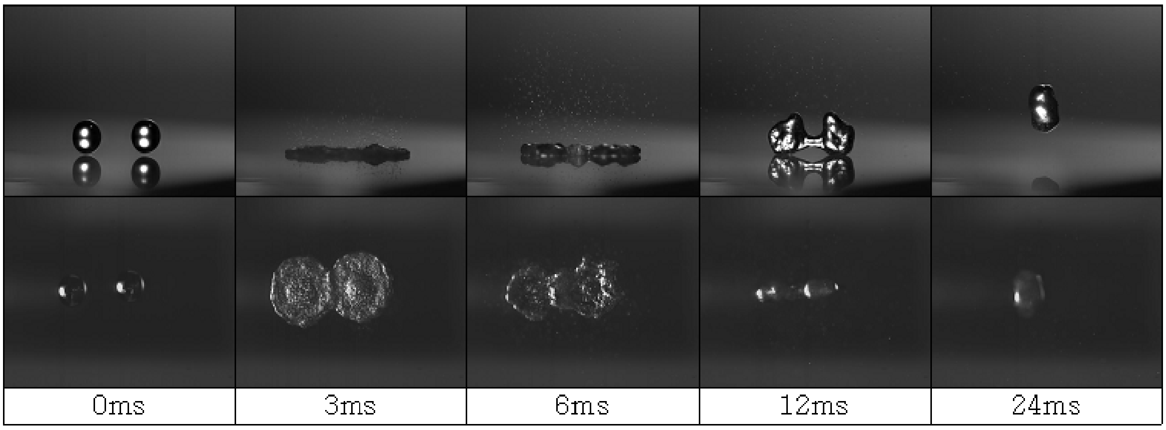

Fig. 4 Dynamic behavior of the two droplet impinging simultaneously onto 300ºC surface at Weber number 24.76 (40 mm) 2D

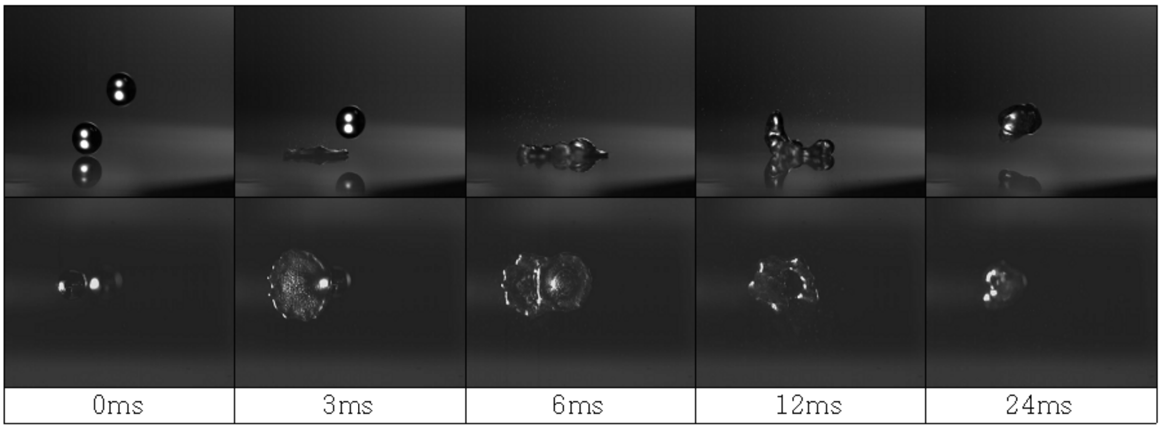

Fig. 5 Dynamic behavior of the two droplet impinging separately onto 300ºC surface at Weber number 24.76 (40 mm) 1D

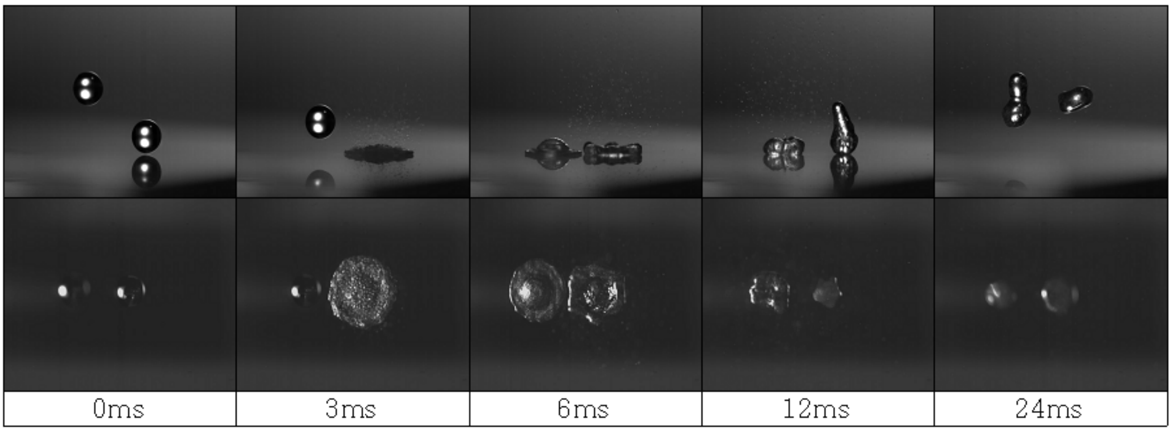

Fig. 6 Dynamic behavior of the two droplet impinging separately onto 300ºC surface at Weber number 24.76 (40 mm) 2D

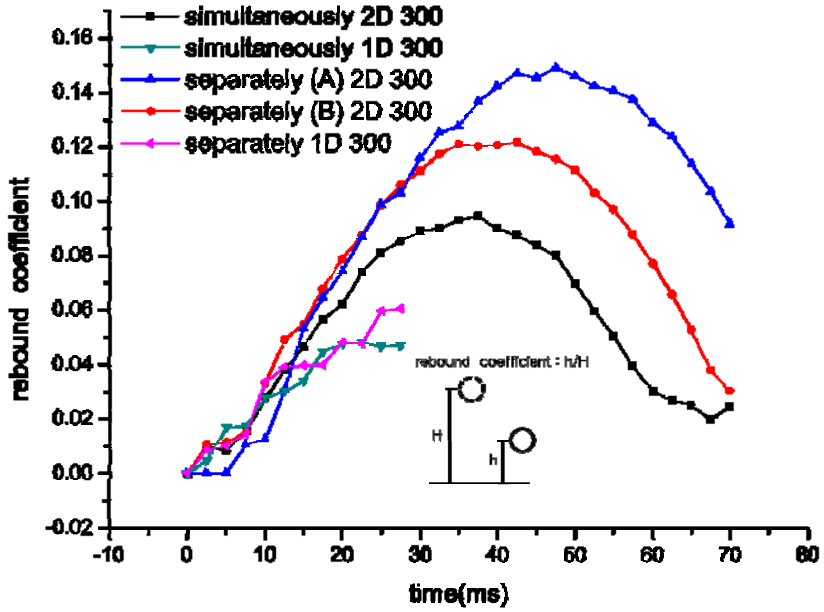

Fig. 7 Rebound coefficient of two droplet impingement

4 Conclusions

A visualization study on the dynamic characteristics of two droplets impinging onto a hot plate was carried out. The sapphire plate was heated up to 300ºC by a brass casting heater. Two high speed cameras were used for side and bottom view visualization, and the frame rate was 20000 fps. De-ionized water droplet was made through a 31G injection needle and the droplet diameter (D) was 2.3 mm. The distances between two droplets were 1D and 2D. Weber number was fixed to 24.76. Induced detachment of coalescing droplets on hot surfaces was observed in both cases. Dynamic behavior of the droplets after impingement was strongly depended on the surface temperature and the distance of two droplets. The rebounding height of droplets at the 1D case was lower than that of the 2D distance at the same Leidenfrost condition. As increasing distance of two droplets, both maximum spreading diameter and rebounding height were increased.

Acknowledgement

This work was supported by the Energy Efficiency & Resources Core technology Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea (No. 20132020000390).

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