Dynamic behavior and heat transfer characteristics of impinging droplets onto high temperature plate

Choog Hyun Lee¹, Dong Yeon Kim¹, Hyun Dong Kim² and Kyung Chun Kim¹

¹ School of Mechanical Engineering, Pusan National University, Busan, Republic of Korea
kckim@pusan.ac.kr
² MEMS Technology Center, Pusan National University, Busan, Republic of Korea

ABSTRACT

Dynamic behaviour and heat transfer characteristics of impinging droplets on a hot surface were studied experimentally. De-ionized water droplet was made through a 31G injection needle and the droplet size was 2 mm. A sapphire plate was heated up to 300°C by a hotplate. A high speed camera was used for visualization, and the frame rate was 4000 fps. Weber number was changed from 0.91 to 117.54 by changing initial height of droplet from 10mm to 210 mm. Hydrophobic characteristics was observed when the temperature of hot surface was over Leidenfrost point. Dynamic behaviour was strongly depended on Weber number and splashing phenomena occurred when the Weber number was higher than 50. Micro-explosion was observed at high Weber number with Leidenfrost condition. From the PIV measurement, it was found that the exploded droplets have considerably high speed compared to the impinging velocity. Maximum heat transfer was coincided with nucleate boiling phase after the droplet impingement.

1. INTRODUCTION

The impingement of droplets on a hot surface is generally used for variety industrials, such as spray cooling, spray coating and rewetting of nuclear reactor. For high enough surface temperatures, impinging droplets which approach the surface do not wet it, but rather recoil from the surface, bouncing off the layer of vapor generated by evaporation from the portion of the droplet that attached the hot surface. The surface temperature at which vapor occurs depends on material properties, surface and flow conditions and is generally referred to Leidenfrost temperature [1]. For example, for water droplets at atmospheric pressure and modest impinging velocities, the temperature above which wetting does not occur is approximately 220 °C [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 °C. The transient heat flux for cases beyond Leidenfrost was found to be in the range $10^7 – 10^8$ W/m². 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/m² 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.

2. DYNAMIC BEHAVIOUR OF IMPINGING DROplet

Droplet impact dynamics on unheated and heated surfaces were studied experimentally using high speed visualization technique. Fig. 1 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 and NAC Memrecam fx K4) with the frame rates 4,000 fps and 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 10 mm to 210 mm above the surface so that We was varied from 0.91 to 117.54.

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 centre 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.

Fig. 1 Schematic diagram of experimental setup

We repeat the droplet impingement experiment numerous times for different Weber numbers (0.9 < We < 117) and surface temperatures (25 ºC < T < 300 ºC), and observed the drop behaviour during impact. Fig. 2 shows images of a droplet impinged on the plate at room temperature (25 ºC) in case of We = 4.65. Due to the hydrophilic surface of the sapphire glass, the impinged droplet was attached and vibrated to dissipate the impact energy. When the Weber number was increased, the maximum spread diameter was increased because of high kinetic energy of the impinging droplet. However, there was no recoiling and rebounding of the droplet. In case of high We number, a wavy structure was observed in the outer ring of the water film at the maximum spreading state. (see Fig. 3)

Fig. 4 shows dynamic behavior of the droplet impinged onto 300 ºC surface in case of We = 4.65. Unlike the droplet impinged onto the unheated surface, the impacted droplet spread, then recoiled and finally bounded off the hot plate within 10 ms due to vapour layer generated at Leidenfrost condition. Similar behaviour was observed when a droplet impinged onto a super hydrophobic surface [11]. When the value of the Weber number was less than 50, droplets showed only rebound action after impingement as shown in Fig. 4. In case of the Weber number was around 50, fingers were occurred at the maximum spreading condition. When the Weber number was higher than 50, droplets showed fingers then broke into tiny droplets. It should be noted that the Weber number 50 corresponds the ratio of the
droplet kinetic energy and the surface tension energy is equal to 1. As the Weber number increased, the number of tiny droplets after splashing was increased.

Fig. 5 shows dynamic behaviours of impinging droplet onto the hot surface when the Weber number was 117.7. Abrupt explosion of thin water film being spread on the hot plate at 300 °C was observed. The bottom-views in Fig. 5 evidently show that shortly after impact, the liquid makes partial contact with the surface. The contact leads to a high rate of heat transfer from the heated surface and consequently formation and growth of vapour bubbles. The vapour pressure increases abruptly causing disruption of the liquid’s bottom surface. Micro-explosion was occurred within 1.5 ms, ejection of tiny droplets with high velocity due to the venting of the vapour bubbles was clearly seen from the side views.

**Fig. 2** Water droplet impinging on surface dropped from a height of 10mm (We=4.65) onto 25°C surface

**Fig. 5** Dynamic behaviours of impinging droplet onto the hot surface when the Weber number was 117.7.
Fig. 3 Water droplet impinging on surface dropped from a height of 200mm (We=117.7) onto 25°C surface.
3. PIV MEASUREMENT OF MICRO EXPLOSION

In order to measure the velocity of tiny droplets after micro-explosion, PIV method was used. Fig. 6 shows the schematic of PIV set up. Olive oil aerosol generated by a Laskin nozzle was filled in an acrylic chamber covered on top over the test section. Time resolved PIV measurement was made using a high speed camera (Photron Fastcam SA1.1,
20,000 fps) with a continuous laser (3 W, 532 nm) sheet illumination. Other conditions were same as the flow visualization experiment carried out to obtain Fig. 5.

Fig. 7 depicts instantaneous velocity vectors of air flow and tiny droplets during the micro-explosion process within 5 ms after impact. The downward velocity vectors appears in Fig. 7(a) attribute to induced air velocity due to the free fall of the droplet. When liquid film spread along the hot surface, exploded water particles moved along 45 degree of vertical upward direction with high speeds (see Figs. 7(b), 7(c) and 7(d)). Violent explosion was observed with the venting of the vapor bubbles after reaching the maximum spreading condition as shown in Fig. 7(e). Explosion was continued for a while before rebound of water fragments from the hot surface (see Figs. 7(f) and 7(g)). Exploded tiny droplets lost their velocity soon after the splashed droplets levitated on the hot surface as shown in Fig. 7(h).

**Fig. 6** Experimental setup for PIV measurement
Fig. 7 Velocity field of droplet at 300°C surface condition (We = 117.7)

Fig. 8 shows temporal variation of the velocity magnitudes obtained at three different points as indicated in Fig. 7. In this figure, the impact occurs at 6 ms. Negative velocity obtained before 6 ms means entrained air velocity due to the falling drop. Soon after the impact, abrupt increases of positive velocities were observed due to micro-explosion. The speed of tiny droplets decreases quickly after arrived at the maximum speed. The maximum speed reaches to 3.7 m/s and it is two times higher compared to the droplet impinging velocity which is 1.97 m/s.

Fig. 8 Temporal variation of vertical velocity component during explosion

4. HEAT TRANSFER CHARACTERISTICS OF IMPINGING DROPLET

Heat transfer characteristics were examined by measuring transient surface temperature variation of the plate when droplets were continuously impinged on the heated surface. Fig. 9 shows the schematic of the experimental setup. The surface was heated up to 320 °C using the electric heater. The sapphire plate was inclined 30 degree with respect to the horizontal plane. Continuous dropping of water droplets was made using a syringe pump with 50 micro liters per
minute. About three droplets per minute were impinged on the heated surface where the thermocouple sensor was attached. Temperature data was recorded with the sampling rate of 1 Hz.

Fig. 9 Experimental setup for surface cooling

Fig. 10 shows the temperature variation at the impingement point of the droplet with time data. Temperature gradient with respect to time is also indicated in Fig. 10. Linear decrease of the surface temperature was observed in the film boiling regime. When the surface temperature was reached to 210 °C, abrupt decrease of temperature was observed due to the critical heat flux condition. One can see the high temperature gradient in the critical heat flux condition. When the surface temperature was reached to 170 °C, the decreasing rate was slow down. Nucleate boiling was observed during the critical heat flux regime.

Fig. 10 Surface temperature and temperature gradient curve under the transient cooling condition
5. CONCLUSIONS

Dynamic behaviour and heat transfer characteristics of droplets impinging on the hot surface with Leidenfrost condition were studied using the high speed visualization technique and the time resolved PIV method. In case of room temperature condition, the droplets were attached to the surface and showed vibrations. In case of 300 °C surface, the droplets spread then bounced back like a droplet impinges onto a super hydrophobic surface. Splash phenomenon was observed when the Weber number exceeded 50. Micro-explosion was observed at high Weber number cases with Leidenfrost condition. The maximum velocity of the exploded tiny droplets found to be two times higher than the impact velocity. Rapid change of surface temperature was observed in the critical heat flux regime. In this regime, rapid decrease of surface temperature attributes to nucleate and transient boiling processes.

ACKNOWLEDGEMENT

This study was supported financially by the National Research Foundation (NRF) of Korea through a grant funded by the Korea government (MEST) (no. 2011-0030663 and no. 2012008749).

REFERENCES