Experimental investigation on heat transfer of a single droplet during collision with a heated wall above Leidenfrost temperature

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1. Introduction

Droplet-wall collision heat transfer during dispersed flow film boiling plays a role in predicting cooling rate and peak cladding temperature of overheated fuels during reflood following a LOCA accident in nuclear power plants. In order to account for effects of droplet heat transfer on cooling of nuclear fuels, a few thermal-hydraulic analysis codes such as COBRA-TF[1] and SPACE[2] separately consider the droplet field from the continuous liquid and vapor fields. The codes use the correlation of Bajorek and Young[3] for the prediction of droplet-wall collision heat transfer during dispersed flow film boiling. The correlation was derived based on the mechanistic model of Baumeister[4] for film boiling heat transfer coefficient of a Leidenfrost droplet floated on a heated surface. The model was formulated only with the physical parameters of the stationary droplet while the droplet collision heat transfer phenomenon is very dynamic. Therefore, it is needed to improve the existing prediction correlation for droplet-wall collision heat transfer by incorporating dynamic characteristics of collision droplets into heat transfer coefficient model.

In this study, effects of droplet velocity on collision dynamics and heat transfer characteristics during droplet-wall collision beyond the Leidenfrost point were examined using the integrated high-speed visible and infrared (IR) imaging technique. The experimental results obtained from the synchronized HSV and IR measurement could provide a better understanding than the previous existing results because various physical parameters associated with droplet-wall collision dynamics and heat transfer phenomena can be simultaneously obtained and the relation between collision dynamics and local heat transfer characteristics can be examined.

2. Methods and Results

The schematic of the experimental setup is seen in Fig. 1. A droplet was generated using the syringe pump and the needle with an inner diameter of 130 μm and an outer diameter of 260 μm. Collision characteristics of the droplet impinged on the heated wall were visualized from side using the high-speed-video (HSV) camera (Phantom v7.3). With synchronization, the temperature distribution at the droplet-wall interface was measured using the high-speed infrared (IR) camera (FLIR SC6000). Diameter of generated droplets before collision was found to be 2 mm from the HSV imaging results.

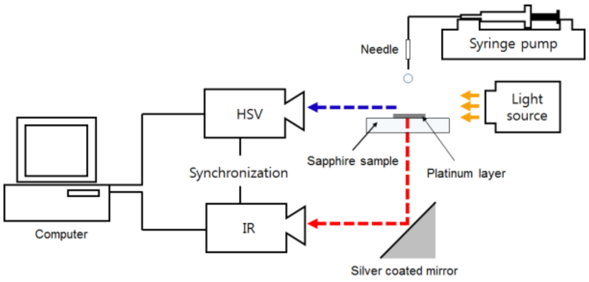

Fig. 1. Schematic of the experimental apparatus

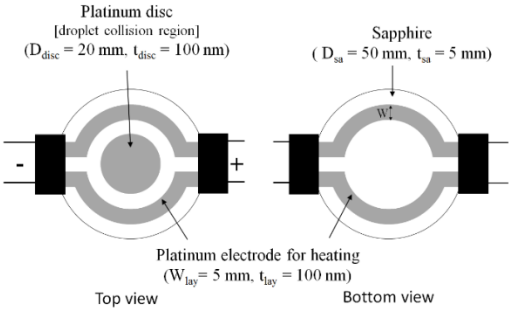

Fig. 2. Schematics of the sapphire heater sample

To measure local surface temperature during the collision, the infrared-opaque platinum film with 100-nm thickness was deposited on the top surface of the sapphire disk. In addition, another platinum film with width of 5 mm was deposited on both the top and bottom surfaces to electrically heat up the substrate via Joule heating. The applied voltage was controlled to maintain the substrate temperature of 425 ℃

The local heat flux was obtained by solving three-dimensional transient heat conduction equation for the heated sapphire plate using the measured surface temperature data as the boundary condition of the collision surface. Natural convection and symmetric boundary conditions were applied to the bottom and sides of the heater substrate, respectively. The three-dimensional temperature field inside the substrate was obtained from the calculation. Then, the local surface heat flux at the heat transfer area can be calculated from the temperature field as

$$q''_w(\mathrm{t}) = -k \frac{\partial T(x,y,z,t)}{\partial z}\bigg|_{z=top} \qquad (1)$$

Fig. 3 shows deformation of the colliding droplet, wall temperature and heat flux with time according to normal weber number. The results of We_n = 1.5, the droplet is rebounded without any wetting and the resulting heat flux was relatively small. On the other hand, for higher We_n of 19 and 49, the maximum heat flux occurs immediately after the initial impact of the droplet on the wall at 0.55 ms. As the impact velocity increases, the droplet spread out rapidly during initial collision. In addition, the high collision velocity caused a strong contact with a heated wall and this resulted in drastic heat transfer.

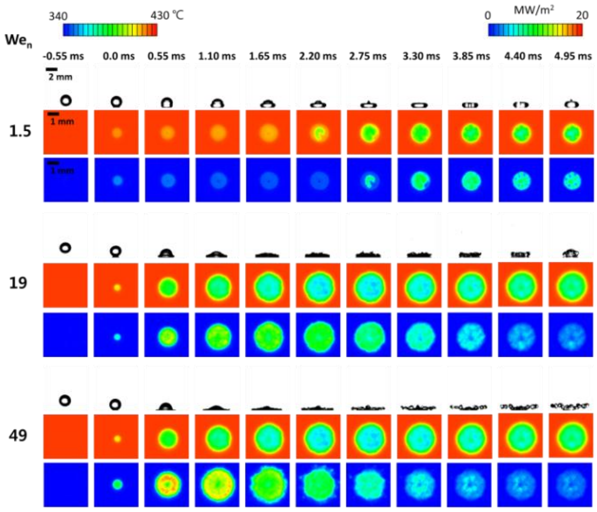

Fig. 3. Droplet dynamics, temperature and heat flux

Spreading diameter is used as a parameter to represent the characteristics of heat transfer area. Fig. 4 shows the maximum spreading diameter obtained in the present study and a comparison with experimental data[5,6,7] and correlations[8,9] of the previous studies. The experimental results show fairly good agreement with those in the previous studies.

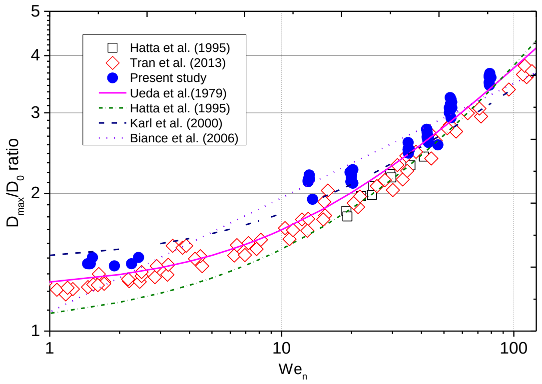

Fig. 4. Maximum droplet spreading diameter as a function of normal We number in vertical collision

Fig. 5 shows the heat transfer effectiveness of single droplet colliding with the heated wall. Baumeister's model always had the same value regardless of the We_n, whereas all the previous and present experimental data[10,11,12,13] indicate that the heat transfer effectiveness increases with the increase of We_n. The significant difference between the results measured from experiment and calculated with correlation results in the increase of the heat transfer area and surface heat flux in accordance with We_n.

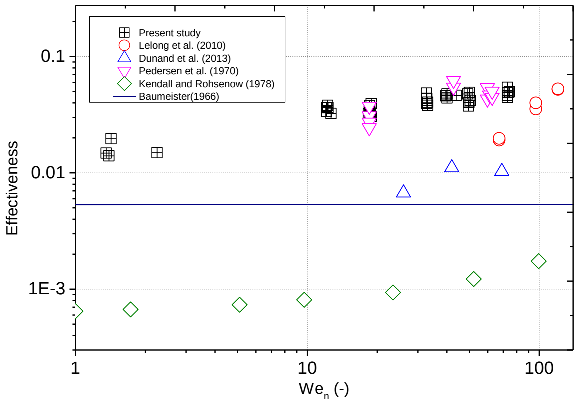

Fig. 5. Effectiveness vs. normal weber number

3. Conclusions

This study experimentally investigated the dynamic behavior and heat transfer characteristics of droplet. The tests were conducted using a water droplet with diameter of 2 mm at atmospheric pressure. Droplet with velocity in the range from 0.2 to 1.5 collided with heated wall. The conclusion was obtained by experiments as follows:

- Maximum spreading diameter and effective heat transfer area are mainly determined by vertical velocity of the impacting droplet.
- Heat transfer effectiveness of single droplet is increased as the normal velocity increases. Tendency of the heat transfer effectiveness was similar to the trend of growth rate of effective heat transfer area.

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