Experimental study of droplet-wall direct contact heat transfer using infrared thermometry

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1. Introduction

When a hypothetical loss of coolant accident (LOCA) in a pressurized water reactor (PWR) occurs, the forced convective cooling of the fuel assemblies by the surrounding liquid water is not available and the temperature of the fuels fast rises. To prevent the fuel assembly melting, emergency core cooling systems are immediately initiated to flood the fuel assembly from the bottom. It is expected that the heated fuel temperature during the reflooding phase is higher than Leidenfrost temperature of water. When water rewets the fuel surface at the temperature higher than Leidenfrost temperature, quenching phenomenon occurs and a lot of droplets are generated near the quenching front. Dispersed droplet flow is formed above the quenching front. Direct contact heat transfer of droplets with the heated wall likely contributes to the cooling of the upper part of the fuel rods. However, the full understanding of complex fluid flow and heat transfer characteristics during droplet-wall collision is very difficult during LOCA [1]. In this regard, this effect has been neglected in the previous studies, and thus prediction of fuel rod temperature has still a large uncertainty.

A few years later, some research groups studied the effects of droplets on heat transfer and developed the prediction models for the fuel temperature. However, these model considered heat transfer mechanism without consideration of dynamics. Therefore, it is necessary to study the heat transfer mechanism considering the dynamic effects on single droplet-wall collision.

We used a technique with the spatially and temporally synchronized high-speed camera and IR camera. The high-speed camera is used to measure droplet diameter, collision angle and velocity. IR camera is used to examine temperature changes on wall. Droplet-wall heat transfer phenomena are observed on the basis of wall temperature and collision angle.

2. Review of previous studies

The major parameters of droplet-wall direct contact heat transfer are diameter of droplet, collision angle, temperature, velocity of droplet, and wall temperature. Our group previously studied the effects of wall temperature and collision angle. In this section, we review the results of our previous studies and determine the direction and scope for further studies.

2.1 Wall temperature

Wall temperature effect was conducted for a water droplet and impact velocity of 0.13 m/s in room temperature and atmospheric pressure condition. The experiments were carried out in the range from 190℃ to 410℃.

Fig. 1 shows representative droplet behavior at three different wall temperature regions. At 190℃, the droplet is spread on wall without rebounding and forms small droplets. At 270℃, droplet is rebounded on wall and makes a lot of small droplets. At 410℃, the droplet is rebounded without any wetting.

The droplet heat transfer rate significantly depends on temperature as shown in Fig. 2. Generally, a vapor layer interrupts heat transfer between the droplet and the wall. When wall temperature is higher than 270℃, the direct contact heat transfer area reduce due to the vapor layer. In the end, the heat transfer rate is smaller [2].

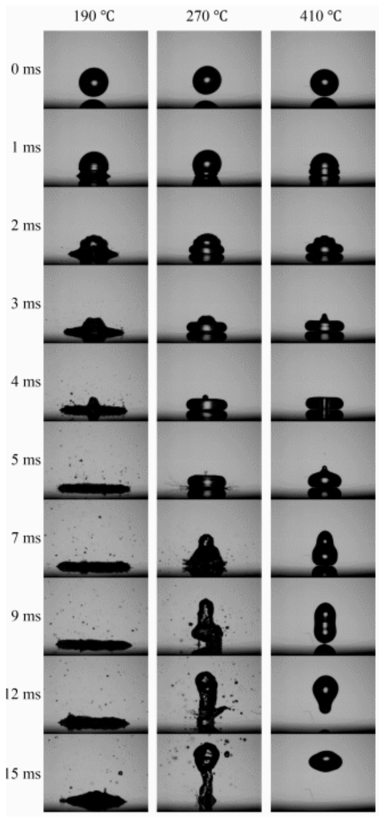

Fig. 1. Droplet collision behavior at 190℃, 270℃ and 410℃

[2]

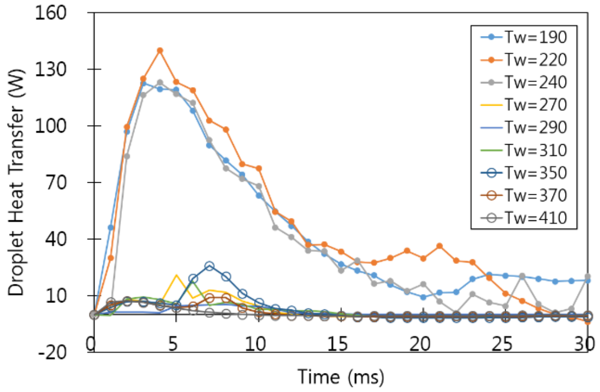

Fig. 2. Droplet collision time versus heat transfer rate [2]

2.2 Impingement angle

When the droplet impinges on the wall, the collision angle affects the direct contact heat transfer area of the droplet with the wall. In order to measure the influence of the collision angle, the experiments were carried out in the range from 20° to 90°. The test were conducted the velocity of 0.42 m/s and the wall temperature of 385℃. Decreasing collision angle from 90°, the heat transfer rate is shown the greatest at 50° and rapidly reduced at 30° in Fig. 3 [3].

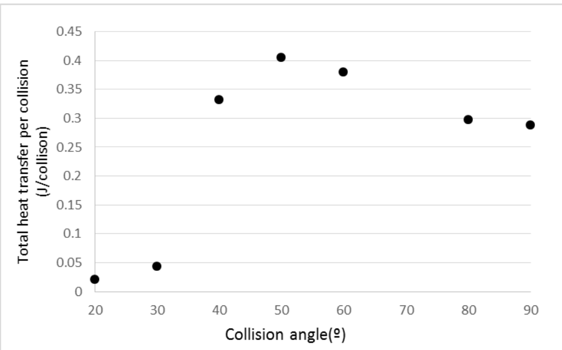

Fig. 3. Droplet collision angle versus Total heat transfer e [3]

In the previous studies of ours were studied the effects wall temperature and wall collision angle. The phenomena of droplet-wall direct contact heat transfer is strongly influenced by these parameters. Additional studies are required to investigate the influence of droplet's impact velocity. This study focuses on single droplet dynamics (velocity, collision angle) and heat transfer characteristics during the collision onto heated wall above the Leidenfrost temperature.

3. Experiments

Fig. 4 is the schematic diagram of experimental setup to measure dynamics and heat transfer. Droplet collision behavior is observed with the high-speed camera from side. Change of the wall surface temperature is observed using the IR camera using the mirror. Wall collision angle is inclined from the tip of needle to the sample using the elevator device. At this time, the cameras are placed in parallel with the sample.

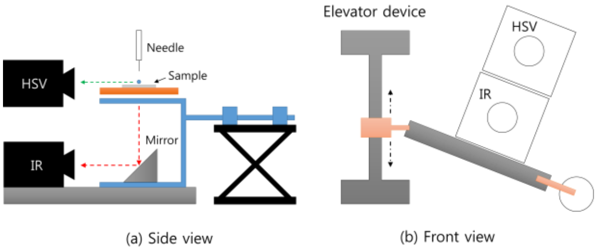

Fig. 4. Schematic diagram of experimental setup [2]

3.1 Droplet generation

Droplet is generated using a needle and a syringe pump. Inner and outer diameter of the needle are respectively 130 μm and 260 μm, and shape of the needle tip is flat. The syringe pump generates droplet of constant diameter. The droplet falls down by gravity and collides with the sapphire sample. Collision velocity of droplet depends on the height.

3.2 Numerical processing for heat transfer rate

Heat transfer rate is calculated through the following process in Fig. 5. Counter distributions are obtained by the IR camera. The wall temperature is changed from counter values using calibration curve. The heat flux is calculated by CFD program to simulate three-dimensional transient problem.

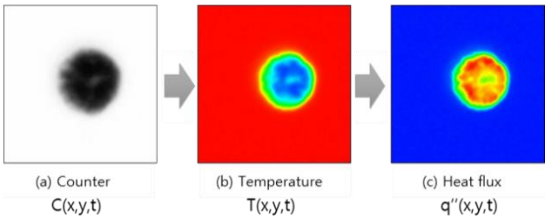

Fig. 5. Calculation procedure for heat flux

In order to solve the three-dimensional transient problem, the governing equation is given by

$$k\nabla^2 T - \rho C_p \frac{\partial T}{\partial t} = 0 \tag{1}$$

where T is the wall temperature, C_p is specific heat capacity, k is thermal conductivity of solid, and ρ is density of solid.

Fig. 6 shows the boundary condition for calculating conduction heat transfer problem. Six planes of the geometry are classified three parts; top, side and bottom. For calculating heat transfer problem, boundary condition are applied at each three parts. An adiabatic condition is applied at the side. A boundary condition of the top is temperature distribution obtained from the IR camera.

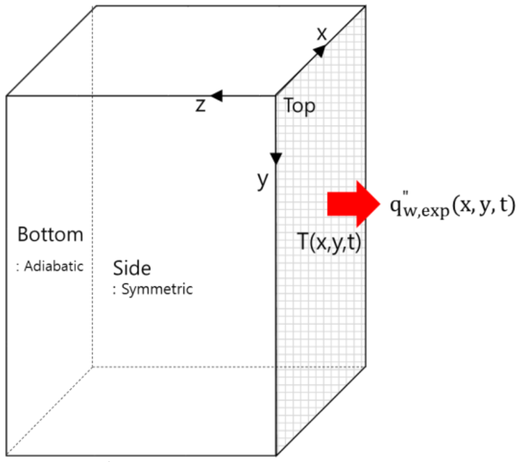

Fig. 6. Setup of Geometry and boundary conditions

3.3 Estimation of the heat transfer coefficient

Time averaged heat transfer coefficient of a droplet [4] is given by

$$h_{exp} = \frac{E_D}{(T_w - T_d)\int_0^{t_R} R_s(t)^2 dt} \quad (2)$$

where E_D is the energy released by the wall due to one droplet impact(J/collision), T_w is wall temperature, T_d is temperature of a droplet, t_R is the resident time, $\int_0^{t_R} R_s(t)^2 dt$ is the total heat transfer area of a collision during t_R.

3.4 Comparison with correlation

Bajorek et al. (2000) modified the model developed by Forslund and Rohsenow for droplet direct contact heat transfer [5]. Forslund et al.(1968) used a heat transfer coefficient developed by Baumeister et al [6]. The heat transfer coefficient in model is expressed as:

$$h_{cor} = \left[\frac{k^3 h_{fg} g \rho_g \rho_d}{(T_w - T_d)\mu(\pi D_d^3/6)}\right]^{1/4} \quad (3)$$

where is h_{fg} is the latent heat, g is the gravity, D_d is a diameter of droplet, k is thermal conductivity, ρ_g is density of vapor, ρ_d is density of droplet, μ is the viscosity coefficient of vapor.

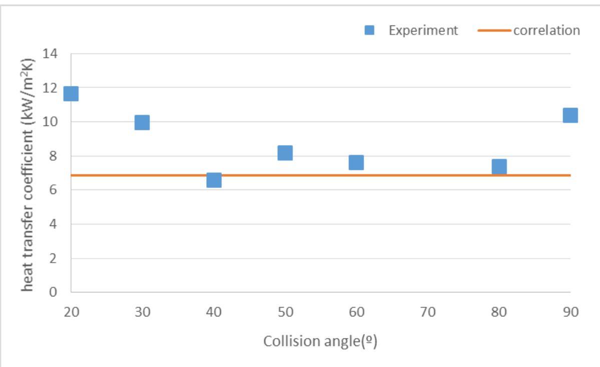

Fig. 7. Heat transfer coefficient versus droplet collision angle

Fig 7 shows the heat transfer coefficient of the test and the correlation. Regardless of the collision angle, the results of correlation is always constant. However heat transfer coefficients had different values depending on the collision angle in test.

4. Summary and Future work

This study reviewed the previous our studies about the effects of wall temperature and collision angle on heat transfer characteristics of single droplet-wall collision. We compared the experimental data with the prediction by droplet-wall direct heat transfer correlation proposed by Bajorek and Young. It was found heat transfer coefficient reasonably match the existing empirical data. .

Future work will cover further systematic studies on the effects of dynamic parameters on droplet-wall collision heat transfer.

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