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Droplets behavior impacting on a hot surface above the Leidenfrost temperature

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ABSTRACT

Experimental studies of droplet behaviors impacting on a hot surface above the Leidenfrost temperature have been performed to provide improvements in the modeling of heat transfer in a ballooned surface characteristic of a loss-of-coolant accident (LOCA). Droplets of known size and velocity were impacted on a hot surface above the Leidenfrost temperature. The spreading of droplets into a liquid film on the surface and the breakup of the droplets were observed using a high-speed camera. For droplets of higher normal Weber number than a threshold value, the higher the normal Weber number of the droplet the smaller the secondary droplets. The conventional correlations showed fairly good agreements with the maximum spreading diameters of the droplets on the hot surface. On the other hand, the size of the secondary droplets resulting from an impact upon the hot surface was not well predicted by the COBRA-TF correlation. A new improved model for the secondary droplet size was developed using the mass conservation with a correction factor. The new model showed good predictions of the secondary droplet size for the present experiment as well as other experiments.

1. Introduction

The phenomena of droplets impacting on a hot surface are encountered in a number of applications including turbines, mist sprays, and pressurized water reactors during the reflood after a large break loss-of-coolant accident (LOCA). Particularly, after a large break LOCA in pressurized water reactors, emergency core cooling systems are initiated and the reactor core is reflooded with cold water. As the quench front propagates upward, water splatters and many droplets of different sizes and velocities are generated. The droplets are then carried by the superheated steam in the flow channel. The cladding surface has very high temperatures generally exceeding the Leidenfrost temperature such that the wetting of the cladding surface with the entrained droplets is prevented.

Droplets entrained in the superheated steam act as a heat sink aiding the cooling of the superheated steam. The wall heat transfer is improved by the direct-contact heat transfer between the wall and droplets. Chatzikyriakou et al. (2010) estimated that the total heat removal rate by droplet impingement on the hot cladding surface above the Leidenfrost temperature was about 1/10 of the heat extracted by single-phase vapor under typical reflood conditions. They concluded that direct cooling by droplets, which is not generally considered in a reflood analysis, could make a significant contribution to keeping the cladding temperature down to acceptable levels.

The fuel rods can be ballooned during a large break LOCA, which results in local flow blockages of the fuel assembly (Grandjean, 2007). Several in-pile tests showed an accumulation of fragmented fuel in the deformed region (i.e. fuel relocation). Fig. 1 shows the fuel rod behaviors by the clad ballooning and fuel relocation phenomena. In the ballooned section of the fuel rods, the flow channels are either completely or partially blocked. As the steam with entrained droplets flows in the blocked region, the droplets will collide with the ballooned surface at the blockage entry. When the clad surface temperature is higher than the Leidenfrost temperature, the droplets will not be able to wet the hot surface.

A lot of experiments have been performed on the droplet breakup by spacer grids during the reflood phase of a large break LOCA (Adams and Clare, 1984; Bajorek and Cheung, 2009; Cho et al., 2011). The droplet breakup behaviors resulting from the impact on the ballooned surface are much different from those by the spacer grids. The droplet behavior by the spacer grids has usually been performed by impinging droplets into the thin edge

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Nomenclature

a	constant (–)
C	constant (–)
c	correction factor (–)
D_i	secondary droplet diameter (m)
D_0	initial droplet diameter (m)
D_{32}	Sauter mean diameter of the secondary droplets (m)
D_{30}	volume mean diameter of the secondary droplets (m)
D_{max}	maximum spreading diameter of impacting droplet on the surface (m)
L	vertical momentum loss (–)
N	number ratio of the secondary broken droplets to the number of impacting droplets (–)
n_i	number of the secondary broken droplets (–)
n_0	number of impacting droplets (–)
R_a	arithmetic mean roughness (μm)
R_0	radius of initial droplet before impact (m)
R_{max}	maximum spreading radius of impacting droplet on the surface (μm)
R_z	mean roughness depth of the surface (μm)
r_n	ratio of droplet velocities normal to the wall before after and before impact (–)
RMS	root mean square error (–)
T_w	surface temperature (°C)
$V_{0,h}$	droplet velocity tangential to the wall before impact (m/s)
$V_{0,n}$	droplet velocity normal to the wall before impact (m/s)
V_0	droplet velocity before impact (m/s)
V_i	droplet velocity after impact (m/s)
We_i	Weber number of the individual secondary droplets (–)
We_n	normal Weber number of the initial droplets (–)

Greek symbols

θ	impinging angle of droplets (radian)
ρ	density of droplets (kg/m^3)
σ	surface tension of droplets (N/m)

Subscripts

0	initial droplets (–)
i	ith droplets or secondary droplets (–)
max	maximum (–)
h	tangential to the surface (–)
n	normal to the surface (–)

of the spacer grids. Since the droplet sizes are comparable to the strip thickness of the spacer grid, the droplet breakup by the spacer grids is due to the cutting and splashing by the strip with finite thickness. On the other hand, the droplet breakup on the ballooned surface is mainly from the splashing on the ballooned and inclined hot surface. In addition, the spacer grids do not have a heat source, whereas the ballooned rods have nuclear decay heat.

The heat transfers associated with the droplets mainly consist of two components (Paik et al., 1985). First, the direct droplet–wall heat transfer due to the droplet impingement is proportional to the interfacial area between the droplet and wall. Therefore, the more the droplet spreads on the wall, the more the heat is transferred to the droplet. Second, the interfacial heat transfer between the droplet and the steam depends on the secondary droplet size after the droplet–wall interaction. After the droplet impacts on the hot surface and breakup occurs, the broken secondary droplets travel within the superheated steam. These secondary smaller droplets act as heat sinks to cool down the superheated steam. Especially, the Sauter mean diameter of the secondary droplets is important for the interfacial heat transfer between the droplets and steam.

The droplet behavior depends on several parameters such as the impact Weber number, surface temperature, surface roughness, and so on. The Weber number represents the ratio of the kinetic energy of the droplet to its surface tension energy. A droplet with a higher Weber number has a higher impact energy that causes the droplet to break up into smaller droplets.

Wachters and Westerling (1966) found that droplets arriving on a hot surface over the Leidenfrost temperature with a Weber number of less than 30 are deformed without any disintegration and rebounded from the surface. At high Weber number, droplets are deformed to form a liquid film separated by a vapor cushion between the droplet and the hot surface. After reaching a maximum deformation on the hot surface, the spreading diameter of the liquid film decreases again due to the effect of the surface

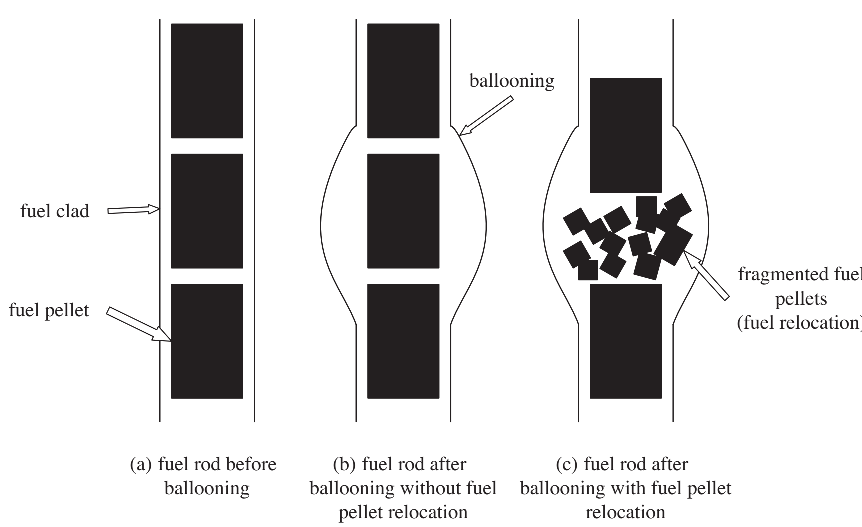

Fig. 1. Geometrical configurations of nuclear fuel under LOCA.