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Development of a dry patch model for critical heat flux prediction

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ABSTRACT

The concern regarding passive safety systems and corium-cooling related to severe accidents has been raised following the Fukushima accident. As a critical heat flux (CHF) is a predominant restricting factor of the heat removal capacities of both types of safety systems, a number of researches have been performed to understand and improve the CHF. Through recent experimental observations, it is known that a dry patch plays an important role in CHF initiation. We developed a dry patch model based on these observations. There exist quenchable and unquenchable dry patches at high wall heat fluxes. Experimental observation shows that the formation of unquenchable dry patches is the main source of CHF initiation. In the dry patch model, we proposed thermal and hydraulic criteria for the onset of the unquenchable dry patch at a high heat flux. An unquenchable dry patch with a critical size can be generated when the following two criteria are satisfied. As a hydraulic criterion, we assume that the coalescence of the whole dry spots occurs, generating a dry patch if all of them are in contact. As a thermal criterion, we consider the temperature of the dry patch. An unquenchable dry patch will be formed if its peripheral temperature reaches the Leidenfrost temperature, such that it may not be rewetted even with bubble detachment. The critical size of the dry patch is obtained by CFD simulation such that its peripheral temperature is equivalent to the Leidenfrost temperature. The wall dry area fraction can be obtained by calculating the probability of the formation of the unquenchable dry patches satisfying both criteria for its critical size. We demonstrated that the dry patch model successfully predicted the experimental CHF data obtained in pool boiling and forced convective flow boiling of water.

1. Introduction

Following the Fukushima accident, ex-vessel cooling of corium has been suggested to remove the decay heat by a passive injection into the cavity and boiling heat transfer system to ensure safety during beyond the design basis accidents. In this system, the flow rate is limited causing critical heat flux (CHF), which threatens the heat transfer reduction capability. Therefore, it is important to avoid CHF. However, as we cannot control the flow rate without a pump, CHF enhancement should be achieved by surface treatment.

For CHF enhancement, a number of researches have been performed with various methods. Cheung et al. [1] coated a vessel for intensive boiling and Kim and Kim [2] deposited nanoparticles on the surface. Liter and Kaviany [3] proved that the surface modulation with porous coating affects the CHF in terms of the capillary limit and wavelength. Chu et al. [4] fabricated microstructures on the surface and tested these to make a CHF prediction model as a function of the roughness. In addition, Honda et al. [5] and Kim et al. [6] made these microstructures and observed the CHF enhancement by the surface extension and wicking effect. Han and Bang [7] fabricated holes and pillars to determine the effect of the Rayleigh–Taylor wavelength on CHF enhancement.

Recently, several researchers found that the dry patch plays an important role for CHF occurrence. Since many dry patches exist at high wall heat fluxes and film boiling occurs under the dry patches, the heat transfer capability degrades significantly. Chu et al. [8] observed the synchronized bubble dynamics using the total reflection technique and transparent ITO heater: separate dry spot generation and an expansion of the dry patch by coalescence of the dry spots. It was found that residual dry patches clearly exist after the bubble departure, which we defined as unquenchable dry patches. They explained that the CHF occurs when the nucleation activity is enhanced by high wall superheat, which expands the dry patch. The temperature gradient of the surface under the dry patch was measured by Song et al. [9] using an infrared thermometry technique to observe the dry area near the CHF point. They showed that the dry spots coalesce as the wall temperature increases. If the dry patch survives for a sufficient period of time, the center temperature of the dry patch increases sharply and its boundary expands, inducing CHF. These two researches explain the CHF occurrence

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Nomenclature

$\overline{N}$	average nucleate site density
A	surface area
A_f	dry patch radius
A_t	gravitational acceleration
L	contact angle
D_d	bubble departure diameter
d_c	cavity diameter
μ	dynamic viscosity
k	thermal conductivity
ΔT	surface superheat
T_w	wall temperature
T_{sat}	saturation temperature
C_{sf}	surface/liquid parameter of the Rohsenow correlation
Pr	Prantl number
h_{fg}	latent heat
h_{co}	film coefficient of heat transfer if there were no radiation
h_r	radiation coefficient of heat transfer
U	velocity
C_p	specific heat at constant pressure
σ	surface tension

by dry patch expansion in their own ways. In addition, the evolution of bubbles and dry spots in the boiling liquid film were observed by Gong et al. using a high speed camera [10]. They investigated the wetting mechanism of the dry spots under various heat fluxes by a receding liquid dam and liquid flow by bubbles in the vicinity. In this research, it is shown that the large dry patch resulting in burnout initiates from the edge of the heating zone, propagating into the center from the pictures. Regarding the thermal aspect, Unal et al. [11] calculated the critical liquid–solid contact temperature and determined the minimum dry patch size for the onset of CHF. They used an idealized two-dimensional transient conduction heat transfer model to predict whether the center temperature of the dry patch is higher than a critical wall temperature. They found that the dry patch radius is approximately 10–23 mm when the heater material is copper, whereas it is 2.25 mm in the case of a nickel heater.

Based on the previous studies mentioned, we developed a dry patch model for CHF prediction based on the onset criteria of the formation of the unquenchable dry patch leading to CHF initiation.

2. Fundamentals of dry patch for CHF

Referring the research of Chu et al. [8], the dry patch can be generated when the dry spots are concentrated and coalesce with one another. Fig. 1 represents the simple process of dry spot coalescence.

After bubbles develop with several dry spots, a mushroom bubble is formed by bubble coalescence. The dry spots existing under the massive bubble merge with each other, eventually forming the dry patch.

2.1. Characteristics of dry spot

The dry spots used for dry patch generation can be divided into two groups according to their temperature and heat transfer method [12].

First, the dry spot is termed a cold spot if the wall temperature beneath it is less than the surrounding wall temperature over its life cycle. As the cold spot is quenched following bubble departure, heat transfer by the dynamics of the cold spot is an effective heat transfer mechanism. Its wall temperature is maintained to be lower than that of its neighbor region during its life time.

Second, the dry spot is termed a hot spot if the wall temperature beneath the dry spot is greater than the surrounding temperature. The hot spot can be quenched or unquenched following bubble departure. Heat transfer by the dynamics of the unquenched hot spot is an ineffective heat transfer mechanism due to its heat transfer characteristic of film boiling. Therefore, the wall temperature of the hot dry spot is higher than that in the surrounding region.

2.2. Dry patch generation and propagation

Generation and propagation of the dry patch predominantly rely on wall superheat as this determines the nucleation site density and bubble hovering period. The latter is an important parameter of dry patch generation since bubble generation leads to dry spot formation under it. If the nucleation site density is high, the dry patch can be generated easily by dry spot coalescence. When the dry patch is generated, liquid cannot rewet the surface under the dry patch if its peripheral temperature is sufficiently high.

CHF is initiated by one dry patch near the edge of the surface, although there exists another dry patch at the surface. This is because the surrounding temperature of the initiating dry patch is higher than in the surface region.

2.3. Quenchable and unquenchable dry patches

At high heat flux, a mixture of quenchable and unquenchable dry patches exists under mushroom bubbles or isolated ones.

A quenchable dry patch can be completely rewetted when mushroom bubbles detach. In contrast, an unquenchable bubble can expand and contract, but not completely rewet when mushroom bubbles or isolated ones detach and grow.

If the wall temperature under the dry patch becomes sufficiently high, it prevents liquid from rewetting the dry patch, and it becomes unquenchable. Unquenchable patches degrade the heat transfer performance due to film boiling underneath, whereas the quenchable patches enhance the heat transfer performance as a result of nucleation boiling when they are rewetted.

Fig. 2 simply describes the difference between quenchable and unquenchable dry patches. As the wall superheat increases, more unquenchable patches are generated, leading to greater degradation of the heat transfer performance while the enhancement of heat transfer by rewetting of the quenchable bubbles occurs.

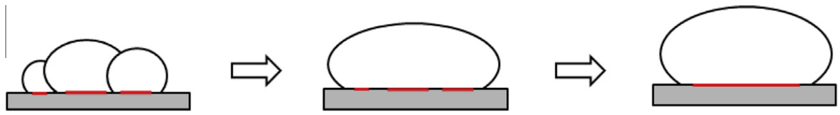

Fig. 1. Bubble mushroom and dry patch generation by bubble and dry spot coalescence.