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Film boiling heat transfer of a hot sphere in a subcooled liquid pool considering heat loss through its support rod

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ABSTRACT

Experiments were performed to determine the film boiling heat transfer of a hot stainless steel sphere of 10 mm diameter, whose initial temperature is about 850 °C, immersed in a 43–81 °C water pool. From the experimental results, and direct visual aid, it was found that non-negligible amounts of heat transfer exist from the sphere to the support rod, which is installed frequently in many studies to hold the specimen in place. The experimental heat transfer results for the sphere without immersion of the support rod showed the maximum deviation of 5.47%, despite the different support rod diameters. With the increase of the immersion depth, the heat ratios of the total heat transfer (Q_{total}) to the actual heat transfer for the sphere (Q_{sphere}) were increased and saturated to 1.13 and 1.97, at a sphere temperature of 650 °C, and rod diameters of 1.6 mm and 5.0 mm, respectively. It was found out that the heat loss through the rod (Q_{rod}) is linearly dependent on rod conductivity multiplied by its cross-sectional area (kA_c). Based on the current database obtained for the sphere without the immersion of the support rod, it is suggested to use the coefficient in the Michiyoshi correlation as a power function, rather than current value of 0.696. With the new coefficient by the authors, the normalized root mean square deviation (NRMSD) turns out to be 4.56%, which improves the prediction capability rather than that of Michiyoshi (10.43%) or Liu and Theofanous (17.87%). Utilizing the relationship between Q_{rod} and kA_c obtained from the present study, we reestimated the databases of Q_{sphere} from other previous studies. The deviations between the modified Michiyoshi model and the corrected databases for those previous studies were within 23.72% over the ranges of 300–950 °C for a sphere temperature between 30 °C and 50 °C for the degree of subcooling.

1. Introduction

A pre-flooded cavity is one of the critical safety systems to mitigate the release of radioactive materials to the public in a pressurized water reactor. When a core melts and falls into a water in a pre-flooded cavity under a severe accident, the hot corium eventually contacts with the subcooled water. This process is called as a fuel-coolant interaction (FCI). After the breakup of this corium jet during FCI, the main heat transfer regime of a corium particle is the subcooled film boiling of a sphere. The thermal evaluation of this part is very important since it finally gives the initial temperature condition and the progression for a molten corium-concrete interaction (MCCI). In other words, for an overall prediction of a severe accident, the high accuracy of a physical model is required to calculate the heat transfer for a subcooled film boiling with a sphere in a natural convection case or a forced convection case.

Much research has been performed over a half century for the heat transfer of a film boiling with a hot sphere in a saturated/subcooled water pool through both analytical and experimental methods. Bromley et al. (1953) firstly generated the equation form for a saturated film boiling, including the natural convection, the forced convection and the radiation. For a subcooled film boiling, Dhir and Purohit (1978) provided the experimental results with the various materials (stainless steel, copper, silver) and dependent variables such as the diameter of the sphere, the water velocity, and the subcooling of the water pool. They also performed the theoretical work with the assumptions for the velocity and temperature fields from a vapor film to a liquid pool. Liu and Theofanous (2000) well organized the literature review for representative previous researches about the film boiling heat transfer. They conducted the experimentation and the analysis using the similar approach to Dhir and Purohit (1978). After 2000s, people began to focus on the influence of the nanofluid (Kim et al., 2009) or the sea water (Hsu et al., 2015), and the prediction for the minimum heat flux point (Sher et al., 2012; Makishi and Honda, 2012) since the film boiling heat transfer mechanism in a pure liquid seems to have been fully understood.

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Nomenclature

A_c	Cross-sectional area
C	Coefficient for physical model
C_p	Specific heat
D_{rod}	Diameter of support rod
D_{sphere}	Diameter of sphere
Gr_D	Grashof number for sphere
h	Heat transfer coefficient (HTC)
H	Immersion depth
J	Dimensionless parameter from physical model
k	Thermal conductivity
m	Dimensionless parameter from physical model
m_{sphere}	Sphere mass
Nu	Nusselt number
Pr	Prandtl number
q″	Heat flux
Q	Heat
Q_{total}	Heat transfer measured in experiment
Q_{rod}	Heat transfer through support rod
Q_{sphere}	Heat transfer through sphere surface
Sp′	Dimensionless parameter related to superheat
T	Temperature
T_{sphere}	Sphere temperature
T_{sat}	Saturation water temperature
ΔT_{sub}	Subcooling degree

Greek symbols

ε	Emissivity
σ	Stefan-Boltzmann constant

Subscripts

l	liquid
v	vapor

Here, as a first step we only focus on the heat transfer for a subcooled film boiling with a sphere in a natural convection case in order to investigate the effect of the support rod attached to a sphere, which have been used for the measurement of its heat flux. We found out that there have been the misinterpretations with the actual heat transfer of the film boiling with a sphere as we reviewed the previous study of Nishio et al. (1987). They showed that the heat transfer differs with H/D_{sphere} (the ratio of an immersion depth to a sphere diameter) in the film boiling, inferring that some amounts of the heat transfers through the support rod. This observation is a very critical point since almost all of the conventional experimental databases were obtained with a presence of the support rod to use thermocouples. This also indicates that the accumulated databases and existing correlations for the film boiling, which did not consider or control an immersion depth, cannot accurately evaluate the heat transfer of the film boiling with a sphere.

There are two sophisticated correlations for the prediction of the natural convection film boiling: Michiyoshi model (Michiyoshi et al. (1989)) and Liu and Theofanous model. The specialty of Michiyoshi model is that it was developed based on the databases with the shallow immersion depth (H/D_{sphere} of 1.2). Liu and Theofanous model was regarded as the accurate one for the wide range of experimental conditions, and was implemented in the severe accident code, MC3D (Raverdy et al., 2017). To check the validities of these models, we compared the experimental data of Nishio et al. and the results of two correlations. The experimental conditions of Nishio et al. were described in Table 1. The calculation for the total heat flux using the correlations is described as the Eq. (1).

$$q''_{total} = q''_{convection} + 0.88q''_{radiation} = \frac{Nu\cdot k_v(T_{sphere}-T_{sat})}{D_{sphere}} + 0.88\varepsilon\sigma(T^4_{sphere}-T^4_{sat}) \quad (1)$$

Fig. 1 showed that the results from the models do not agree well with the results of Nishio et al. The average deviations are 10.14% for Michiyoshi model and 21.99% for Liu and Theofanous model with Nishio's data (H/D_{sphere} of 1.2). Referring the parameters in Table 1 and Table 2, the discrepancies would result from H/D_{sphere} and D_{rod} (the support rod diameter), since the influences by the other conditions such as T_{sphere} (the sphere temperature) and ΔT_{sub} (the subcooling degree) and D_{sphere} (the sphere diameter) are already counted into the correlations. Thus we thought that quantification for the effects of a support rod and reestimation for the actual heat transfer of a sphere are demanded to improve the prediction capability of the existing models for the heat transfer of a film boiling. Therefore, we performed the experiments of the subcooled pool film boiling with the change of H/D_{sphere} and D_{rod}. We also investigated the effects of T_{sphere} and ΔT_{sub} through the experiments. Based on the results and the analyses, we estimated the actual heat transfer of the film boiling with a sphere from our and previous studies.

Table 1
The experimental conditions of Nishio et al.

Author	Sphere material	Measured Sphere temperature (°C)	ΔT_{sub} (°C)	D_{sphere} (mm)	H/D_{sphere}	D_{rod} (mm)
Nishio	Platinum	~900	30	10	0.75–3.0	2

2. Experiments

2.1. Apparatus and procedure

The entire experiment apparatus is described in Fig. 2 with the geometry of the specimen and the support rod. The experiment system consists of the pneumatic cylinder to drop a sphere, the furnace to heat a specimen, the support rod to fix the position of the specimen, the ungrounded sheathed K-type SS316L thermocouples of 1.6 mm diameter to measure the temperatures of the specimen and the water, and

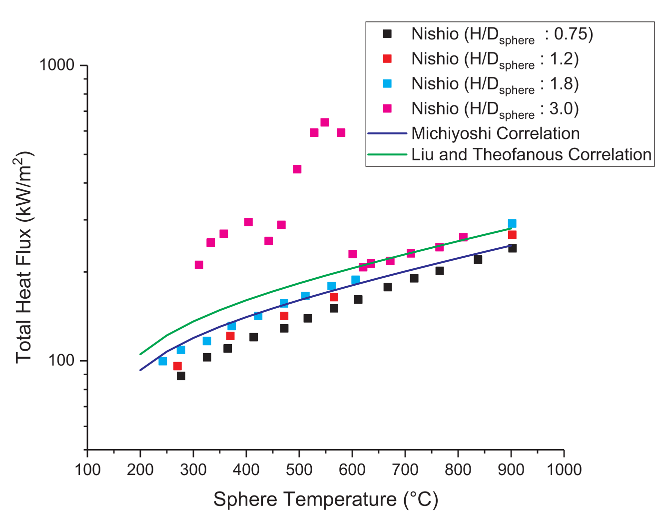

Fig. 1. Total heat fluxes vs. sphere temperature with Nishio et al. (experiment) and prediction models.