International Journal of Heat and Mass Transfer 127 (2018) 1180–1187

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Development of a semi-empirical model for forced convection film boiling on a sphere in water based on visual observations

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ARTICLE INFO

Article history:
Received 30 May 2018
Received in revised form 22 August 2018
Accepted 22 August 2018

Keywords:
Film boiling
Sphere
Subcooled water
Forced convection
Heat transfer

ABSTRACT

High-temperature film boiling in forced convection is dominant heat transfer regime after corium jet breakup in fuel-coolant interaction (FCI). Considering radiation contribution to heat transfer in a high superheat condition, we modified the Epstein-Hauser model by reflecting the radiation term on the energy balance at vapor-liquid interface. This correction resulted in an increase of convective heat transfer in the vapor film compared to the convective heat transfer from no correction. For the reference case, which is D_{sphere} (sphere diameter) of 4 mm, ΔT_{sub} (subcooling) of 40 K, and u (liquid velocity) of 1 m/s, the convective heat transfer from the correction showed 1.1–2.4 times higher than those from no correction at T_{sphere} (sphere temperature) of 1000–3000 °C. High-temperature experiments were conducted for forced convection film boiling on spheres (kanthal-a1 and SS316L) at atmospheric pressure under the conditions for D_{sphere} of 10 mm, ΔT_{sat} (superheat) of 600–1200 K, ΔT_{sub} of 20–70 K, and u of 0.5–1.3 m/s. The experimental results showed that the original Epstein-Hauser model does not well predict the dependencies on subcooling, superheat, and Reynolds number. Based on the visual observations, we developed the corrected Epstein-Hauser model with a new physical coefficient, which lies between 1 and 2. It showed the highest accuracy (10.99%) in terms of normalized root mean square deviation (NRMSD), compared to the original Epstein-Hauser model (61.92%) and Liu-Theofanous model (19.72%).

1. Introduction

For a severe accident scenario of a nuclear power plant with the pre-flooded cavity, fuel-coolant interaction (FCI) occurs between a falling jet of molten corium and a water in the cavity. FCI is the most important phase in an accident progression since the coolability in FCI eventually determines initial conditions of molten corium-concrete interaction (MCCI), such as an initial temperature and a structure of a deposition (cake or debris). During FCI, after the corium jet breakup, the heat is mainly transferred from fragmented corium particles to a water by a regime of a forced convection film boiling. Usually, we have predicted this heat using the model of the forced convection film boiling on a sphere.

Several researchers have been investigated the forced convection film boiling through experimental and theoretical studies. Bromley et al. [1] firstly suggested an equation for a saturated forced convection film boiling with a horizontal cylinder. Kobayasi [2] performed a similar theoretical derivation for the saturated forced convection film boiling on a sphere, adding numerical calculations for the flow separation angle. Dhir and Purohit [3] obtained heat transfer coefficients for a subcooled forced film boiling on the stainless sphere (D_{sphere} (sphere diameter): 19 mm, ΔT_{sat} (superheat): 100–500 K, ΔT_{sub} (subcooling): 0–50 K, u (liquid velocity): 0–0.45 m/s), and proposed a correlation based on their data. The Epstein-Hauser [4] developed a physical model with the theory of a stagnation point flow for the forced convection film boiling on a sphere. The Liu-Theofanous model [5] extensively reviewed many previous researches on this field, conducted the large range of the experiments (D_{sphere}: 6–19 mm, ΔT_{sat}: 200–900 K, ΔT_{sub}: 0–40 K, u: 0–2 m/s), and constructed a general correlation for the film boiling on a sphere. In addition, numerous theoretical and experimental works were performed for the forced convection film boiling on a sphere or a horizontal cylinder [6–18].

Among the developed correlations on a sphere, the Epstein-Hauser model is a most-used heat transfer one implemented in various FCI codes [19], since it has no significant logical leap and was developed under generally acceptable assumptions. However, regarding the anticipated FCI conditions (ΔT_{sat}: 2000–3000 K, ΔT_{sub}: unknown), the conventional correlations have such critical limitations: 1. No consideration of the radiation in a derivation process, and 2. Much low superheat conditions for a validation (Table 1). To compensate these, in this paper, we corrected the Epstein-Hauser model by reflecting the radiation on the heat

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.100
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Nomenclature

a_v	velocity gradient at stagnation point for vapor, $\left(\frac{\rho_v}{\rho_l}\right)^{-0.5}\frac{3u_l}{D_{sphere}}$
A	dimensionless superheat, $\frac{c_{pv}\Delta T_{sat}}{h_{fg}Pr_v}$
B	dimensionless subcooling, $\left(\frac{\rho_v}{\rho_l}\right)^{-0.5}\frac{c_{pl}\Delta T_{sub}}{\beta h_{fg}Pr_l^{0.5}}$
C	coefficient for model
c_p	specific heat
D_{sphere}	diameter of sphere
h	heat transfer coefficient (HTC)
h_{fg}	evaporation heat
m_{sphere}	sphere mass
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
Gr	Grashof number
q''	heat flux
T_{sphere}	sphere temperature
T_{sat}	saturation temperature
ΔT_{sat}	superheat degree
ΔT_{sub}	subcooling degree
u	liquid velocity

Greek symbols

ε	emissivity
β	$\left(\left(\frac{\rho_v}{\rho_l}\right)^{0.5}\frac{\nu_v}{\nu_l}\right)^{0.5}$
η	dimensionless vapor film thickness, $\delta\left(\frac{2a_v}{\nu_v}\right)^{0.5}$
ν	kinematic viscosity
δ	vapor film thickness
ρ	density

Subscripts

l	liquid
v	vapor

balance at the vapor-liquid interface. We also performed the experiments with the extended ranges as ΔT_{sat} of 500–1200 K, ΔT_{sub} of 20–70 K, and u of 0.5–1.3 m/s. We suggested the coefficient for the corrected Epstein-Hauser model with the bases of the experiment visualization.

2. Modification of Epstein-Hauser model

2.1. The brief review of Epstein-Hauser model

The Epstein-Hauser [4] model occupies the majority on the prediction of the film boiling heat transfer in FCI codes such as MC3D [20], TEXAS-V [21], and TRACER-II [22], since it was developed under generally acceptable assumptions and has only one empirical factor. They derived the following equation applying boundary conditions for a sphere wall, a vapor-liquid interface, a bulk liquid, and solving conservation equations for vapor and liquid boundary layers at the stagnation point:

$$\frac{1}{24}\eta_{EH}^4+\left(\left(\frac{2}{\pi}\right)^{0.5}B\right)\eta_{EH}=A \tag{1}$$

where η is dimensionless vapor film thickness, A is a dimensionless parameter representing superheat, and B is a dimensionless parameter representing subcooling. The detailed definitions of these parameters are described in nomenclature or the literature [4]. The Epstein-Hauser model tried to get a simple form of η, so they approximated a solution of the Eq. (1) from extreme cases of the relation between A and B:

$$\eta_{EH}=\left\{\begin{matrix}(24A)^{0.25} & A\gg B\\ \frac{A}{\left(\frac{2}{\pi}\right)^{0.5}B} & A\ll B\end{matrix}\right\}\rightarrow\left[\frac{1}{24A}+\left(\frac{2}{\pi}\right)^2\left(\frac{B}{A}\right)^4\right]^{-1/4} \tag{2}$$

They extended this analysis from the stagnation point (the bottom of the sphere) to the middle of the sphere, and obtained Nusselt number (*Nu*) with η as follows:

$$\frac{\beta Nu_{EH}}{Re^{0.5}}=C\left(\frac{3}{2}\right)^{0.5}\frac{1}{\eta_{EH}} \tag{3}$$

where *Re* is Reynolds number, C is a coefficient, β is dimensionless parameter related to the combination of density and viscosity for vapor and liquid layer. Without any treatment on the theoretical derivation, C equals 1. However, they additionally introduced the empirical factor of 2 for the coefficient C in the Eq. (3), yielding better agreement with the experimental results. They finally suggested the Eq. (4).

$$\frac{\beta Nu_{EH}}{Re^{0.5}}=2\left(\frac{3}{2}\right)^{0.5}\frac{1}{\eta_{EH}} \tag{4}$$

Table 1
The validated ranges of Epstein-Hauser model [4] and Liu-Theofanous model [5] (sphere experiment only).

Models	ΔT_{sat} (K)	ΔT_{sub} (K)	u (m/s)	D_{sphere} (mm)
Epstein-Hauser model	100–500	0–50	0–0.45	19
Liu-Theofanous model	100–900	0–40	0–2.3	6–19

2.2. The correction on Epstein-Hauser model

The total heat flux and the radiation heat flux by a film boiling are calculated as follow,

$$q''_{total}=q''_{conv}+Jq''_{rad} \tag{5}$$

$$q''_{rad}=\varepsilon\sigma(T_{sphere}^4-T_{sat}^4) \tag{6}$$

where q''_{conv} is a convective heat flux from the sphere wall to the vapor-liquid interface, q''_{rad} is a radiation heat flux, J is a radiation factor, ε is an emissivity, and σ is Stefan-Boltzmann constant. The emissivity was estimated as the Eq. (7) [23]. It leads to the emissivity of a solid, when the liquid emissivity is nearly 1 (water).

$$\varepsilon=\frac{1}{\frac{1}{\varepsilon_{solid}}+\frac{1-\varepsilon_{liquid}}{\varepsilon_{liquid}}\left(\frac{r_{solid}}{r_{vapor}}\right)^2} \tag{7}$$

On the past analyses of film boiling heat transfer, there always exists the factor J with the radiation for the reason that both the convection and the radiation do not equally contribute to the vapor-liquid interface. For the value of the factor J, we decided to use 0.88 as suggested from [1,24].

The Epstein-Hauser model neglected the radiation on the heat balance at the vapor-liquid interface, as depicted in Fig. 1 and Eq. (8):

$$q''_{conv}=q''_{evap}+q''_{liquid} \tag{8}$$

where q''_{evap} is heat flux used for an evaporation at the vapor-liquid interface, and q''_{liquid} is heat flux from the vapor-liquid interface to the bulk liquid.