International Journal of Heat and Mass Transfer 124 (2018) 576–585

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Modeling film boiling within chimney-structured porous media and heat pipes

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ARTICLE INFO

Article history:
Received 8 January 2018
Received in revised form 2 March 2018
Accepted 26 March 2018

Keywords:
Film boiling
Porous medium
Deposit
Capillary pressure
Steam chimney

ABSTRACT

A porous medium with separated paths for liquid and vapor flows does not fail even after part of the porous medium is dried out. Instead, a vapor film resides within the porous medium, and it grows very slowly. This heat transfer regime was named as "confined film-boiling regime" in this study, and a heat transfer model for this regime was suggested in this paper. Especially, this paper mainly focuses on heat transfer of a CRUD (Chalk River Unidentified Deposit), which is a naturally occurring porous medium found in nuclear reactors. In the present model, the balance between capillary pressure and pressure drops of liquid and vapor flows determined thickness of the vapor film. In addition, we assumed that capillary pressure was changed with applied heat flux. This assumption was validated with a planar heat pipe case: the root-mean-square-error (RMSE) was 16% for the model with the heat flux dependent capillary pressure, while one for a model with the constant capillary pressure was 790%. Furthermore, this approach also turned out to be valid for the case of the CRUD: the model predicted the wall superheat during the film boiling of the CRUD, and its relative error was only within 20% when it was compared with the measured wall superheats. Finally, sensitivity analysis for CRUD parameters found that the heat transfer performance of the CRUD is largely sensitive to chimney density and pore size.

1. Introduction

Boiling within a porous medium with separated liquid and vapor paths has attracted many researchers, because it has been found out that the porous medium with separated paths gives better heat transfer performance comparing to the porous medium without separated paths. In heat pipe application, several novel designs have been suggested by using the separate path of liquid and vapor flows. For example, there are heat pipes with bi-porous medium [1,2], heat pipes with honeycomb shape [3], and heat pipes with a big chimney for vapor vent [4,5]. On the other hands, in nuclear industry, a naturally formed porous medium with a separate vapor path, which is called a CRUD, has received a great attention from many researchers. The present paper mainly focuses on the film boiling in the CRUD.

In a light water reactor (LWR), the CRUD has been one of the issues that have resulted in various operational and safety problems [6]. For example, the CRUD on a boiling surface can suppress neutron flux and generation of power by concentrating boron, a powerful absorber of neutron, within its pore. Furthermore, it can also corrode the fuel cladding by developing high temperature and corrosive environment within the CRUD. If this occurs severely, the fuel rod can fail so that radioactive materials within the fuel cladding may be no more held in it.

The CRUD on a boiling surface is a porous medium with two different characteristic pore sizes. One part of the CRUD, which is mostly composed of pores smaller than a micron, is the portion where liquid is drawn by capillary force. Therefore, we named this region as a "wick region". According to a recent finding, a microstructure of this region is characterized by pores with fractal-like shapes [7]. This can enable us to utilize fractal-based porous structure models to estimate pore size distribution, permeability, and so on [8]. On the other hand, the other part of the CRUD is composed of pores larger than a few microns. These pores are used as a venting path of a vapor generated during boiling, thus it has been called as a "steam chimney". This part is usually characterized by diameter of chimney (d_{ch}) and number density of chimneys (n_{ch}).

Many authors have suggested models for the CRUD under boiling. Firstly, some of them have suggested heat transfer regimes of the CRUD by analyzing boiling curves from CRUD heat transfer experiments [9–11]. Although there are some minor differences in their models, there is a consensus that there is a stable wick-boiling regime where liquid is supplied by capillary force of the wick region, while the vapor generated by boiling escapes

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.03.093
0017-9310/

Nomenclature

Symbols

ΔP	pressure drops (Pa)
D_f	fractal dimension for the pore volume
D_T	fractal dimension for the tortuous capillary path
d	vapor escape distance along film (m) (Eq. (8))
d_{ch}	chimney diameter (m)
f_{ch}	fraction of area occupied by chimneys
h_{lv}	latent heat of vaporization for water (J/kg)
k	thermal conductivity (W/(m·K))
L	CRUD thickness (m)
n_{ch}	chimney density (m^{-2})
q	heat flux (W/m^2)
r	pore or meniscus radius (m)
u	fluid velocity in x-direction (m/s)
v	fluid velocity in y-direction (m/s)
α	empirical constant for Eq. (5)
β	empirical constant for Eq. (5)
δ_v	vapor film thickness (m)
ϕ	porosity
κ	permeability (m^2)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	surface tension of water (N/m)

Subscripts

l	liquid
v	vapor
sv	vapor saturated CRUD
p	pore
men	meniscus

the CRUD through chimneys. The models for this regime have been suggested by many authors [12–17], and some of them have been validated with the CRUD heat transfer experiments with the stable wick boiling regime [16,17].

However, it has been also observed that there is a regime beyond the stable wick-boiling regime where heat transfer performance begins to decrease as heat flux increases. When the stable wick-boiling models were compared with the boiling curves from the experiments, the stable wick-boiling models overestimated the heat transfer performances [16,17]. From this observation, some authors have suggested a regime where a vapor film resides within the CRUD [10,11]. In this paper, we call this regime as a “confined film-boiling regime”, as we suggested in our previous paper [11].

The confined-film boiling regime has been observed and modeled not only in nuclear energy application, but also in heat pipe application. Moss and Kelly conducted experiments for planar heat pipe wicks, and they observed the vapor film within the wick through neutron radiography [5]. They have also suggested the model that uses “capillary limit” approach, where the balance of capillary pressure and hydraulic resistances of the fluids determines the vapor film thickness. They have found that the model overestimated the vapor film thickness for high heat flux, when the constant pore size was used to estimate capillary pressure. In other words, the model tends to underestimate heat transfer performance of the wick for high heat flux condition. Similar approach has been adopted in CRUD application by Jin and Short, and the model from their study has underestimated the effective thermal conductivity of the CRUD, when it was compared with the experimental values [10].

In the present paper, we developed a model for the confined-film boiling regime of the CRUD. We followed the “capillary limit” approach, which had been widely used in heat pipe application. However, we improved the model by looking into the relation between heat flux and capillary pressure. This was done by analyzing the data from heat pipe experiments by Moss and Kelly [5]. Next, we extended the model to the application for CRUD, which is the main topic of this paper. The fractal porous medium model is adopted to overcome the limitations coming from unknown information about CRUD pore structure. Finally, We validated the model against the CRUD heat transfer experiments from the WALT test facility [9].

2. Model description

2.1. Confined film-boiling using capillary limit approach

The confined film-boiling regime is closely related to the concept of “capillary limit” that is usually used in the heat pipe field. The capillary limit is the limiting condition where heat transfer performance degrades, as the capillary pressure of heat pipe is no longer able to endure a pressure difference across a phase interface. Since the pressure difference across the interface can be expressed as sum of pressure losses by fluid flows, the capillary limit is usually expressed as follow:

$$P_c \geqslant \Delta P_l + \Delta P_v. \tag{1}$$

The confined film-boiling regime of a porous medium is not much different from the capillary limit of a heat pipe. The vapor film and the separated vapor path act as the vapor chamber in the heat pipe, while the porous medium itself acts as the liquid wick. Therefore, the liquid pressure drop in Eq. (1) can be obtained by considering the liquid flow through the porous medium, while the vapor pressure drop in Eq. (1) can be obtained by considering the vapor flow path.

For the capillary pressure in Eq. (1), the Young-Laplace equation is usually used. Here, the curvature of the interface is usually obtained by using the radius of a meniscus in a pore:

$$P_c = \frac{2\sigma}{r_{men}}. \tag{2}$$

Generally, the meniscus radius of Eq. (2) is obtained by dividing a pore radius by a contact angle. However, it has been found that the meniscus radius can be changed as heat is applied to the pore [18,19]. In this study, we suggested the model that considered the effect of heat flux on a meniscus radius.

Here, the model is suggested by investigating two different examples. The first one is from the confined film-boiling regime of heat pipes. In this example, we deal with the experiment conducted by Moss and Kelly, where the vapor film thickness was measured during the confined film-boiling regime of planar heat pipe [5]. Using the measured vapor film thickness, the meniscus radius required for a given heat flux can be obtained. Therefore, from this example, the relation between meniscus radius and heat flux was examined. On the other hand, the second example is from the confined film-boiling regime of the CRUD, which is the naturally occurring porous medium found in a nuclear reactor. Since morphology of pores varies from a CRUD to a CRUD, it is difficult to obtain the detailed information about pore size and permeability of each CRUD. In this example, we overcame this limitation by adopting a model that predict permeability of the CRUD.

2.2. Confined film boiling of heat pipe

Confined film boiling of heat pipe was investigated through the experiment conducted by Moss and Kelly [5]. As mentioned above,