International Journal of Heat and Mass Transfer 108 (2017) 868–879

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Modeling heat transfer through chimney-structured porous deposit formed in pressurized water reactors

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ARTICLE INFO

Article history:
Received 19 October 2016
Received in revised form 13 December 2016
Accepted 13 December 2016

Keywords:
Nucleate boiling
Porous medium
Deposit
Wick boiling
Steam chimney

ABSTRACT

The model was developed to predict the heat transfer within the Chalk River Unidentified Deposit (CRUD), which is a kind of fouling found on the fuel rods of pressurized water reactors (PWR). The CRUD tends to develop steam chimneys that separate the liquid from the vapor phase. Therefore, the model describes the CRUD as a porous medium with steam chimneys. Unlike the previous approaches that assume that the evaporation takes place at the lateral surfaces of the chimneys, in the present study it is postulated that the vapor is generated by the bubble nucleation at the CRUD–clad interface, as observed via the visualization study for the chimney-structured porous medium. The generated bubble escapes through the steam chimney. The heat transfer in the CRUD can be described by three mechanisms of heat removal, which are nucleate boiling, liquid convection in the CRUD, and forced convective heat removal from the surface of the CRUD. The predicted CRUD–clad interface temperatures and overall heat transfer coefficients were compared to the experimental results, which were produced under the simulated PWR conditions (approximately 15 MPa, 300 °C). The prediction data presented better agreement with the experimental data; the normalized Root Mean Square Error (RMSE) of the present model is 18.6% in contrast with the 42.4% obtained with the Cohen model. After the validation with the experimental data, the prediction of temperature in the model was used to investigate how the heat transfer characteristics tended to change within the CRUD. Furthermore, the parametric study regarding the CRUD properties revealed that the effect of permeability on heat transfer is not significant in the nucleate boiling regime.

1. Introduction

The fouling of the corrosion product on the surfaces is one of the issues that occur in the heat transfer system; the corrosion product deposit, named Chalk River Unidentified Deposit (CRUD), is usually found in the water-cooled reactors in nuclear power plants, as well. The high power density of the fuel rods in the reactor can initiate the nucleate boiling on their surfaces, and this further accelerates the formation of deposit. Once the CRUD is formed on the fuel rod surface, the CRUD layer can offer thermal resistance to the fuel heat that is transferred to the coolant flowing through the reactor; thus, it can increase the fuel cladding surface temperature. The increased corrosion in a high-temperature environment can lead to the fuel rod failure, which results in the release of radioactive materials from the fuel rod. In addition, the chemical species in the coolant can be captured within the CRUD, under boiling conditions. Boron, which is the effective neutron absorber, is one of the species that is captured (boron hideout) in the CRUD. The hideout of boron in the CRUD can distort the power distribution of the reactor core by absorbing neutrons, which will result in the reduction in the safety and operational margin of the reactor.

The CRUD is composed of corrosion products, such as nickel ferrite, nickel oxide, and zirconium oxide [1]. The corrosion products with various shapes form the porous structure. The observation of the CRUD also revealed that it has channels with a diameter of a few microns, which are called steam chimneys. Many researchers postulated that the steam chimney is the channel from which steam escapes from the CRUD [2,3]. The effect of the CRUD structure on the thermal resistance has been studied with the synthesized CRUD, and it has been observed that a CRUD with steam chimneys has a lower thermal resistance compared to a CRUD without chimneys [2]. This confirms that the steam chimney is the most important feature for the enhancement of the heat transfer of the CRUD. However, it is difficult to confirm the postulated heat transfer mechanisms, because this micro-scale porous deposit in the harsh environment—high temperature and high pressure to

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.12.046
0017-9310/

Nomenclature

q	heat flux
u	velocity of fluid
H_{fg}	latent heat
c_p	specific heat
d_p	effective pore diameter
n_{ch}	number of chimneys per unit area
d_{ch}	diameter of steam chimney
k	thermal conductivity
s	porous shell area fraction ($\mathbf{s} = 1 - (\pi \boldsymbol{n_{ch}} \boldsymbol{d_{ch}^2}/4)$)
U_o	overall heat transfer coefficient
R	gas constant
T	temperature
P	fluid pressure
L	CRUD thickness
L_b	thermal boundary layer thickness
h_0	forced convective heat transfer coefficient
Re	Reynolds number
Pr	Prandtl number
D_f	fractal dimension for size of pore
D_T	fractal dimension for tortuous pore path
D_p	particle diameter
n	Exponent for Eq. (3.2)

Greek symbols

ρ	density
$\boldsymbol{\phi}$	porosity
$\boldsymbol{\beta}$	Multiplier for Eq. (3.2)
$\boldsymbol{\mu}$	dynamic viscosity
$\boldsymbol{\sigma}$	liquid surface tension
$\boldsymbol{\alpha}$	thermal diffusivity

Subscripts

l	fluid in liquid phase
f	saturated liquid
g	saturated vapor
m	CRUD filled with liquid
o	CRUD-coolant interface
w	CRUD-fuel rod interface
TBL	thermal boundary layer ($x = L - L_b$)
sat	saturated state

simulate the reactor conditions—is not adequate for the fine measurement of the heat transfer characteristics.

Despite the difficulties in conducting experiments, there has been effort to study the heat transfer characteristics of the CRUD. Experiments conducted in the Westinghouse Advanced Loop Tester (WALT) aimed to obtain the effective thermal conductivity of the CRUD under simulated PWR conditions [4,5]. During the experiment, the CRUD is formed on the heater rod by injecting corrosion products. After the CRUD was formed, the heat flux was adjusted to obtain the boiling curve of the heater rod with the CRUD. As a result, the researchers suggested the effective thermal conductivity values under boiling and non-boiling conditions. For the non-boiling conditions, the thermal conductivity of the solid part of the CRUD structure could be estimated, and it was given as 1.179 W/(m·°C). Therefore, the effective thermal conductivity could be obtained by averaging the thermal conductivities from the solid part and the liquid part of the CRUD. On the other hand, the trends of effective thermal conductivities under boiling conditions were qualitatively assessed along the heat fluxes, and it was revealed that the heat transfer data under these conditions contained both the boiling regime data and the dryout regime data.

Although the experimental data are limited, there are a number of models for the CRUD heat transfer under a boiling regime. The model developed by J. Uhle is one of the models that estimates the boiling heat transfer for the corrosion product deposit in the channel with forced convective flow, despite the fact that this model was developed for the steam generator fouling [6]. They postulated that the liquid saturation in the deposit is determined by the pore size and its distribution at each elevation in the deposit. The liquid fills small pores via capillary action, and the vapor occupies the large pores. In addition, they also suggest that the phase change between liquid and vapor occurs at the menisci in the pores. Therefore, it is important to find the characteristic pore radius where the liquid and the vapor pressures are balanced. This requires information about the pore size distribution, which is usually hard to obtain from the available experimental and field data.

Other branches of studies are based on the model developed by Cohen [2,3,7–9]. In this model, the CRUD has two regions. One region is the shell region, which is composed of small pores. In this region, the pore is occupied only by liquid. The other region is the steam chimney region, and this is the large channel surrounded by the shell region. This region is occupied by the vapor formed from the phase change of the liquid. For this model, the phase change occurs at the interface between the two regions. In other words, the evaporation occurs around the perimeter of the chimney. As a result, the liquid flows through the shell region and it escapes the CRUD via steam chimneys after it changes to vapor. This model is constantly studied and extended by many researchers; C. Pan extended the 1-D model to a 2-D model [3], and I. Haq further improved the model by considering the solute concentration effect on the saturation temperature [8]. In addition, J. Henshaw estimated the chemical condition within the CRUD, by adopting detailed chemical reactions in the CRUD [7]. Moreover, the convection term has been added to the energy balance equation in the shell region, and this term was found to have a significant effect on the temperature distribution in the CRUD [9]. Regarding the Cohen models, the extent of phase change depends on the evaporative heat transfer coefficients and on the saturation temperature at the chimney surface. However, the evaporative heat transfer coefficients vary among studies, and range from 2 MW/(m^2·K) to 4.69 MW/(m^2·K) [2,3]. Furthermore, some studies have adopted the assumption of the infinite heat transfer coefficient for the evaporation at chimney surfaces to simplify the problem [8,9]. This implies that there is difficulty in determining the evaporative heat transfer coefficient at the shell–chimney interface. In addition, it can be questioned whether the phase change occurs at the shell–chimney interface.

The lack of experimental data and fine measurements regarding the heat transfer characteristics of the CRUD can be backed up by the studies conducted in the field of heat pipes, which has a similar heat transfer mechanism to that of the CRUD. Recent studies have shown that the artificially formed vapor channel on the porous wick can increase the heat transfer and the critical heat flux [10–13]. The role of the vapor channel is similar to that of the steam chimney in the CRUD—it creates the path for the vapor to escape. A visualization experiment for the boiling heat transfer in the chimney-structured wick was conducted by [13]. They observed that the incipience of boiling occurs at the bottom of the patterned channel. In addition, they found that the bubble nucleates at the wick-substrate interface.

The current work is based on the recent observations regarding the boiling process in the porous wick structure. We suggest that