

Review of Phase-Change and Liquid-Vapor State Modeling Approaches in PWR CRUD

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1. Introduction

Chalk River Unidentified Deposits (CRUD) formed on pressurized water reactor (PWR) fuel cladding constitute a porous layer, which affects heat transfer between cladding and coolant. Coolant is supplied through fine pores by capillary action, while vapor can escape through larger steam chimneys. The phase state of coolant inside CRUD becomes especially important. Water vapor has a much lower thermal conductivity than liquid water. Thus, the distribution of vapor and liquid phases within the CRUD significantly influences its effective thermal conductivity. Vapor accumulation within CRUD can increase thermal resistance, whereas evaporation can enhance heat removal through latent heat transfer. Further, the porous structure couples the capillary liquid supply to phase change and heat transfer phenomena within the CRUD deposit. Current predictions of CRUD effective thermal conductivity depend strongly on how the liquid and vapor phases are represented inside the porous deposit. A better understanding of vapor formation and distribution is therefore needed to reduce the uncertainty associated with these phase-state assumptions.

Direct in situ observation of phase change inside micron-scale CRUD is challenging because of the small pore structure and the high pressure and temperature of PWR operation. Experimental studies under representative PWR conditions may provide information on the local liquid-vapor state, but direct measurements inside the porous deposit remain limited.

Existing models can be broadly grouped according to how the liquid and vapor phases are represented. Wick-boiling models generally assume that liquid is supplied through the porous matrix by capillary action and that vapor leaves through steam chimneys [1]. Later models questioned whether the pore space can remain completely liquid-filled and introduced a vapor or dryout region inside the CRUD [2,3]. Other approaches estimated the thickness of an explicit vapor film [4] or represented the vapor state using an averaged vapor fraction without resolving a liquid-vapor interface [5].

The present work compares these models with particular attention to how the amount and spatial distribution of vapor are represented. The comparison

focuses on the difference between explicit vapor film models and the enthalpy-based vapor fraction used in the Seo model.

2. Phase-Change and Liquid-Vapor State Modeling Approaches

2.1. Cinosi et al.: Wick boiling and phase-dependent conductivity

Cinosi et al. [1] investigated heat transfer through porous CRUD using a two-dimensional wick boiling model. The CRUD was represented as a porous solid with fine pores and larger steam chimneys. Water was supplied through the porous matrix by capillary action. Evaporation occurred at the chimney wall, and the generated steam escaped through the chimneys to the bulk coolant.

Before considering wick boiling, the thermal conductivity of porous CRUD was calculated using the Maxwell relation,

$$k_{CRUD} = k_{FLUID} \left[\frac{1 - \left(1 - \frac{a * k_{SOLID}}{k_{FLUID}}\right)(1 - \varepsilon)}{1 + (a - 1)(1 - \varepsilon)} \right], \quad (1)$$

where,

$$a = \frac{3k_{FLUID}}{2k_{FLUID} + k_{SOLID}}, \quad (2)$$

k_{CRUD} , k_{FLUID} , k_{SOLID} and ε denote the thermal conductivity of CRUD, the thermal conductivity the fluid in the pores, the thermal conductivity of the solid CRUD, and the porosity, respectively. The same equation was used for water and vapor. The value of k_{FLUID} was changed according to the fluid occupying the pore space.

The thermal conductivities of liquid water and vapor used in the calculation were 0.453 and 0.15 W/(m·K), respectively. The calculated thermal conductivity of CRUD filled with vapor was less than half that of CRUD filled with water [1]. In the wick boiling model, the fine pores were mainly assumed to contain liquid water, while the vapor generated by evaporation was removed

through the steam chimneys. This assumption was based on observed CRUD morphology, where fine pores provide liquid supply by capillary action and larger interconnected chimneys provide sites for evaporation and vapor escape [1]. Short et al. [2] later examined this assumption.

2.2. Short et al.: Breakdown of the liquid-saturation assumption

Short et al. [2] developed MAMBA-BDM, a two-dimensional multiphysics model coupling heat conduction and convection, Darcy flow, solute transport, precipitation, and spatially dependent material properties. In the model, the pore space within the CRUD was assumed to remain liquid-filled, while the saturation temperature was imposed at the CRUD-chimney boundary.

The model predicted unrealistically high liquid superheat and an effective CRUD thermal conductivity of about 5.04 W/(m·K), substantially higher than the experimental values, which ranged from approximately 0.52 to 1.82 W/(m·K) [2]. These experimental effective conductivities were inferred from temperature measurements and a thermal resistance relation under PWR-relevant boiling conditions, rather than measured directly as an intrinsic material property. Based on these results, the authors questioned the assumption that the CRUD pore space remains completely liquid-filled and suggested that a vapor or dryout region should be considered [2]. They also noted that a two-phase model should include capillary pressure at the liquid-vapor interface.

2.3. Jin and Short: Explicit vapor film and liquid-vapor interface

Jin and Short [3] developed MAMBA-2Phase by introducing a vapor region inside the CRUD. The model assumed a vapor region near the cladding and a liquid region near the coolant, separated by a liquid-vapor interface.

A mixed two-phase region was not used because it was difficult to represent consistently within the Darcy flow and heat transfer formulation. Under local equilibrium, a two-phase region would remain close to the saturation temperature. In addition, the capillary pressure difference and the sharp change in thermophysical properties at the liquid-vapor interface caused numerical convergence problems. The liquid and vapor regions were therefore solved separately and coupled through the interface [3].

The calculation started with an assumed vapor film thickness. The local pressure and saturation conditions were checked, and the interface position was adjusted during the calculation. Heat transfer, fluid flow, chemistry, and solute transport were solved in the liquid

region, while heat transfer and vapor transport were solved in the vapor region. The results showed that a thin vapor region near the cladding can affect CRUD thermal conductivity and cladding temperature. However, the assumed separation between the liquid and vapor regions still requires experimental confirmation.

2.4. Shen et al.: Quantification of vapor film thickness

Shen et al. [4] estimated the vapor film thickness from a pressure balance at the liquid-vapor interface. The vapor pressure was balanced against the liquid pressure together with capillary or disjoining forces, and the resulting film thickness depended on CRUD structure and heat flux.

The effects of CRUD porosity, chimney density, particle size, CRUD thickness, and heat flux on the vapor film thickness were examined. Based on these results, a multivariate regression correlation was developed to estimate the film thickness [4]. The correlation was introduced to reduce the repeated calculations required when the vapor film thickness was coupled with the two-phase film boiling model.

2.5. Seo: Enthalpy-based vapor fraction and present model limitation

Seo [5] developed a multiphysics model for CRUD growth and boron hideout during long-term PWR operation. The heat transfer model includes conduction through the porous CRUD, convection due to capillary coolant flow, and evaporation associated with steam chimneys. The liquid-vapor interface is not resolved explicitly in the volume-averaged CRUD domain. Instead, the vapor fraction is calculated from the local enthalpy using the saturated liquid and vapor states:

$$x_v = \frac{H_f(T_{surf}) - H_f(T_{sat})}{H_g(T_{sat}) - H_f(T_{sat})} \quad (3)$$

The vapor fraction is used to calculate the coolant and effective CRUD thermal conductivities together with the liquid, vapor, and solid thermal conductivities and the porosity. Seo noted that vapor layer formation and the capillary interface are difficult to represent in the volume averaged model. The vapor fraction is therefore calculated without explicitly treating capillary surface tension or the shape of the vapor region. A maximum value is also imposed on the vapor fraction to avoid numerical divergence [5].

Seo also stated that the vapor phase is only approximately represented by the enthalpy relation and that a more detailed treatment of vapor behavior is needed for better prediction of coolant thermal conductivity [5]. For this reason, the present work first

focuses on how vapor is represented inside CRUD before modifying the effective thermal conductivity model.

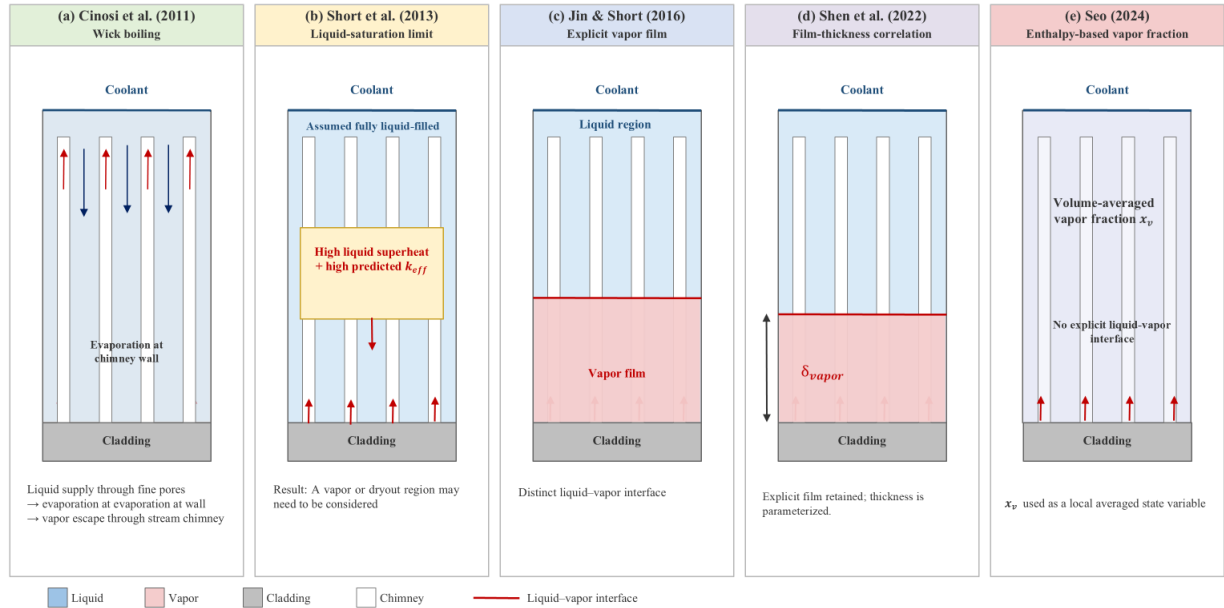


Fig. 1. Schematic comparison of liquid-vapor state treatments in representative PWR CRUD models, based on Refs. [1-5].

3. Discussion of Vapor Representation

3.1. What phase state is physically plausible inside CRUD?

The five studies use different ways to describe the liquid and vapor phases in CRUD, as summarized in Fig. 1. Cinosi et al. [1] assumed that liquid is supplied through the porous matrix and vapor leaves through steam chimneys. Short et al. [2] showed that keeping the pore space completely liquid can lead to unrealistically high superheat and overprediction of heat transfer. Jin and Short [3] introduced a vapor film near the cladding, and Shen et al. [4] developed a correlation for the thickness of this film. Seo [5] used a local enthalpy-based vapor fraction instead of resolving a liquid-vapor interface.

These studies show that vapor needs to be considered, but they do not establish a single spatial distribution of vapor inside CRUD. Capillary pressure, saturation conditions, heat flux, and vapor escape through steam chimneys may all affect whether a vapor film can remain near the cladding.

3.2. Considerations for vapor representation in the Seo model

In the Seo model [5], vapor is represented by an enthalpy-based fraction, while the location and shape of the vapor region are not explicitly resolved. The previous studies reviewed above provide different information that may be useful when examining this representation.

Short et al. [2] showed that the completely liquid-filled assumption was not physically appropriate under the boiling conditions examined, while Jin and Short [3] and Shen et al. [4] considered an explicit vapor region near the cladding.

These results do not directly determine how vapor should be represented in the Seo model. These studies can help assess whether the vapor fraction alone is enough to describe the effect of vapor on effective thermal conductivity, or whether the location of vapor should also be considered.

3.3. Explicit film thickness versus enthalpy-based vapor fraction

The film models and the Seo model represent vapor in different ways. In Jin and Short [3] and Shen et al. [4], the vapor region is located near the cladding, and its size is described by the film thickness. In Seo [5], the vapor fraction is calculated from enthalpy and gives an averaged measure of vapor content, but it does not show where the vapor is located. Film thickness and vapor fraction therefore represent different information. They cannot be compared directly as equivalent quantities. Instead, the comparison is made in terms of the phase-state information retained by each representation. An explicit vapor film assigns vapor to a specific region, while an averaged vapor fraction gives only the amount of vapor within the computational volume. The same average vapor fraction could therefore correspond to different spatial distributions, such as a cladding-

adjacent film, isolated vapor pockets, or vapor connected to steam chimneys. These different distributions may not produce the same thermal response.

A simple relation between the two may be possible under limited assumptions. For example, if the CRUD is treated as a planar layer with uniform porosity, the ratio of vapor film thickness to total CRUD thickness could be related to a dryout fraction. In actual CRUD, however, the same vapor fraction could result from a vapor film near the cladding, isolated vapor regions, or vapor connected to steam chimneys. Therefore, the vapor fraction alone may not be enough to describe the spatial distribution of vapor.

3.4. Relation to future effective thermal conductivity modeling

A remaining question is whether the effective thermal conductivity of CRUD can be determined from vapor fraction alone or whether the spatial distribution of vapor must also be considered. The reviewed models represent this information differently. An explicit vapor film specifies where vapor is located, while the Seo model provides an averaged vapor fraction without resolving the liquid-vapor interface.

The next step is therefore to examine how different vapor distributions affect the thermal response for a given vapor fraction. Representative distributions, such as a cladding-adjacent vapor region or a more distributed vapor state, can be compared to determine whether the same average vapor fraction leads to different effective thermal conductivities. This would show whether vapor fraction alone is sufficient or whether additional spatial information is needed in the conductivity treatment.

4. Conclusions

The reviewed studies show that the main uncertainty is not simply whether vapor forms inside CRUD, but how the vapor state should be represented. A volume-averaged vapor fraction describes the amount of vapor, while an explicit vapor region also provides spatial information. These representations are therefore not equivalent for heat-transfer modeling.

The comparison indicates that vapor amount and vapor location should be treated as separate aspects of the phase state. This distinction provides a basis for deciding what phase-state information should be retained when effective thermal conductivity is evaluated.

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