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Evaluating Scaling Effects of Steam Condensation Physics-based Model for Small Modular Reactor

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INTRODUCTION

The features of small modular reactors (SMRs) include their capacity to be factory-built, their modular design, their transportability, and multi-units capacity addition [1]. In a light-water-type SMR, water serves as both the coolant and moderator. During postulated accidents, steam reacts with the fuel cladding material (Zircoloy) to produce hydrogen [2]. Overpressure then leads to steam and hydrogen gas from the reactor pressure vessel being released to the reactor containment. Thus, the steam condenses in the containment wall, and heat is released to the containment wall and its outside water pool, which is called the passive containment cooling system (PCCS) [3]. Verification and validation effort of models for reactor systems (for e.g., PCCS) is necessary for further development of the models and in identifying the existing gaps, respectively.

This study focused on assessing condensation heat transfer (CHT) models for enhancing the passive safety of small modular reactors (SMRs). It also encompassed a review of the theoretical and semi-theoretical CHT models and correlations. Condensation models such as the degradation factor, heat and mass transfer analogy (HMTA), and boundary layer models are used to study advanced nuclear reactor PCCS. The previous CHT models were developed for small tube geometries, which differ from the containment of SMR. This study examined the scaled relations of the CHT models for a physics-based model for analyzing laminar and turbulent film condensation downward flow conditions inside scaled tube geometries.

THEORY

The previous works on CHT were grouped into theoretical, experimental, and numerical studies. The experimental studies were sub-grouped into separate and integral effect tests covering a wide range of geometric, physics, fluid, and operating conditions. Similarly, the theoretical and the numerical studies were sub-grouped into conceptual modeling, simulations, and multiphysics computational fluid dynamics using commercial software, system, and in-house-developed codes. Many of the earlier studies on the reactor in containment condensation considered the effect of non-condensable gases (e.g., air, nitrogen, hydrogen, and helium). At the most basic level, condensation is defined as the process of changing, through heat transfer, vapor into liquid on a cold wall. In this process, vapor that comes into contact with a cold surface releases latent energy by releasing heat to that cold surface. This heat transfer eventually reduces its temperature to the saturation temperature, and finally the vapor is transformed into a liquid phase (i.e., condensate [3]). The condensate creates resistance between the hot vapor and the cold wall, reducing heat transfer performance. There are two types of condensation: film-wise and drop-wise (see Fig. 1). Film-wise condensation occurs on a clean surface, whereas drop-wise condensation occurs on a coated surface, which inhibits wetting [4]. In film-wise condensation, the condensate film covers the surface and flows down as the result of shear or gravitational forces [4]. In drop-wise condensation, drops form in surface cavities.

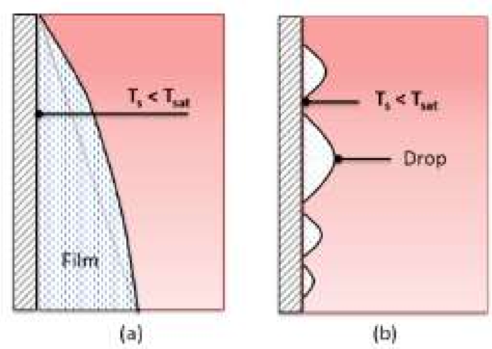

Fig. 1: Condensation schematics: (a) film-wise and (b) drop-wise [4].

The CHT analytical studies were grouped into theoretical and semi-theoretical models. These models were further categorized into boundary layer models, diffusion layer models, heat and mass transfer analogy (HMTA) models, and fluid film models [5-6]. The Nusslet (1916) study analyzed laminar film condensation laid down on a vertical flat plate by a quiescent vapor [7]. It was the first closed-form, physics-based solution. Many other theoretical correlations were developed based on Nusselt's studies, including the effects of subcooling, surface waviness, interfacial shear stress, and turbulence. Minkowycz and Sparrow (1966) [8], Dehbi et al. (1991) [9], and Oh and Revankar (2005) [10] analyzed CHT by developing boundary layer models, whereas Colburn and Hougen (1934) [11], Kim and Corradini (1990) [12], and Peterson et al. (1993) [13] used HMTA.

The CHT analytical studies for vertical tube geometries were examined by various researchers (Wang and Tu (1988) [14], Siddique et al. (1994) [15], Munoz-Cobo et al. (1996) [16]), A. Dehbi and S. Guentay (1997) [17], and K.Y. Lee (2007) [18]) which were similar to the reactor passive cooling applications. However, there was no correlation for the scaling of tube geometry effects. To fill this gap, the present work evaluates the scaling evaluation using Le (2012) physics-based model [19]. Nusselt's analysis was used as the starting point for Le's model, which consist of a laminar film CHT and a quiescent vapor, followed by a laminar and turbulent mixed-convection film CHT, as shown in Fig 2.

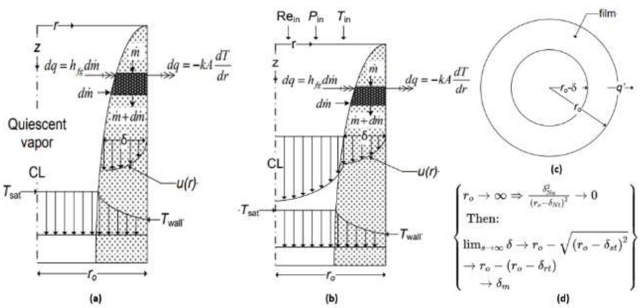

Fig.2: Le's CHT model [19]: (a) laminar film and quiescent vapor, (b) laminar film and non-quiescent vapor, (c) tube-to-wall physics model, and (d) film thickness mathematical relation.

Fig. 2(a) shows that the vapor was stagnant and pure and had a uniform saturation temperature, and that the film was laminar. The wall temperature and fluid properties were constant. It also simplified the physics with an only axial pressure gradient, $\frac{dP}{dz} = \rho_v g$, and no shear stress at the liquid-vapor interface. Furthermore, the film was considered to have radial conduction heat transfer but no axial advection and diffusion of momentum. Fig. 2(b) considered laminar vapor flow with a shear force at the liquid-vapor interface. All other approximations were the same. The liquid and interface velocities were separated by the forced and natural convections. The turbulent vapor was developed replacing the fluid properties for turbulent conditions. The following equations were considered in the CHT modeling.

HTCs:

$$h_f(T_i - T_w) = (h_c + h_s)(T_b - T_i) \quad (1)$$

$$h_{tot} = \left[\frac{1}{h_f} + \frac{1}{h_c + h_s}\right]^{-1} \quad (2)$$

Where, h_f is the HTC for the film, h_c is the HTC for condensation, h_s is the sensible HTC, and h_{tot} is the total HTC. The film HTC and film Nu can also be represented as:

$$h = \frac{k_l}{\delta} \qquad (3)$$

$$\mathrm{Nu} = \frac{h2r_o}{k_l} \quad (4)$$

Where, δ is the film thickness, k_l is the thermal conductivity of the film, and r_o is the radius of the condensing tube.

REFERENCE TEST DATA

In this study, the Kuhn (1995) were used to assess the CHT models and correlations [20]. Test sections consisted of vertical condenser tubes with annular jacket cooling in a counter-current flow arrangement in which the steam-NCG mixture flowed downward in the condenser tube and the cooling water moved upward. The condenser tube in Kuhn (1995) was 3.37 m long and had a 47.5 mm inner diameter and a thickness of 1.65 mm [20].

Le's model was evaluated using Kuhn's experimental data on pure steam (as shown in Fig. 3). For the model assessment, two test cases were used: a low-pressure case (run 1.1-1) and a moderate-pressure case (run1.3-2R2). As with the Le's model, experimental temperature differences pertaining to four physics phenomena were investigated for vapor mixtures and condensate films by conducting constant and curve fit experiments.

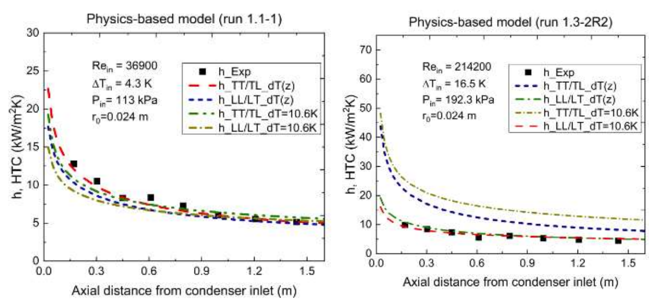

Fig. 3: Verification results for the Le's, using UCB Kuhn's test for HTC for run1.1-1 and run 1.3-2R2.

The physics phenomena were TT, TL, LT, and LL, where T and L represent the turbulent and laminar flow modes, respectively. The first flow mode was for a vapor-mixture and the second was for a condensate film. The constant temperature difference method was straightforward to implement, as it did not require experimental condensing wall temperature data. For run1.1-1 (as shown in Fig. 3), the model-predicted HTC values for the temperature differences and flow mode cases were within a standard deviation of 10% and the corresponding standard deviation for Nu within 5%.

The TT and TL cases did show deviation and the HTC was overpredicted by a factor of approximately 2. On the other hand, the LL and LT cases produced HTC that were within 15% deviation of the test data. Thus, the Nu values were validated for both the TT and TL cases and were predicted within 5% deviation.

SCALE EVALUATION RESULTS

Review and evaluation of the models revealed that multiple approaches could be used to model CHT, and that predictability depended on the physics layout, test conditions, and boundary values. The degradation factor method employed the closed-form analytical model and empirical solutions. HMTA with thermal resistance, heat, and mass transfer analogy was widely used by researchers with HTC prediction capabilities, and it had a standard deviation of 3.24% for steam-helium mixtures and 6.38% for steam-air mixtures (Kuhn, 1995) [18].

The condensation modeling approach also used the BLM to solve mass, momentum, and energy for the liquid films and steam-NCG mixtures. System codes such as RELAP5 3D, GOTHIC, and MELCOR were used primarily in empirical correlations and HMTA; they were required by regulatory agencies for reactor design licensing and evaluations. The first closed-form CHT solution was a physics-based approach, and the Le's models demonstrated abilities to predict with an error margin but subjected to test and physics conditions. The scaling effects were evaluated using the physics-based model. This scaling evaluation will be continued with the scaled test datasets from Missouri S&T [3] to investigate the CHT modeling capabilities for fostering SMR safety.

Le's model was evaluated for scaled geometries using the Kuhn (1995) test conditions (i.e., run1.1-1 and 1.3-2R2) for pure steam (see Fig. 4 and Fig. 5).

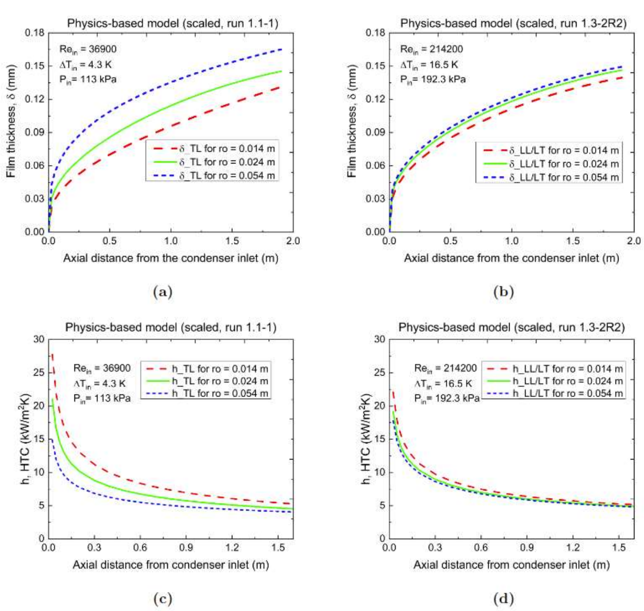

Fig. 4: Model's scaled results for UCB Kuhn's test (run1.1-1 and run1.3-2R2) data: (a)–(b) δ and (c)–(d) h.

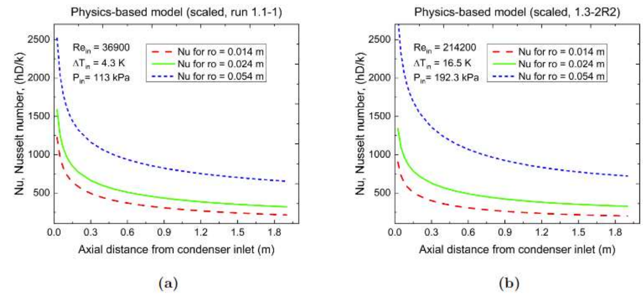

Fig. 5: Model's scaled results for UCB Kuhn's test (run1.1-1 and run1.3-2R2) data:(e)–(f) Nu.

The results for both test cases were similar; however, the film thickness and HTC values for run 1.3-2R2 showed fewer scaling effects compared to Nu. This was because the flow modes differed. Run 1.1-1 provided better predictions for turbulent vapor-mixture cases (i.e., TT and TL), whereas run 1.3-2R2 provided better predictions for laminar vapor-mixture cases (i.e., LL and LT).

CONCLUSION

This study discusses condensation heat transfer studies and evaluates physics-based model scaling with well-cited experimental conditions. This study led to the following observations and findings:

- Test case and the complexity of the physics conditions (e.g., turbulence effects and recirculating effects) can lead to challenges in predicting scaling effects for parameters such as film thickness and HTC.
- Scaling effects occur with heat transfer non-dimensional numbers such as Nusselt's number, which is influenced by the vapor-mixture flow modes (e.g., turbulence and laminar flow) and vapor-film interface conditions (e.g., temperature, shear effects).

Such findings may prove useful in predicting the scaling effect when the vapor-mixture region is comprised of different flow modes. Further studies on scaling evaluation will be performed using scaled test dataset from Missouri S&T CHT scaled experiments.

NOMENCLATURE

SMR = Small modular reactor
PCCS = Passive containment cooling system
CHT = Condensation heat transfer
HMTA = Heat and mass transfer analogy
h, HTC = Heat transfer coefficient
S&T = Science and Technology
P = pressure
ρ = density
g = gravitation acceleration
Nu = Nusselt number

T = Temperature [K]
δ = Film thickness
r = tube radius

Subscript:
f = film,
i = interface
c = condensation
s = sensible
tot = total
l = laminar
b = bulk

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