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

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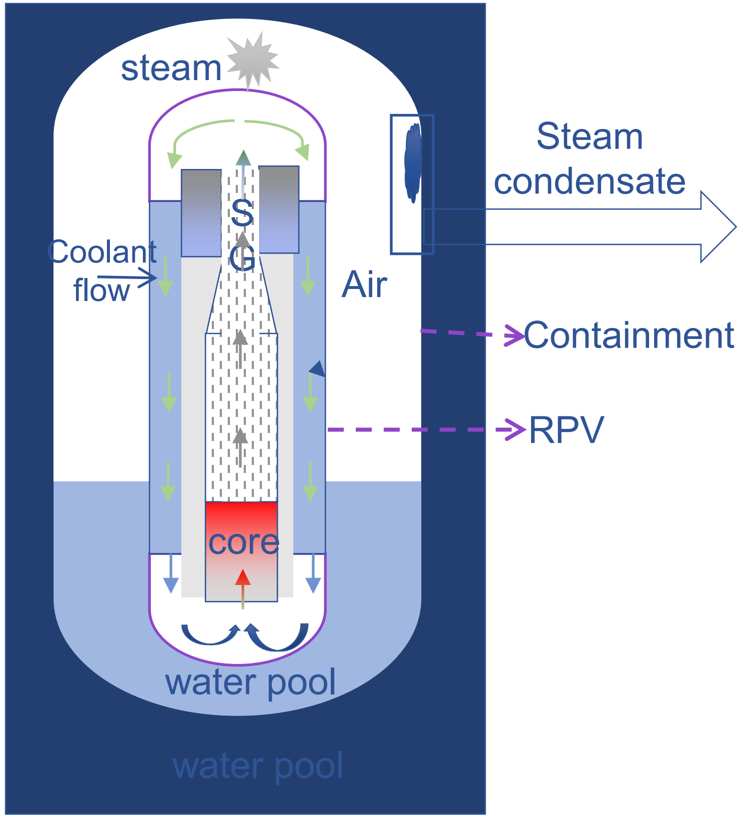
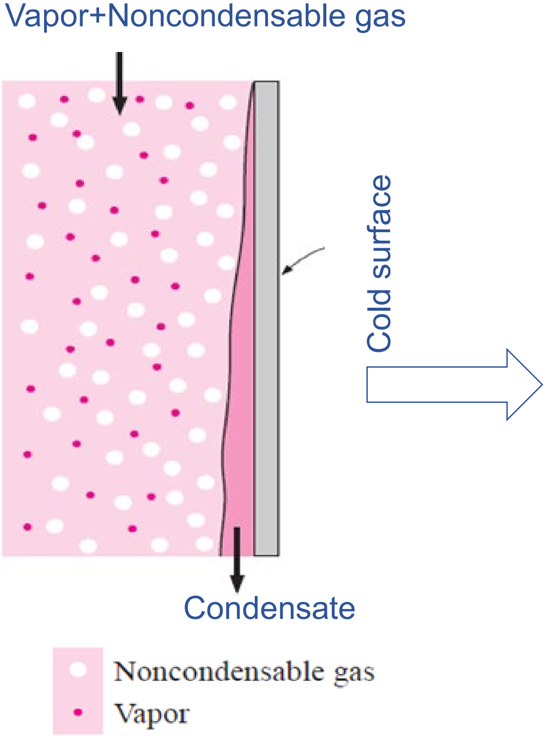
Introduction: Problem Overview

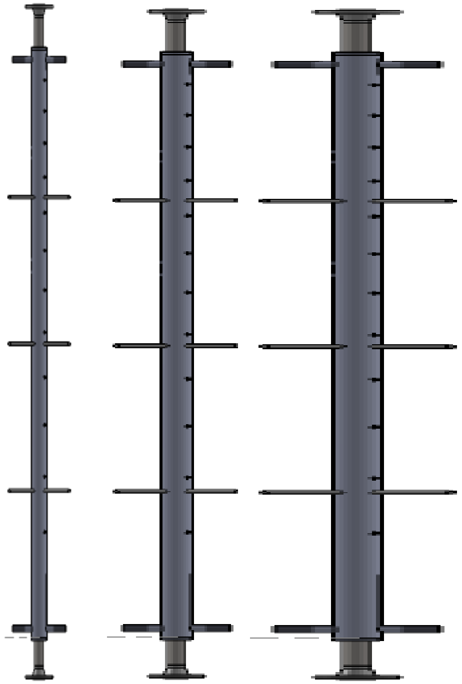


SMR



[1]

Condensation



Scaled test

Introduction: Objectives and Motivations

- In order to avoid steam release accidents, water-cooled small modular reactor (SMR) systems require:
  - Adequate modeling of the steam condensation heat transfer (CHT) in the containment, as well as heat release to the outside water pool, which is called the passive containment cooling system (PCCS) [2-4].
  - Verification and validation effort of models for reactor systems (e.g., PCCS) is necessary for further development of the models and in identifying the existing gaps, respectively.
  - However, **previous CHT modeling studies did not cover scaled-sized containment geometries adequately.**
- This study examined the scaled relations of a CHT model:
  - A physics-based model for analyzing laminar and turbulent film condensation downward flow conditions inside scaled tube geometries.

Condensation Studies

- Condensation studies were grouped into:
  - **Experimental studies**, which were sub-grouped into:
    - Separate effect tests, and
    - Integral effect tests

    covering a wide range of geometric, physics, fluid, and operating conditions.
  - **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.
  - 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].
    - 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.

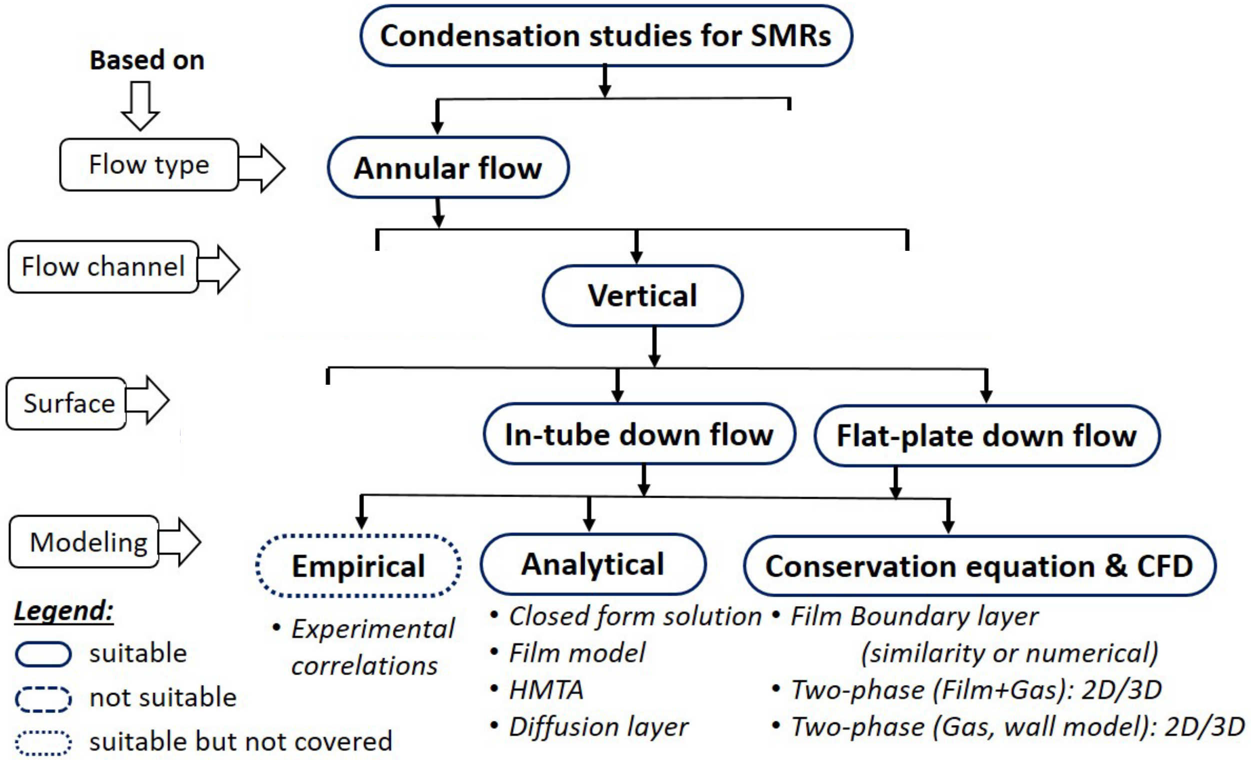


Fig. 1: Overview of condensation studies for SMR [5].

Objectives and Motivations (cont'd)

- 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].
  - These previous studies were similar to the reactor passive cooling applications.
  - However, there was no correlation for the scaling of tube geometry effects.

- This study evaluates the scaling evaluation using Le (2012) physics-based model [19]:
  - Nusselt's analysis was used as the starting point.
  - It consist of a laminar film CHT and a quiescent vapor, followed by a laminar and turbulent mixed-convection film CHT.
  - The physics phenomena were TT, TL, LT, and LL, where T and L represent the turbulent and laminar flow modes, respectively.

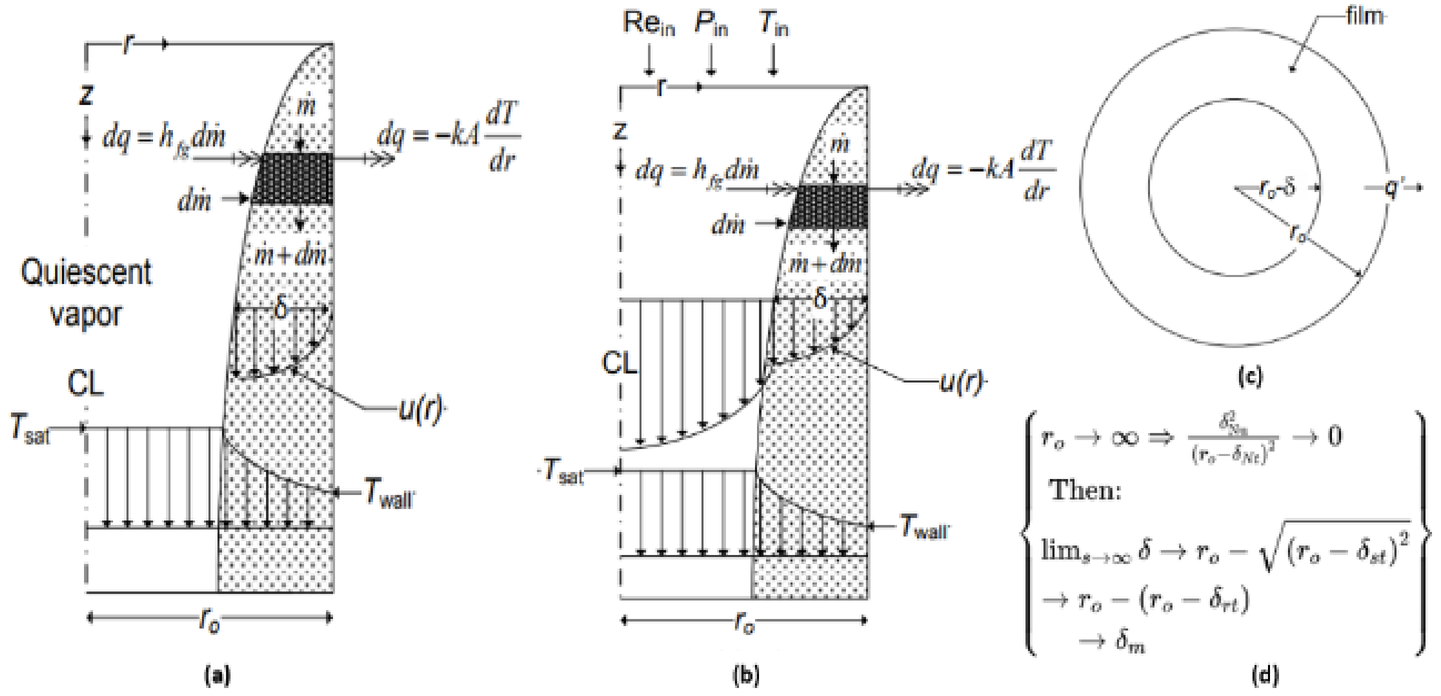


Fig. 2: Le's CHT model [19]: (a) laminar film and quiescent vapor, (b) laminar film and non-quiescent vapor, (c) tube-to-wall physics model, and (d) film thickness mathematical relation.

Physics Modeling

- Approximations:
  - Laminar film, quiescent vapor, and non-quiescent vapor.
  - The wall temperature and fluid properties were constant.
  - No shear stress at the liquid-vapor interface.
  - Film have radial conduction heat transfer only.
  - Considered laminar vapor flow with a shear force at the liquid-vapor interface.

- 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:

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

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

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 Dataset

- Kuhn's experimental data on pure steam:
  - Used for the model assessment.
  - Two test cases were used:
    - a low-pressure case (run 1.1-1)
    - a moderate-pressure case (run 1.3-2R2).
  - The condenser tube was 3.37 mm long and had a 47.5 mm inner diameter and a thickness of 1.65 mm [20].

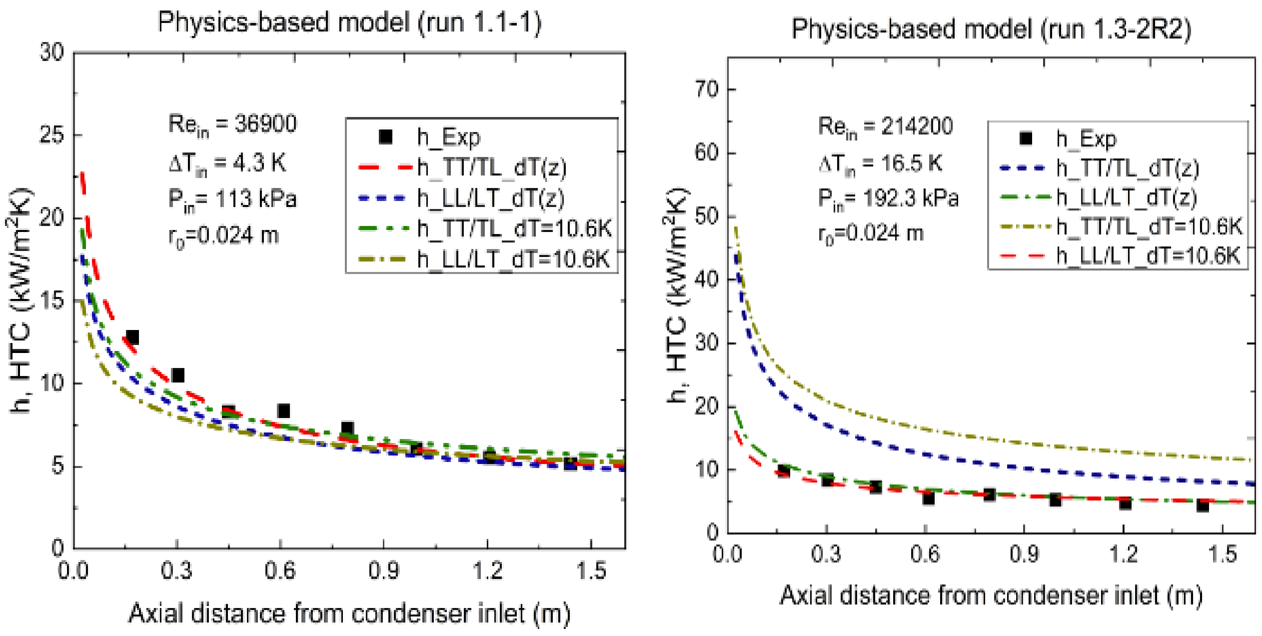


Fig. 3: Verification results for the Le's, using UCB Kuhn's test for HTC for run1.1-1 and run 1.3-2R2 [20].

Scaling Evaluation

- Physics model was evaluated for:
  - scaled geometries of 1”, 2”, and 3” condensing vertical pipes with the same heights
  - the Kuhn (1995) test conditions (i.e., run 1.1-1 and 1.3-2R2) for pure steam.

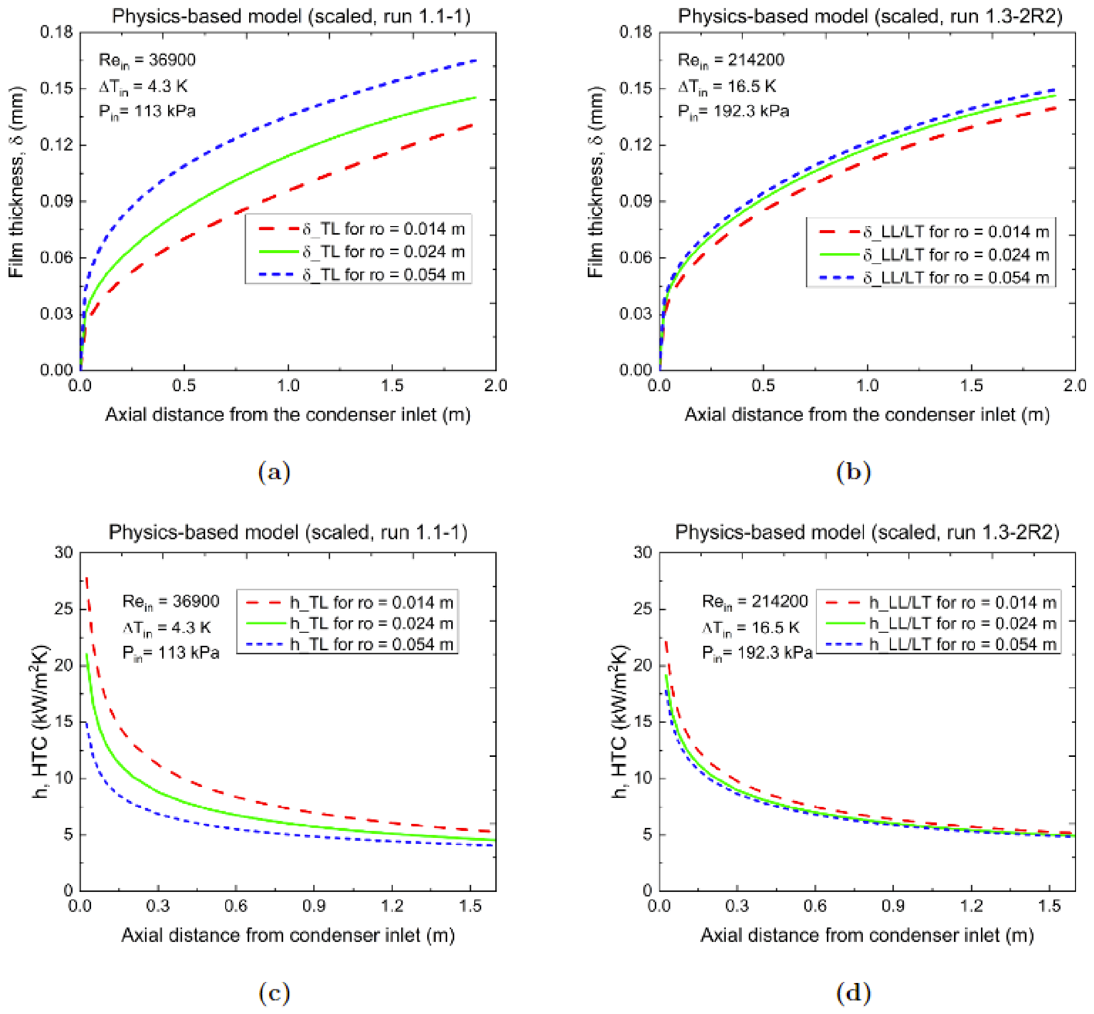
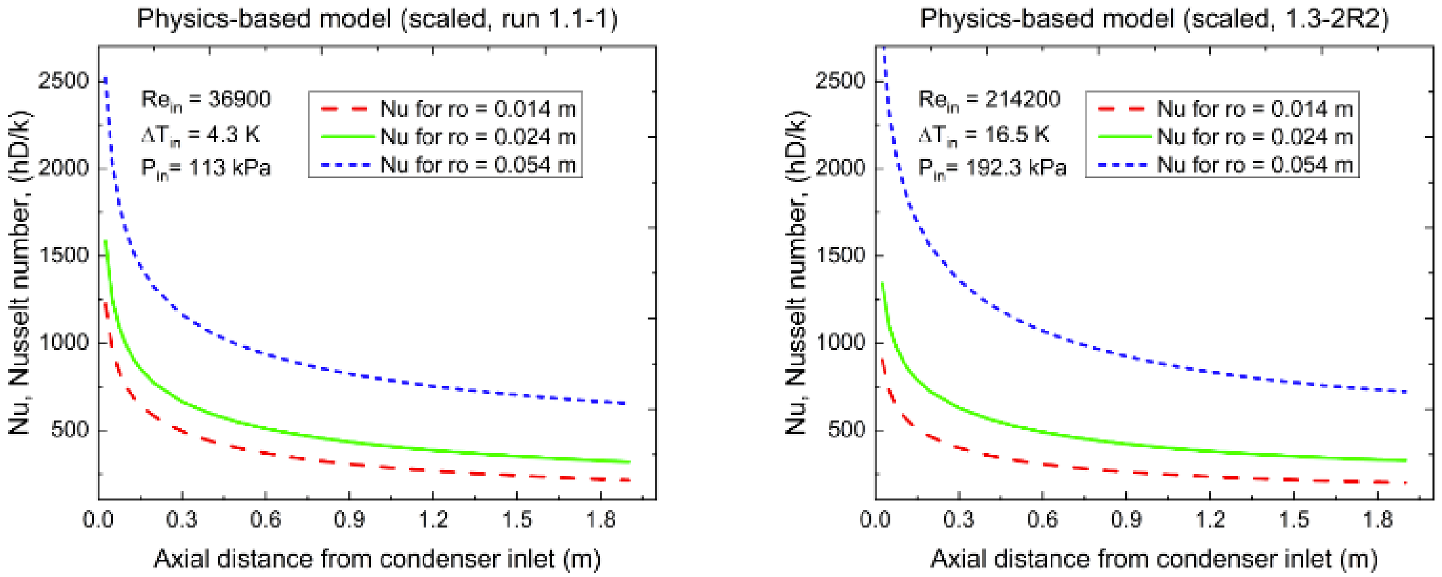


Fig. 4: Model’s scaled results for UCB Kuhn’s test (run 1.1-1 and run 1.3-2R2) data: (a)–(b) δ and (c)–(d) h.

Scaling Evaluation (cont'd)

- 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).



(a) (b)

Fig. 5: Model's scaled results for UCB Kuhn's test (run 1.1-1 and run 1.3-2R2) data:(e)–(f) Nu.

Summary, Conclusions, and Path Forward

- The physics-based model scaling with a well-cited experimental condition led to the following observation 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.
- Future research direction would be:
  - Evaluating with scaled-geometries test data and system code (e.g., RELAP) results.

References

1. F. P. INCROPERA, D. P. DEWITT, T. L. BERGMAN, & A. S. LAVINE, "Fundamentals of heat and mass transfer," Vol. **6**, pp. 408-409, New York: Wiley, (1996).
2. IAEA, "Small Modular Reactors: A new nuclear energy paradigm, pre-print," International Atomic Energy Agency (IAEA), Vienna, Austria (2022).
3. M. GROSSE, M. STEINBRUECK, E. LEHMANN, P. VONTOBEL, "Kinetics of hydrogen absorption and release in zirconium alloys during steam oxidation," *Oxidation of Metals*, **70**, 149–162 (2008).
4. P. K. BHOWMIK, J. P. SCHLEGEL, V. KALRA, C. MILLS, AND S. USMAN, "Design of condensation heat transfer experiment to evaluate scaling distortion in small modular reactor safety analysis," Journal of *Nuclear Engineering and Radiation Science*, vol. **7**, no. 3 (2021).
5. P. K. BHOWMIK, J. P. SCHLEGEL, AND S. REVANKAR, "State-of-the-art and review of condensation heat transfer for small modular reactor passive safety: Experimental studies," *International Journal of Heat and Mass Transfer*, vol. **192**, p. 122936, (2022).
6. M. K. YADAV, S. KHANDEKAR, AND P. K. SHARMA, "An integrated approach to steam condensation studies inside reactor containments: a review," *Nuclear Engineering and Design*, 300, 181-209 (2016).
7. W. NUSSELT, "Die oberflachenkondensation des wasserdamphes. Z. Vereins desutscher Ininuere," (1916).
8. W. MINKOWYCZ, E. SPARROW, "Condensation heat transfer in the presence of noncondensables, interfacial resistance, superheating, variable properties, and diffusion," *International Journal of Heat and Mass Transfer* **9**, 1125–1144 (1966).
9. A. DEHBI, M. GOLAY, M. KAZIMI, "Condensation experiments in steam-air and steam-air-helium mixtures under turbulent natural convection," *National Conference of Heat Transfer*, AIChE Symp. Ser, pp. 19–28 (1991).
10. S. OH, S. REVANKAR, "Boundary layer analysis for steam condensation in a vertical tube with noncondensable gases," *Int. J. Heat Ex* **6**, 93–124 (2005).
11. A.P. COLBURN, O.A. HOUGEN, "Design of cooler condensers for mixtures of vapors with noncondensing gases," *Industrial & Engineering Chemistry* **26**, 1178–1182 (1934).
12. M.H. KIM, M. CORRADINI, "Modeling of condensation heat transfer in a reactor containment," *Nuclear Engineering and Design* **118**, 193–212 (1990).
13. P. PETERSON, V. SCHROCK, T. KAGEYAMA, "Diffusion layer theory for turbulent vapor condensation with noncondensable gases," *Journal of Heat Transfer* **115**, 998–1003 (1993).
14. C.Y. WANG, C.J. TU, Effects of non-condensable gas on laminar film condensation in a vertical tube. *International Journal of Heat and Mass Transfer* **31**, 2339–2345 (1988).
15. M. SIDDIQUE, M. W. GOLAY, M.S. KAZIMI, "Theoretical modeling of forced convection condensation of steam in a vertical tube in the presence of a noncondensable gas," Nuclear technology **106**, 202–215 (1994).
16. J. MUNOZ-COBO, L. HERRANZ, J. SANCHO, I. TKACHENKO, G. VERDU, Turbulent vapor condensation with noncondensable gases in vertical tubes. *International Journal of Heat and Mass Transfer* **39**, 3249–3260 (1996).
17. A. DEHBI, S. GUENTAY, "A model for the performance of a vertical tube condenser in the presence of noncondensable gases," *Nuclear Engineering and Design* **177**, 41–52 (1997).
18. K.Y. LEE, "The Effects of Noncondensable Gas on Steam Condensation in a Vertical Tube of Passive Residual Heat Removal System," Ph.D. thesis, Department of Mechanical Engineering, Pohang University of Science and Technology, Pohang, Korea (2007).
19. Q. T. LE, "Physically based closed-form solutions for film condensation of pure vapors in vertical tubes," University of Manitoba, Canada, (2012).
20. S.Z. KUHN, "Investigation of Heat Transfer from Condensing Steam-Gas Mixtures and Turbulent Films Flowing Downward Inside a Vertical Tube," Ph.D. thesis, University of California, Berkeley. UMI, 300, North Zeeb Road, Ann Arbor, MI 48103, (1995).

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Thank you for your attention!

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