Validation of a Condensation Heat Transfer Model for SMR PCCS Analysis

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1. Introduction

The Passive Containment Cooling System (PCCS) in an SMR is a critical passive safety feature designed to control containment pressure and temperature during severe accidents. The heat removal performance of the PCCS is highly governed by the non-condensable gas (air) boundary layer built up on the outer tube surface. Therefore, a reliable condensation model is essential for safety analysis codes.

However, widely used correlations employ power-law forms, which cause calculated heat transfer coefficients to diverge to infinity as the air fraction approaches zero. This numerical singularity leads to computational failures during transient system codes. To resolve this computational instability, we evaluate and validate an exponential decay-type model that defines a clear physical boundary limit and integrates a dynamic dialing factor to ensure physical fidelity under various operating conditions.

2. Methods and Results

The validation of the proposed model incorporates a systematic evaluation from physical mechanism formulation to experimental comparative validation.

2.1. PCCS Boundary Layer Concept

To capture the essential heat and mass transfer characteristics, the physical mechanism of the liquid condensate film and non-condensable gas diffusion boundary layer built up on the outer tube surface was formulated.

2.2. Gas Property Variations

The non-linear impact of air mass fraction (w_{air}) on mixture properties was analyzed. As w_{air} rises, the dramatic increases in density and viscosity strongly suppress steam diffusion toward the wall.

2.3. Coolant Temperature Profile and Air Ingress Effect

The sensitivity of the coolant temperature profile along the tube length was investigated under varying air mass fractions. As depicted in Fig. 1, an increase in air ingress leads to a flattened coolant temperature profile along the tube length, visually demonstrating the severe attenuation of effective condensation heat transfer driven by non-condensable gas accumulation.

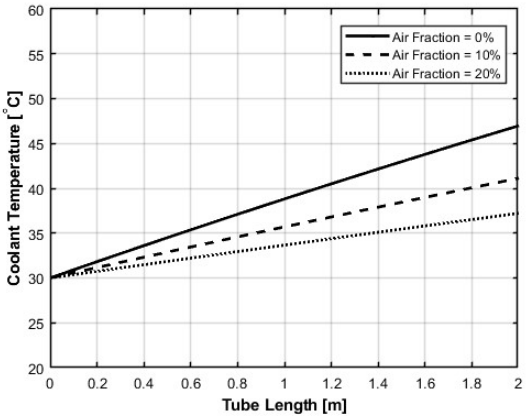

Fig. 1. Effect of Air Ingress

2.4 .Baseline Exponential Model Calibration (U_{base})

To resolve the numerical divergence inherent in power-law correlations, an exponential baseline model was evaluated for PCCS outer-tube conditions.

$$U_{base} = C_1 \cdot e^{-C_2 \cdot w_{air}} \quad (1)$$

$$Nu_{base} = \left(\frac{C_1 d_t}{k_{gas}}\right) e^{-C_2 W_{air}} \quad (2)$$

Using the benchmark Uchida [1] experimental dataset under atmospheric conditions in Table 1, the baseline parameters were calibrated using MATLAB non-linear least-squares optimization. The upper physical bound at pure steam conditions ($w_{air} = 0$) was determined as $C_1 = 1985.4\ W/m^2 \cdot K$, and the exponential decay constant was calculated as $C_2 = 4.6210$.

Table I: Summary of Uchida [1] experimental dataset

Parameter	Value	Unit
System Pressure (P)	1.013 (1.0 atm)	bar
Tube Outer Diameter (d_t)	0.038 (38 mm)	m
Air Mass Fraction (W_{air})	0.001 ~ 0.30	-
Coolant Temperature	20 ~ 100	℃
Flow Regime	Stagnant/Natural Convection	-

Fig. 2 illustrates the comparative behavior between condensation models. While the conventional Kataoka [2] power-law model exhibits an unphysical asymptotic divergence near $w_{air} \to 0$, the proposed exponential baseline model U_{bas} maintains a stable upper physical boundary, successfully preventing numerical singularities during code initialization.

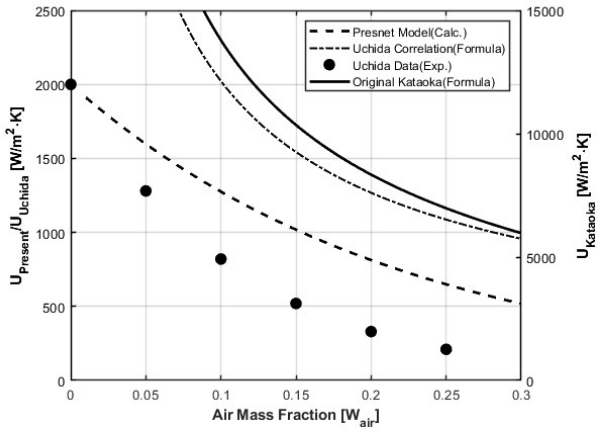

Fig. 2. Comparison of Condensation Models

2.5. Dimensionless Nu-Based validation

To rigorously evaluate the model's physical consistency across varying transport properties, the local transport characteristics were parameterized using the Reynolds number (Re) and Schmidt number (Sc) :

$$Re = \frac{G \cdot d_t}{\mu_{gas}}, \qquad Sc = \frac{\mu_{gas}}{\rho_{gas} \cdot D_{AB}} \tag{3}$$

Using these non-dimensional groups and the measured outer-tube heat transfer coefficient (U_{exp}), the experimental Nusselt numbers (Nu_{exp}) were derived to serve as the baseline benchmark :

$$Nu_{exp} = \frac{U_{exp} \cdot d_t}{k_{gas}} \tag{4}$$

where d_t is the tube outer diameter (0.038m) and k_{gas} is the thermal conductivity of the steam-air mixture.

2.6. Scaling Factor (k) Formulation and Error Analysis

To extend the baseline model (Nu_{base}) to dynamic operating regimes, a dimensionless scaling factor $k(\mathrm{Re}, \mathrm{Sc})$ is introduced :

$$k = \left(\frac{Re}{Re_0}\right)^a \left(\frac{Sc}{Sc_0}\right)^b \tag{5}$$

$$Nu_{pre} = Nu_{base} \cdot k \tag{6}$$

At the reference atmospheric stagnant condition (Uchida [1]), k naturally reduces to unity $k \approx 1.0$. The comprehensive parity plot in Fig. 3 validates Nu_{pred} against Nu_{exp}. Unlike power-law formulations that severely overpredict heat transfer under low air fractions, the calibrated exponential framework tightly bounds all data points within a $\pm 30\%$ error margin, proving both high physical realism and numerical stability.

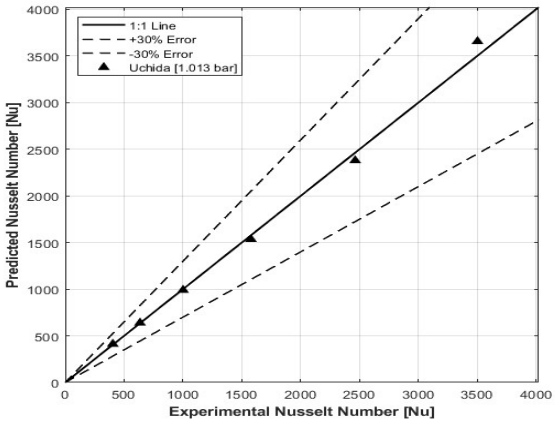

Fig. 3. Comprehensive Model Evaluation

3. Conclusion

The numerical stability and predictive capability of an exponential baseline model for PCCS external tube condensation were systematically evaluated. By establishing a physical upper bound ($C_1 = 1985.4\ W/m^2 \cdot K$) under pure steam conditions and calibrating the decay exponent ($C_2 = 4.6210$) against Uchida's benchmark dataset, the model successfully eliminated computational singularities during code initialization while capturing non-condensable gas degradation physical within a $\pm 30\%$ error band.

Furthermore, a dimensionless scaling structure $k(\mathrm{Re}, \mathrm{Sc})$ was formulated to incorporate flow shear and high pressure effects without introducing redundant constants. As a future work, the current baseline framework will be extended to high pressure and forced-flow regimes by determining the exponents (a, b) of the scaling factor k through cross-validation against databases (e.g., Dehbi [3], Su et al. [4]).

ACKNOWLEDGEMENT

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REFERENCES

[1] H. Uchida, A. Naito, and C. Togo, "Evaluation of Post-Accident Containment Pressure-Temperature Response," Proc. 3rd Int. Conf. Peaceful Uses of Atomic Energy, Geneva, Vol. 13, pp. 93-104, 1965.

[2] I. Kataoka and M. Ishii, "Model for Condensation in the Presence of Noncondensable Gas under High Pressure," Nucl. Eng. Des., Vol. 155, pp. 201-212, 1995.

[3] A. A. Dehbi, M. W.Golay, and M. S. kazimi, “condensation of steam in the Presence of Noncondensable Gases for Passive Containment Cooling Applications,” Nuclear Technology, Vol. 96, No. 1, pp. 62-73, 1991.

[4] J. Su, Z. Sun, and G. Fan, “Experimental study on Steam Condensation Heat Transfer Outside Vertical Tubes in the presence of Air,” Annals of Nuclear Energy, Vol. 54, pp. 110-116, 2013.