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Presentation: Reactor Containment Passive Safety Analysis: Steam Condensation in Presence of Non-condensable Gas Scaled Experiment and Modeling

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Changing the World's Energy Future

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Idaho National Laboratory

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Reactor Containment Passive Safety Analysis: Steam Condensation in Presence of Non-condensable Gas Scaled Experiment and Modeling

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Introduction: Problem Overview

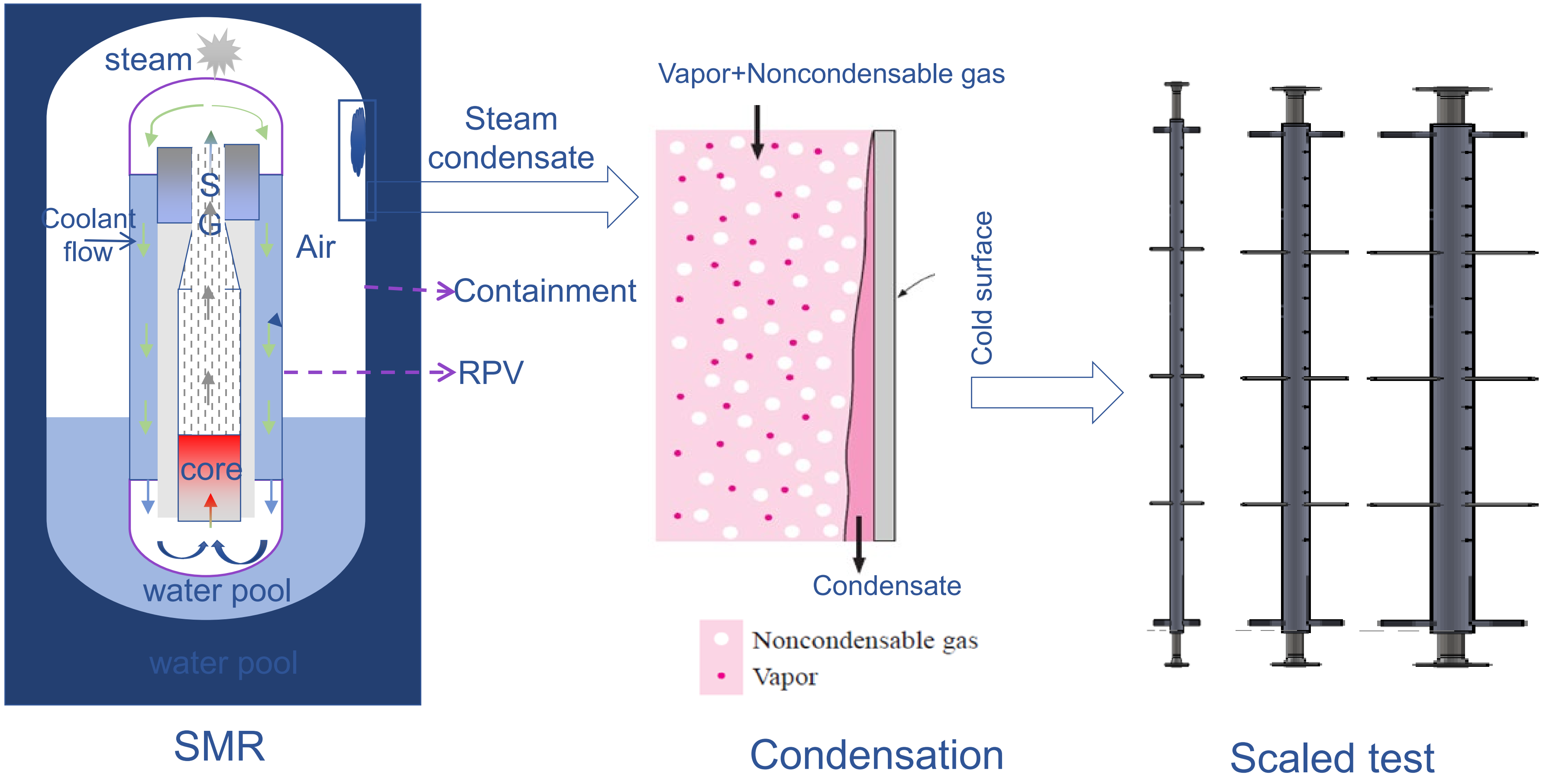

Fig. 1: Overview of the condensation scaled separate effect experiment.

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Introduction: Objectives and Motivations

- Small modular reactors (SMRs) have attractive features, such as factory-built construction, modular design, easier transportation, and multi-units capacity addition.
  - Wordwide, over 80 different SMRs are currently in the design and development stage, with most being light-water-cooled [1-2].

- However, the verification and validation of the required models is a must for obtaining regulatory approval, which supports
  - evaluation model development and the assessment process for the reactor system, similar to the passive containment cooling system (PCCS) for various loss-of-coolant accidents (LOCAs) [3–4].

- The previous condensation heat transfer (CHT) works were grouped into theoretical, experimental, and numerical studies [5].

- The experimental studies were subgrouped into separate and integral effect tests with a wide range of varying geometric, physics, fluids, and operating conditions [6].

- Similarly, the theoretical and numerical studies were subgrouped into conceptual modeling, simulations, and multiphysics-computational fluid dynamics (CFD) using commercial software, system, and in-house-developed codes [7].

- Many of the earlier studies on the reactor in containment condensation considered the effect of non-condensable gases (NCGs), such as air, nitrogen, hydrogen, and helium [8–13].

- PCCSs are especially important for SMRs, due to their compact nature. SMRs usually incorporate suppression-type, submerged, or air-cooled PCCSs.

Introduction: Objectives and Motivations (cont'd)

- Previous PCCS CHT experimental studies mostly focused on
  - small and fixed geometric (mostly using a 2-in. pipe) and testing conditions causes challenges to geometric scaling and operational condition relevant to the prototypic conditions for SMRs [5–6].
- Therefore, a scale test dataset and simplified modeling approach is required in most cases for early-stage reactor system design and analysis.

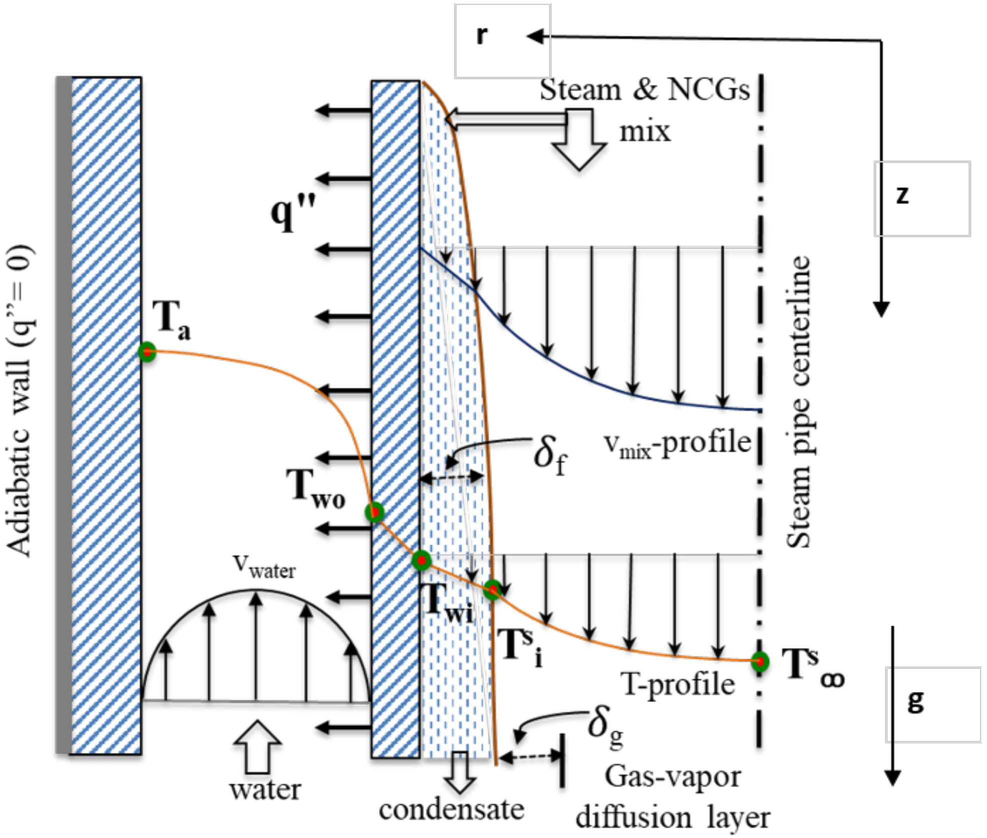
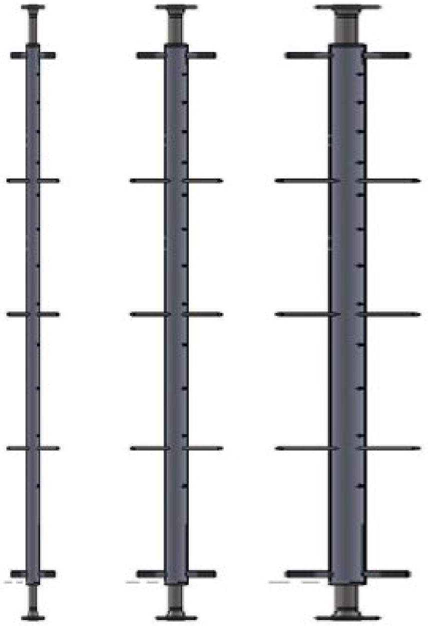


Fig. 2: Schematics of CHT: physical phenomena [14].

Experimental Facility

- This study utilized three scaled test sections
  - 1-, 2-, and 4-in.-diameter steam condensers with annular/jacket cooling of 2-, 3-, and 6-in.-diameter tubes
  - to obtain steam condensation test data (mostly axial temperature) in the presence of NCG (i.e., nitrogen),
    - varying steam-NCG mix flow rates, and annular cooling flow rates.

Scaled condenser test units



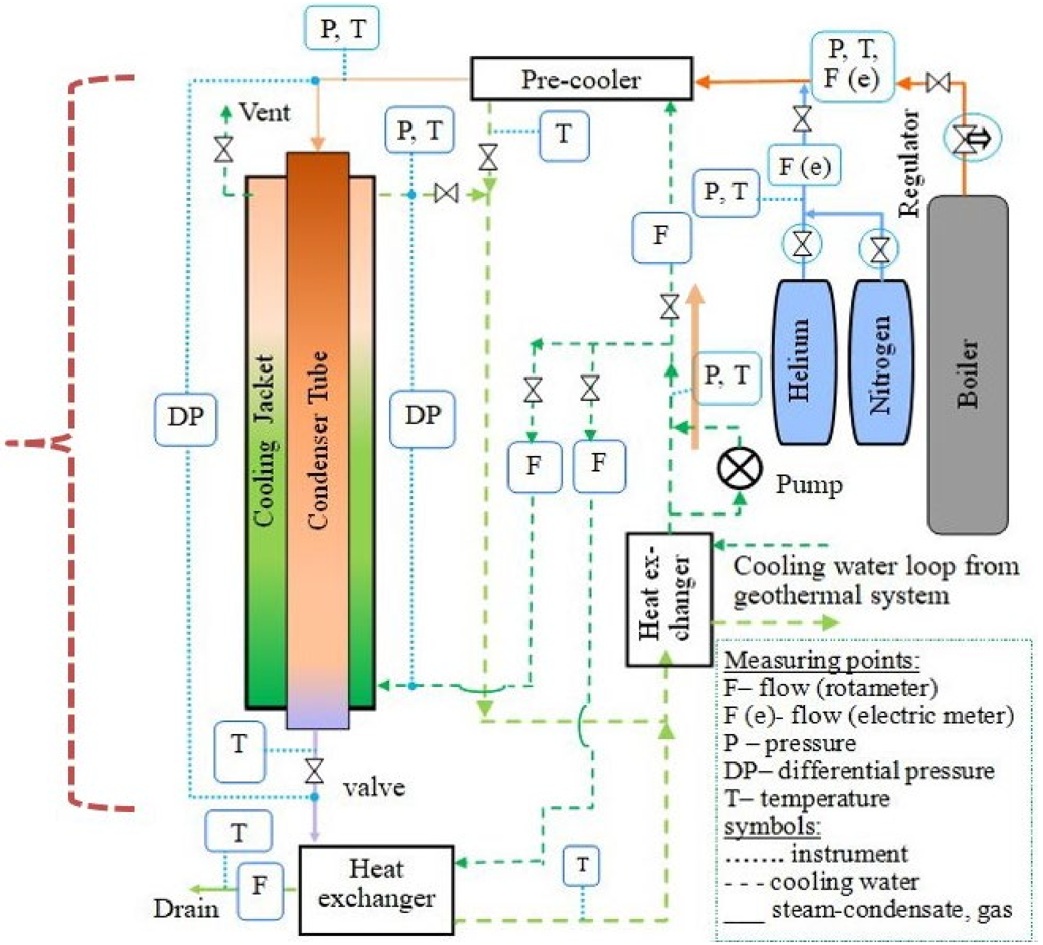


Fig. 3: Final test facility instrument and control schematic [12].

Data Reduction Method

- The test data reduction method for CHT, consists of the following three primary stages of estimating parameters:
  - Estimating coolant bulk temperature (T_b) and local heat flux (q'')
  - Local HTC, blowing parameter, and film thickness
  - Dimensionless parameters: Reynolds (Re) and Nusselt (Nu) numbers
  - Uncertainty quantification

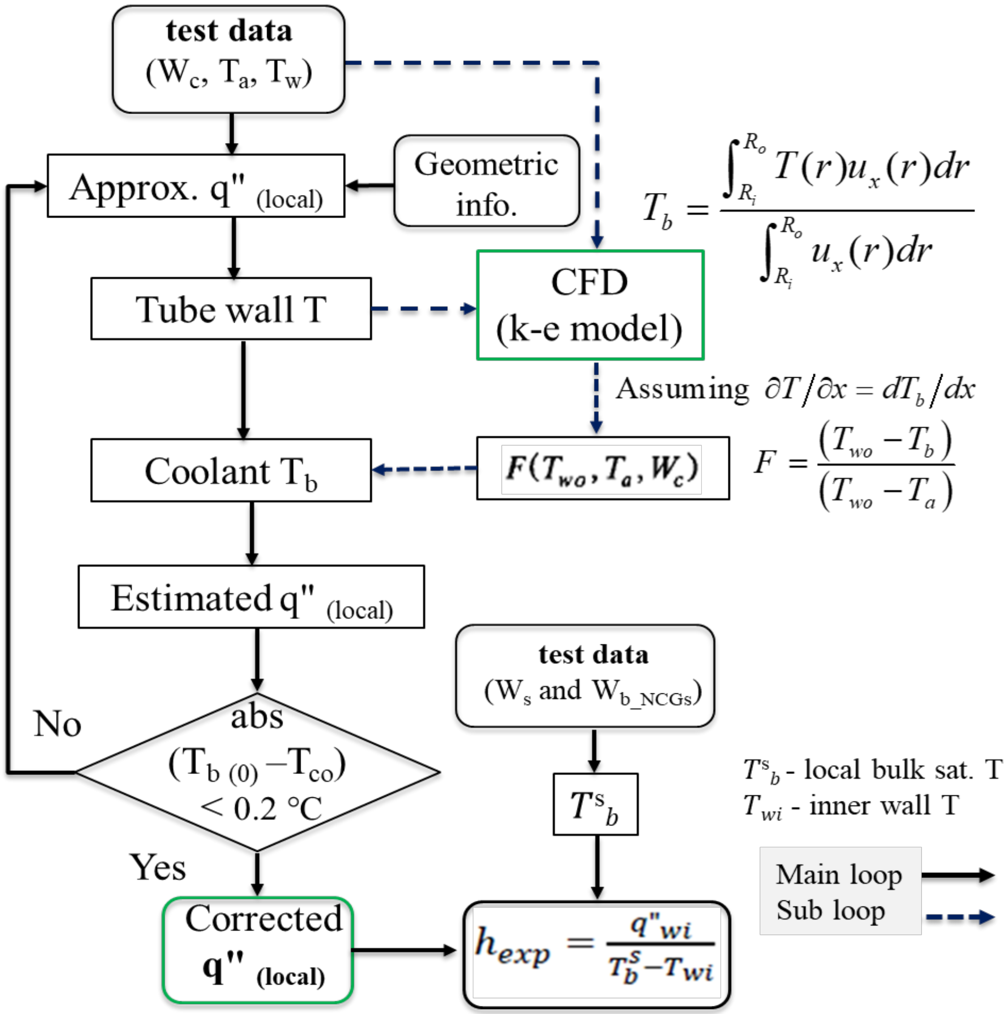


Fig. 4: Local heat flux and HTC estimation [14].

Models and Equations

Parameters	Models and Equations
T_b and local q''	$q''_{wi}(z)_{approx.} = -\frac{W_c c_p}{\pi d_i}\frac{dT_a(z)}{dz}$ and $T_{wi} = T_{wo} + \frac{r_i q''_{wi}(z)\ln\left(\frac{d_o}{d_i}\right)}{k_w}$; $q''_{wi}(z) = -\frac{W_c c_p}{\pi d_i}\frac{dT_{b,c}(z)}{dz}$ where, $T_{b,c}$, T_{wi}, T_{wo}, and T_a, are the temperature of the coolant (bulk), condensing tube inner wall, condensing tube outer wall, and jacket water cooling. W is the mass flow rate, z is the axial length, d for diameter, k for thermal conductivity, cp for specific heat capacity; subscript c for coolant.
Local HTC, blowing parameter β, and film thickness δ	$h_{exp} = \frac{q''_{wi}}{T_b^S - T_{wi}}$, and $\Gamma = \frac{g}{\mu}\rho_1(\rho_1 - \rho_m)\frac{\delta_f^3}{3} + \frac{\rho_1 \tau_i \delta_f^2}{2\mu_1}$; $\tau_i = 0.5 f_{io}\rho_m(u_m - u_i)^2 \frac{\beta_f}{\exp(\beta_f) - 1}$; $\beta_f = \frac{m''}{\rho_m u_m f_{io}/2}$ and $\delta_{fo} = \left(\frac{3u_1\Gamma}{g\rho_1(\rho_1 - \rho_m)}\right)^{1/3}$ where, h for HTC, δ for film thickness, Γ for liquid flow per unit perimeter, g for gravity, μ for dynamic viscosity [kg/m s], τ interfacial shear stress; and subscript i and l for inner/interface and liquid, respectively.
Dimensionless numbers: Re and Nu	$\frac{Re_f}{1 - \left(\frac{\rho_m}{\rho_1}\right)} = \frac{\delta_f^{*3}}{3} + \frac{\tau_i^* \delta_f^{*2}}{2}$; $Nu_f = \frac{h_f L}{k_c} = \left(Nu_{f,h}^4 + Nu_{f,tu}^4\right)^{1/4}$; $Nu_{f,la} = \frac{1}{\delta_f^*}$ and $Nu_{f,tu} = aRe_f^b\, Pr^c\left(1 + e\tau_i^{*f}\right)$ where, Re for Reynolds number, Nu for Nusselt number, Pr for Prandtl number, and L for characteristics length. Subscript f for film, m for mix, i for interface, tu for turbulent.
Dimensionless Numbers: Re and Nu	$\frac{Re_f}{1 - \left(\frac{\rho_m}{\rho_1}\right)} = \frac{\delta_f^{*3}}{3} + \frac{\tau_i^* \delta_f^{*2}}{2}$; $Nu_f = \frac{h_f L}{k_c} = \left(Nu_{f,h}^4 + Nu_{f,tu}^4\right)^{1/4}$; $Nu_{f,la} = \frac{1}{\delta_f^*}$ and $Nu_{f,tu} = aRe_f^b\, Pr^c\left(1 + e\tau_i^{*f}\right)$ where, Re for Reynolds number, Nu for Nusselt number, Pr for Prandtl number, and L for characteristics length. Subscript f for film, m for mix, i for interface, tu for turbulent.
Uncertainty quantification	$\frac{\sigma_{exp}}{h_{exp}} = \left[\left(\frac{\sigma_{W_{cw}}}{W_{cw}}\right)^2 + \left(\frac{\sigma_{c_p}}{c_p}\right)^2 + \left(\frac{\sigma_{d_i}}{d_i}\right)^2 + \left(\frac{\sigma_{(T_c - T_w)}}{(T_{sat} - T_{wi})}\right)^2 + \left(\frac{\sigma_{(cw/dx)}}{dT_{cw/dx}}\right)^2\right]^{1/2}$ and $\frac{\sigma_f}{f} = \left[\left(\frac{\sigma_{h_{exp}}}{h_{exp}}\right)^2 + \left(\frac{\sigma_{h_{Nu}}}{h_{Nu}}\right)^2\right]^{1/2}$ where, σ for error, dx for node length, sat for saturation, exp for experiment.

Table I: Data reduction method and the relevant models/equations [14].

Models and Equations (cont'd)

Parameters	Semi-empirical Models/Correlations
Vierow (1990) [15]	$$f = \frac{h_{exp}}{h_{Nu}} = f_1 \cdot f_2 = \left(1 + aRe_{mix}^{d}\right) \cdot \left(1 - bM_{NCGs}^{c}\right)$$ where, f with f_1, including the effect of interfacial shear (δ_{shear}) and surface waviness to improve the film heat transfer.
Kuhn et al. (1996)[16]	$$f = \frac{h_{exp}}{h_{Nu}} = \frac{\delta_{shear}}{\delta_{Nu}} \cdot \left(1 + a\left(\frac{Re_f}{4}\right)^{d}\right) \cdot \left(1 - bM_{NCGs}^{c}\right)$$ This is the modified Vierow (1990) f with f_1, including the effect of interfacial shear (δ_{shear}) and surface waviness. The details parameter information of f is available in Table 2 of Bhowmik et al. (2022) [6].
Park and No (1999) [17]	$$f = \frac{h_{tot}}{h_f} = 0.0012\ W_{nc}^{-1.4} Ja^{-0.63} Re_f^{0.24}$$ for $1715 < Re_g < 21670, 0.83 < Pr_g < 1.04, 0.111 < M_{air} < 0.836,$ $0.01654 < Ja < 0.07351$, and $12.4 < Re_f < 633.6$. where, dependence of steam-NCGs mixture Re and Prandtl number, Pr on CHT and developed f using gas mass fraction, Jacob number, Ja and liquid film Re.
Lee and Kim (2008) [18]	$$f = \tau_g^{*0.3124}\left(1 - 0.964M_a^{0.402}\right)$$ for $0.06 < \tau_g^* < 46.65, 0.038 < M_{air} < 0.814$ where, f for steam-NCGs mixture in a U-tube in a reflux condensation, using gas mass fraction and shear force of the mixture.

Table II: Semi-empirical models/equations [6]

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Test Data

- Scaled experiments were conducted by applying
  - Steam and steam-NCG mixtures to three different test sections.
  - Nitrogen served as the NCG. Test data were collected for varying
    - steam-NCG mixture mass fractions (M, %),
    - steam-NCG mass flow rates, and
    - coolant flow rates.
  - Figure 5, Figure 6, and Figure 7, respectively, present representative sample
    - test datasets for the 4-in. test section, collected under a wide range of NCG mass flow rates (i.e., high, moderate, and low).
    - Tests A-run0.9N0a, A-run2.1N4, and A run2.1N8 represent the high (i.e., 13.22 kg/hr), moderate (i.e., 8.08 kg/h), and low (i.e., 4.41 kg/h) NCG:N2 flow cases, respectively.

Test Data (cont'd)

Test Section	Steam flow	Pin	Tin	NCF: N_2 flow	M
1-in	30-53	109.6-109.9	100.2-103	2.9-14.7	5.5-23.6%
2-in	30.7-42.2	111.4-115.7	102.6-105.4	2.6-12.9	6.1-31.6%
4-in	54.7-60.1	140.4-150.4	99.4-103.5	4.4-3.2	7-18.1%

Table III: Selected steam-N2 mix condensation test conditions/ranges.

Note: Here, TS for test section, inlet mass flow rate (F [kg/hr)] for steam and NCG[N], inlet pressure (Pin [kPa]), inlet temperature (Tin [∘ C]), and NCG mass fraction (M, %).

Results

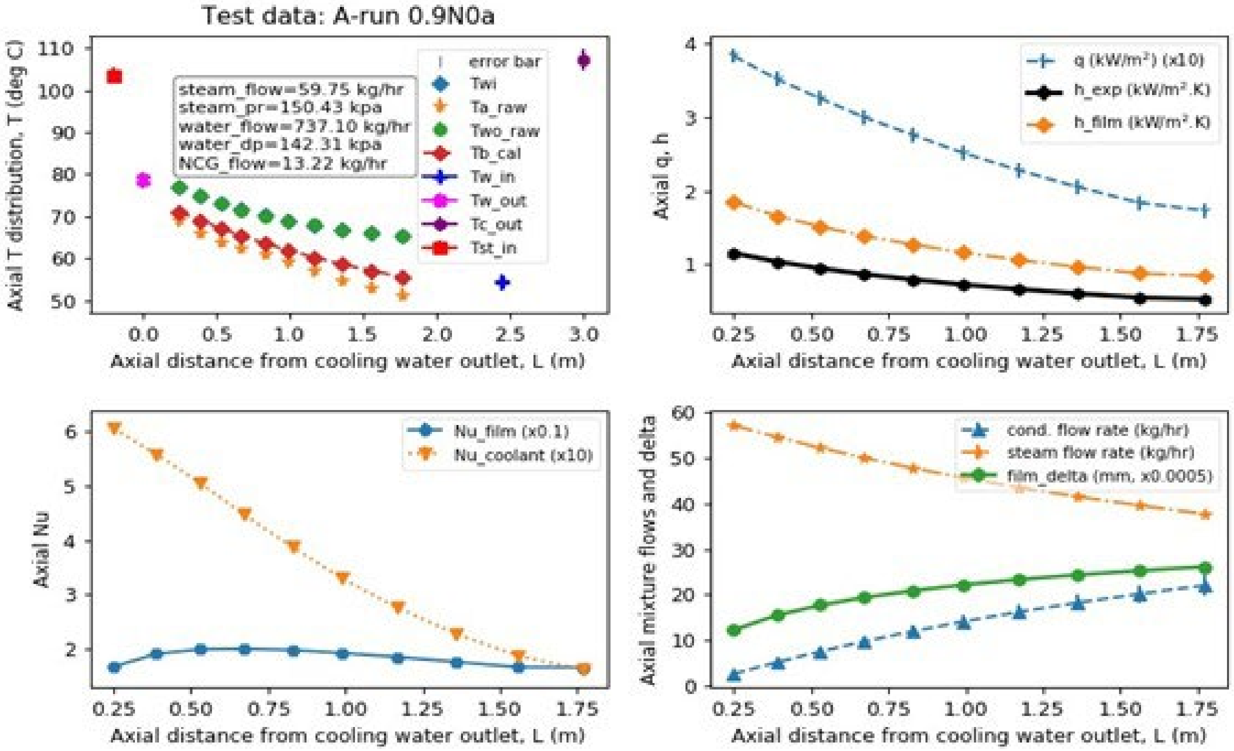

Fig. 5: Test data: A-run0.9N0a (4-in. test section; NCG: N2, high flow)

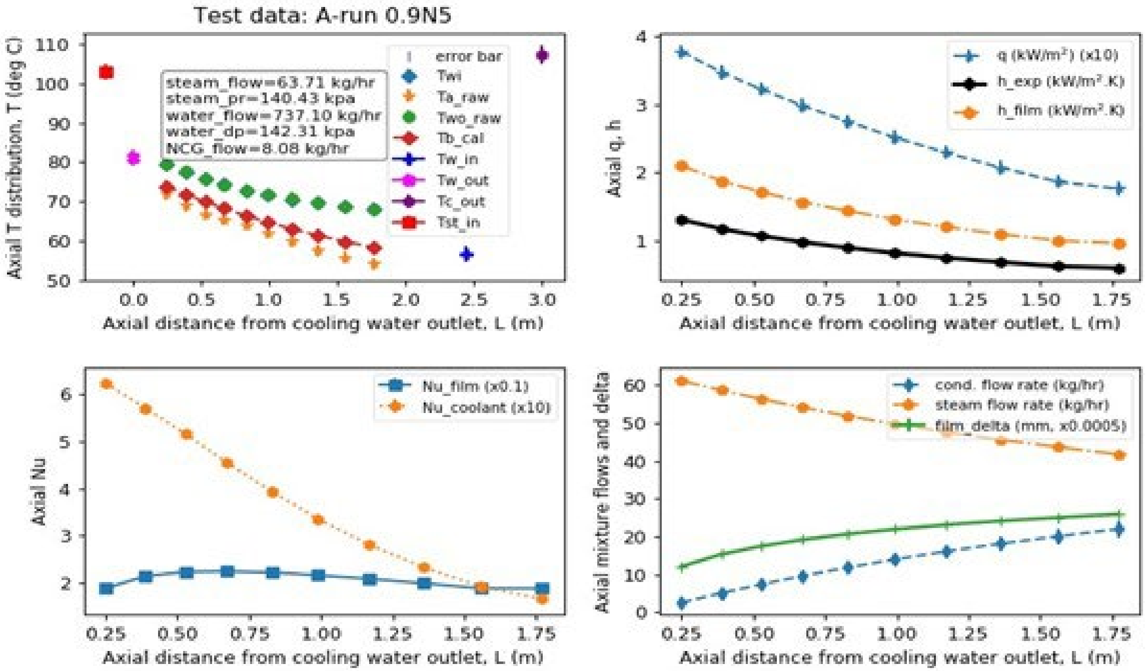

Fig. 6: Test data: A-run0.9N5 (4-in. test section; NCG: N2, medium flow).

Results and Discussion

The following observations resulted from the experiments and test data analysis:

- Test data showed the CHT, HTC, and condensation rate all decreased with an increase in NCGs. In contrast, these values increased as the steam mass flow increased.
  - The test data were collected at a certain distance from the inlet and outlet to avoid entrance and exit effects.
- A series of similar tests was conducted for varying steam mass flow rates, pressures, and NCG mass fractions. Test data showed qualitative consistency.
  - However, better consistency of the test data would be achievable by introducing adequate control elements (e.g., control valves) to control the testing conditions (e.g., steam-NCG mix inlet mass flow rates, temperature, and pressure), as well as controlling the cooling and condensate discharge.

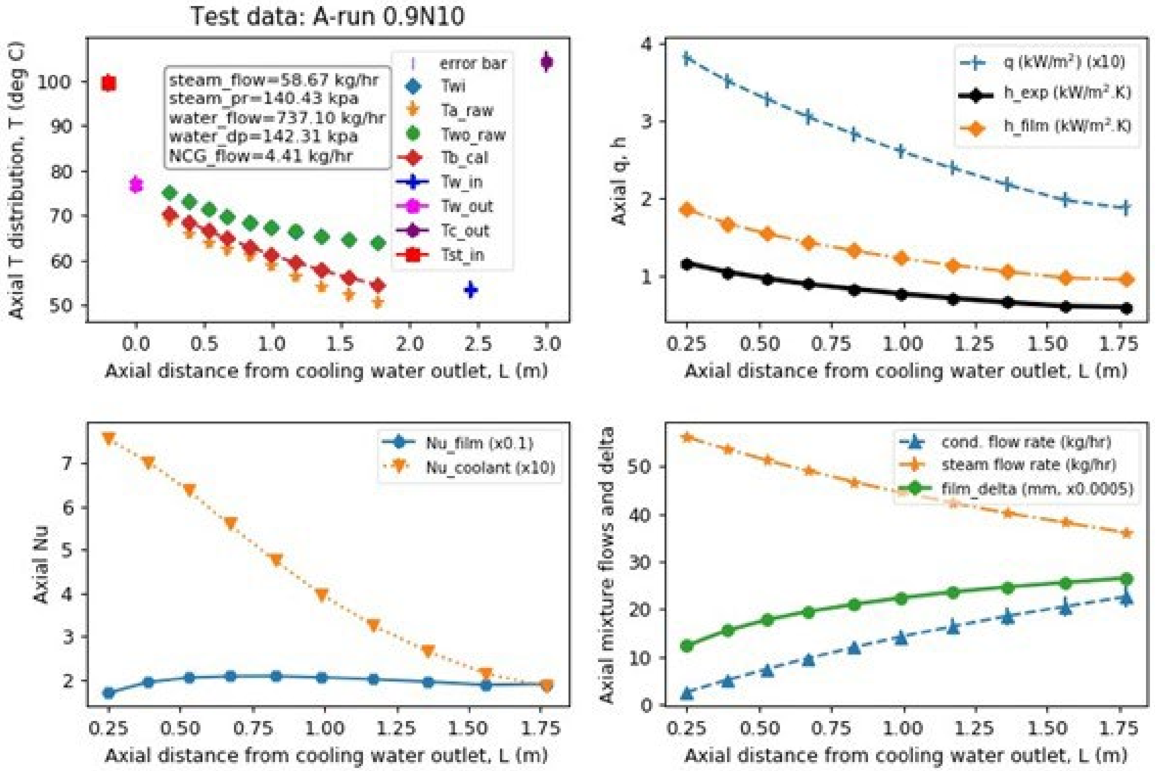

Fig. 7: Test data: A-run0.9N10 (4-in. test section; NCG: N2, low flow).

Results and Discussion (cont'd)

- The estimated DF, for the various test sections and steam-nitrogen tests exhibited that
  - with an increase in the diameter of the condenser tube, the DF decreased and ranged from 0.1 to 0.7, 0.05 to 0.4, and 0.05 to 0.25 for the 1-in., 2-in., and 4-in. test geometries, respectively.
  - Note that there are a few inconsistent data points for the 2-in. tests, which are outliers.
  - This test dataset could improve verification and validation efforts of computation models and tools [19, 20], which will further improve understanding of the detailed thermal-hydraulics behavior.

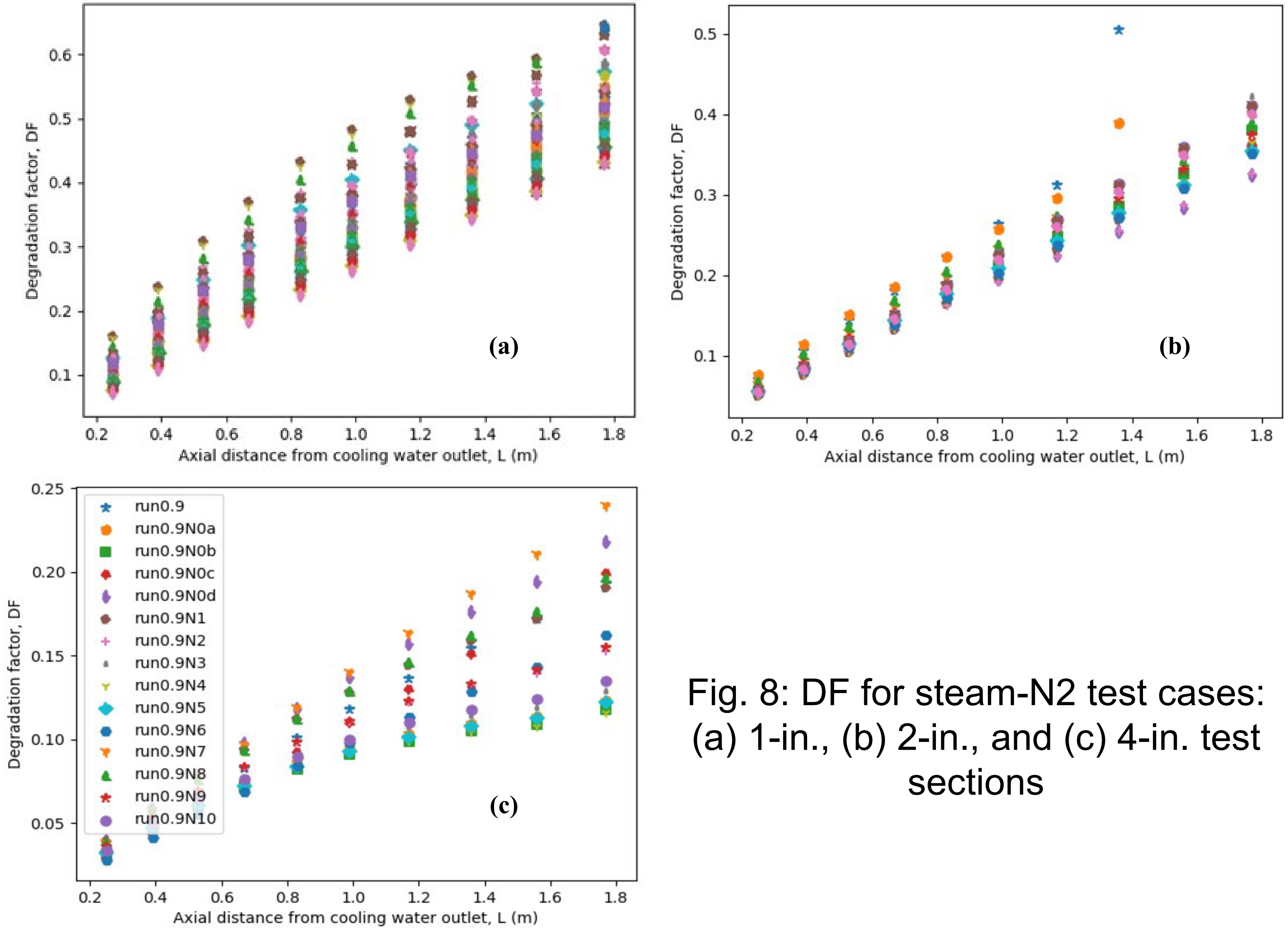

Fig. 8: DF for steam-N2 test cases: (a) 1-in., (b) 2-in., and (c) 4-in. test sections

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Summary, Conclusions, and Path Forward

To analyze the physical phenomena behind SMR PCCSs, this study presents scaled experiments regarding steam condensation in the presence of NCGs. The tests involved vertical downward steam flow and condensation within the inner surfaces of condenser tubes, coupled with annular or pool-cooling methods. A few observations and conclusions can be derived from this study:

- This study focused on later-stage accident phases—mostly long-term cooling—for standard SMRs, which occur
  - about 72 hours into the cooling period following an initiation of an accident and utilized three different scaled geometry test sections.
- Steam condensation considered in the study comprised of film-wise and dropwise; however, for dominating steam condensation in reactor containment during long-term cooling, this study focused on the film-wise type condensation on the containment surface.
- This study presents scaled test data and results for steam condensation in the presence of nitrogen, which simulates air for the containment system. The percentage of air presence in steam release accidents varies over the accident phases.
  - As this study focuses on long-term cooling and film condensation, the physics approximation of NCGs is considered as a barrier to bulk steam for film heat transfer, which is related to NCG partial pressure—an important phenomenon of interest.
- Simple semi-empirical representation of the test data using the degradation factor provides a general relation with experimental and theoretical HTC estimation, including the effect of NCG.
- Future research could encompass validating steam condensation CFD and system code models, and obtaining qualified data, which would identify
  - scaling factors, scaling distortion, and uncertainty associated with geometric and testing conditions, for decision-making to develop qualified test facilities at prototypic conditions.

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