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Changing the World's Energy Future

Palash Kumar Bhowmik, Joshua P. Schlegel, Piyush Sabharwall

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Steam Condensation Scaled Experiment in the Presence of Non-condensable Gas for Reactor Containment Passive Safety Analysis

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Introduction: Problem Overview

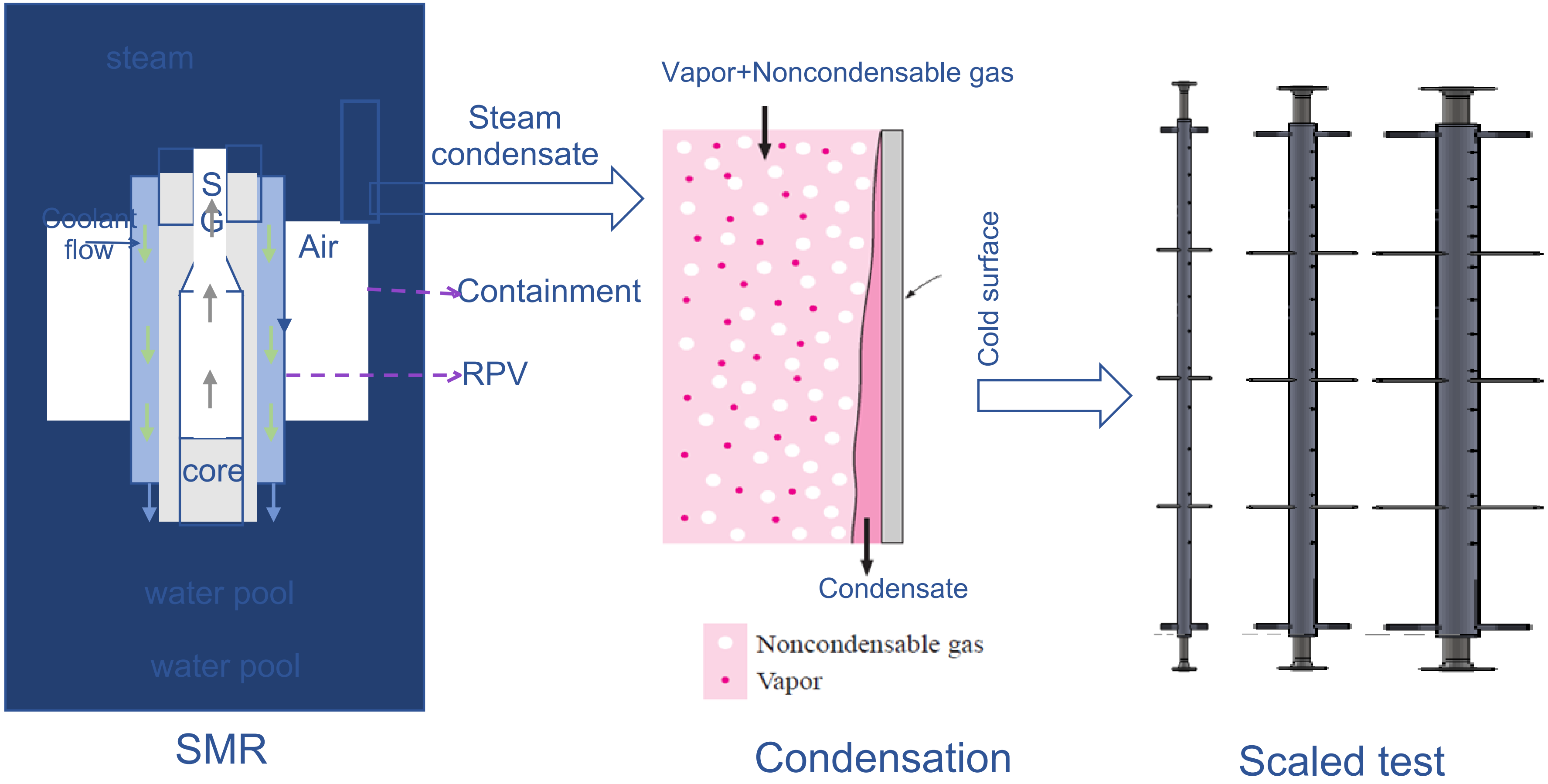


Fig. 1: Overview of the condensation scaled separate effect experiment.

Introduction: Objectives and Motivations

- Around the world, over 80 different small modular reactors (SMRs) are currently in the design and development stage, with most being light-water-cooled [1-2].
- Accidents involving steam release to the reactor containment could occur during reactor system loss-of-coolant accidents (LOCAs),
  - such as main steam line breaks, small-break LOCAs, large-break LOCAs, and steam generator tube ruptures [3-4].
- In addition, during LOCAs and reactor fuel overheating, steam could react with fuel-clad zirconium to produce hydrogen, and the resulting steam-hydrogen mix could be released into the containment [5].
- The presence of non-condensable gases (NCGs) during this process can create a layer between the condensate and the steam, reducing the condensation heat transfer (CHT) rate [6].
- In nuclear reactor systems, CHT is crucial for removing heat from the reactor containment system, especially during steam release accidents;
  - however, NCGs (i.e., containment air and hydrogen) reduce heat transfer and condensation performance [7-9].
- PCCSs are especially important for SMRs, due to their compact nature.
  - SMRs usually incorporate suppression-type, submerged, or air-cooled PCCSs [10-12].

Introduction: Objectives and Motivations (cont'd)

- Steam release accidents and steam condensation in the reactor containment system occur in two stages:
  - (a) initially (i.e., during the steam release transient condition), condensation occurs when steam hits the containment wall (i.e., cold surface); and
  - (b) condensation phenomena that occur throughout long-term cooling are followed by a more uniform steam-air mixture and natural circulation condition [12-14].

- This long-term cooling phase can last for days (U.S. NRC guidelines specify 72 hours of cooling after the initiation of accidents),
  - with the condensate being returned to the reactor in order to cool the reactor core [3, 7, 15].

- In order to evaluate steam release accidents, water-cooled SMR systems require:
  - Adequate modeling of the steam CHT in the containment, though PCCS.
  - 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, **there is lack of data from scaled-experiment facilities.**

- This study covered steam condensation scaled experiment:
  - in the presence of non-condensable gas (NCG))—helium, simulating hydrogen—for reactor containment passive safety analysis.

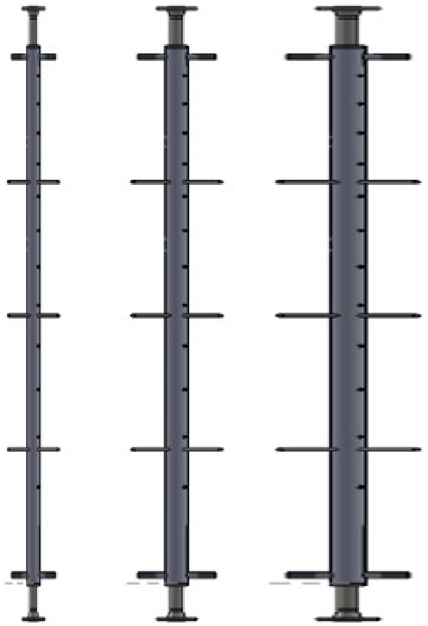
Experimental Facility

- Condensation experimental studies were grouped into:
  - **Separate effect tests**, and
  - Integral effect tests

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

- The length scale ratio between TS and Westinghouse-SMR (W-SMR) are 1:11,
  - whereas the area scale ratios are 1:3250, 1:1800, and 1:950, for 1-, 2-, and 4-in.-diameter condensing tubes [16, 17].

Scaled condenser test units



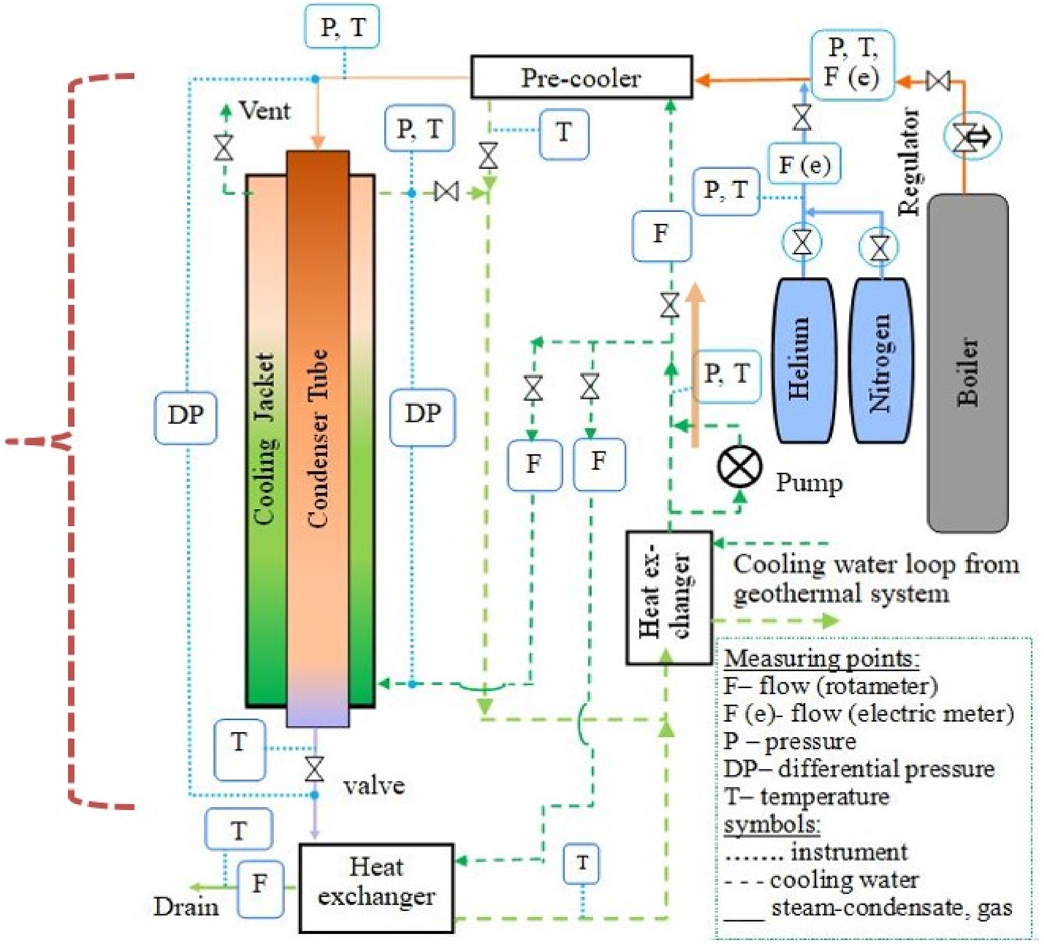


Fig. 2: Final test facility instrument and control schematic [12].

Data Reduction Method

- The test data reduction method for CHT, outlined in Figure 3, 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

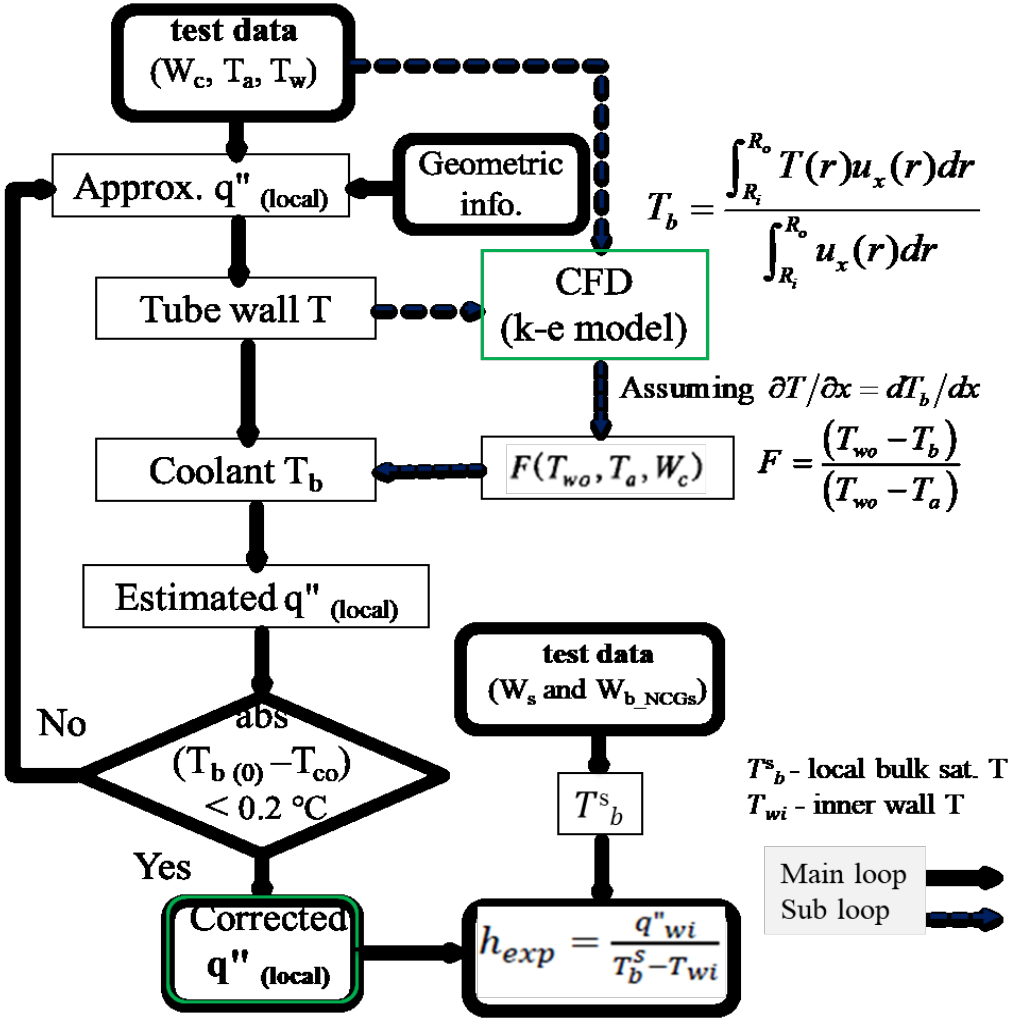


Fig. 3: Local heat flux and HTC estimation [12].

Models and Equations

Parameters	Models and Equations
and local	and ; where, 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 , and film thickness	, and ; and where, h for HTC, δ for film thickness, Γ for liquid flow per unit perimeter, g for gravity, 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	; ; and 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.
Scaling Parameter	and Where, is the general scaling ratio, and is the flow area scale.
Uncertainty quantification	and where, for error, dx for node length, sat for saturation, exp for experiment.

Table I: Data reduction method and the relevant models/equations [12].

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Test Data

- Scaled experiments were conducted by applying
  - Steam and steam-NCG mixtures to three different test sections.
  - Helium (He) 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 4, Figure 5, and Figure 6, 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-run2.1N2, A-run2.1N4, and A run2.1N8 represent the high (i.e., 18.36 kg/hr), moderate (i.e., 11.02 kg/h), and low (i.e., 1.84 kg/h) NCG:He flow cases, respectively.

Results

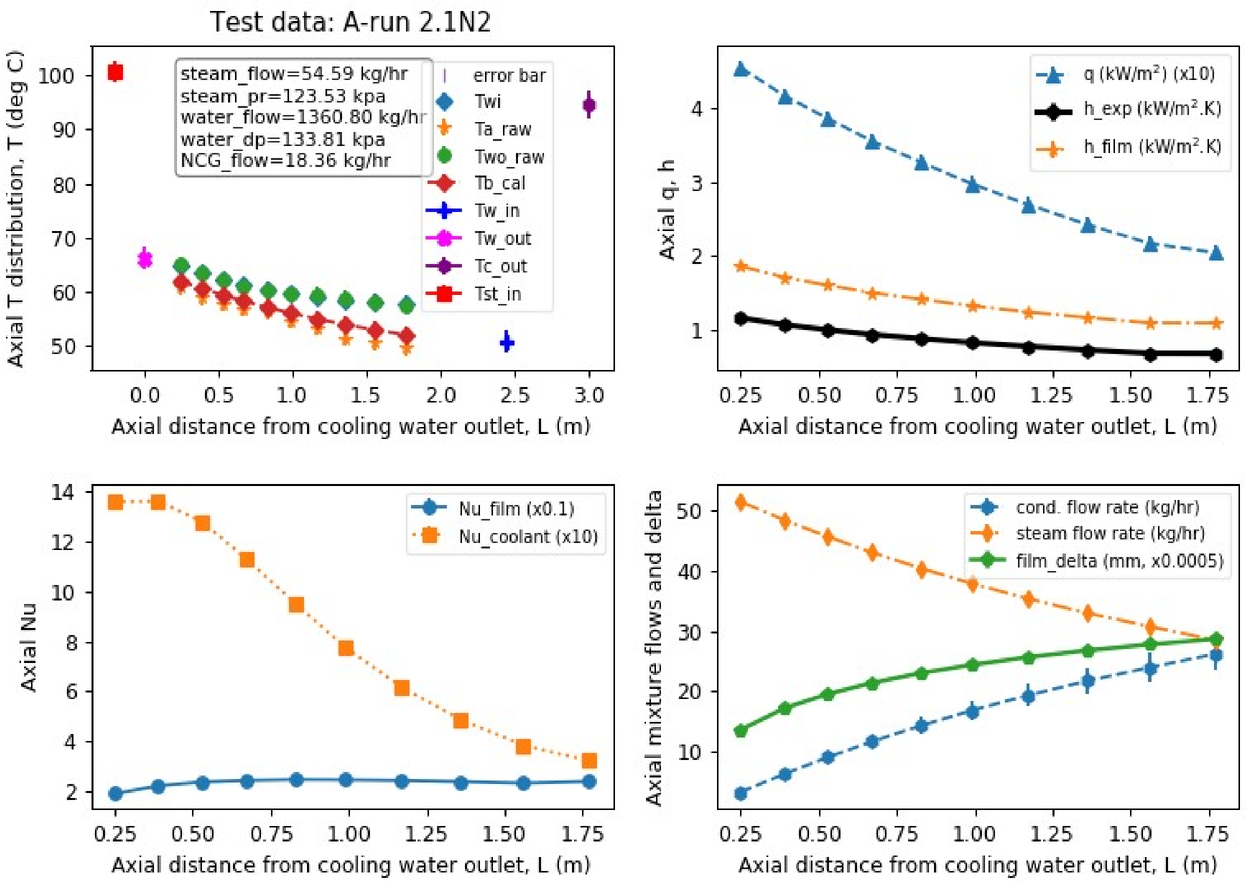

Fig. 4: Test data: A-run2.1N2 (4-in. test section; NCG: He, high flow)

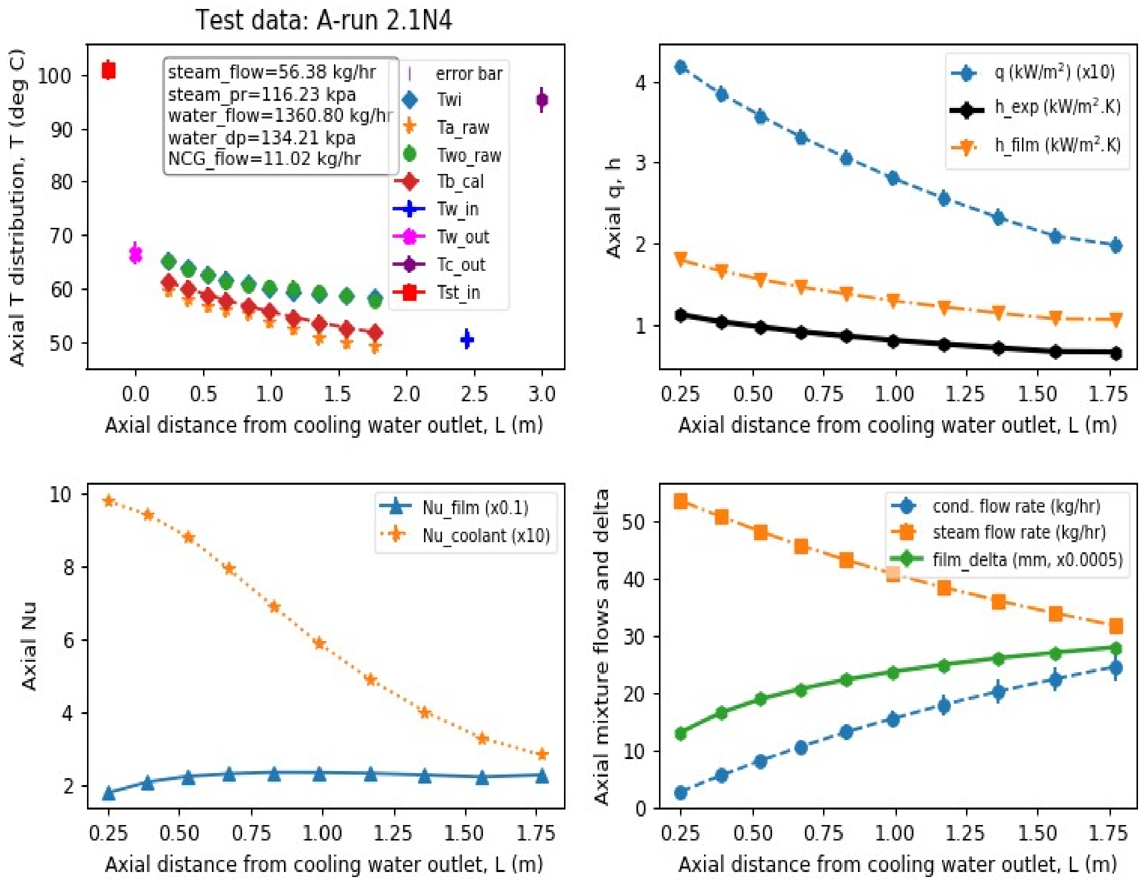

Fig. 5: Test data: A-run2.1N4 (4-in. test section; NCG: He, medium flow).

Results and Discussion

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

- The presented test data range
  - steam flow (55 to 66 kg/hr) and
  - helium flow (1.8 to 19 kg/hr) mix
- In most cases, the test data showed
  - the CHT, HTC, and condensation rate decreased with an increase in NCGs.
  - In contrast, these values decreased as the steam mass flow increased.
- The NCGs flowed from elevated pressure and forced the steam-condensate mixture out of the test section,
  - Thus, increasing flow turbulence as a result of forced convection.
- The test data were collected at a certain distance from the inlet and outlet
  - to avoid entrance and exit effects (due to sudden area changes) by reducing the amount of distortion.

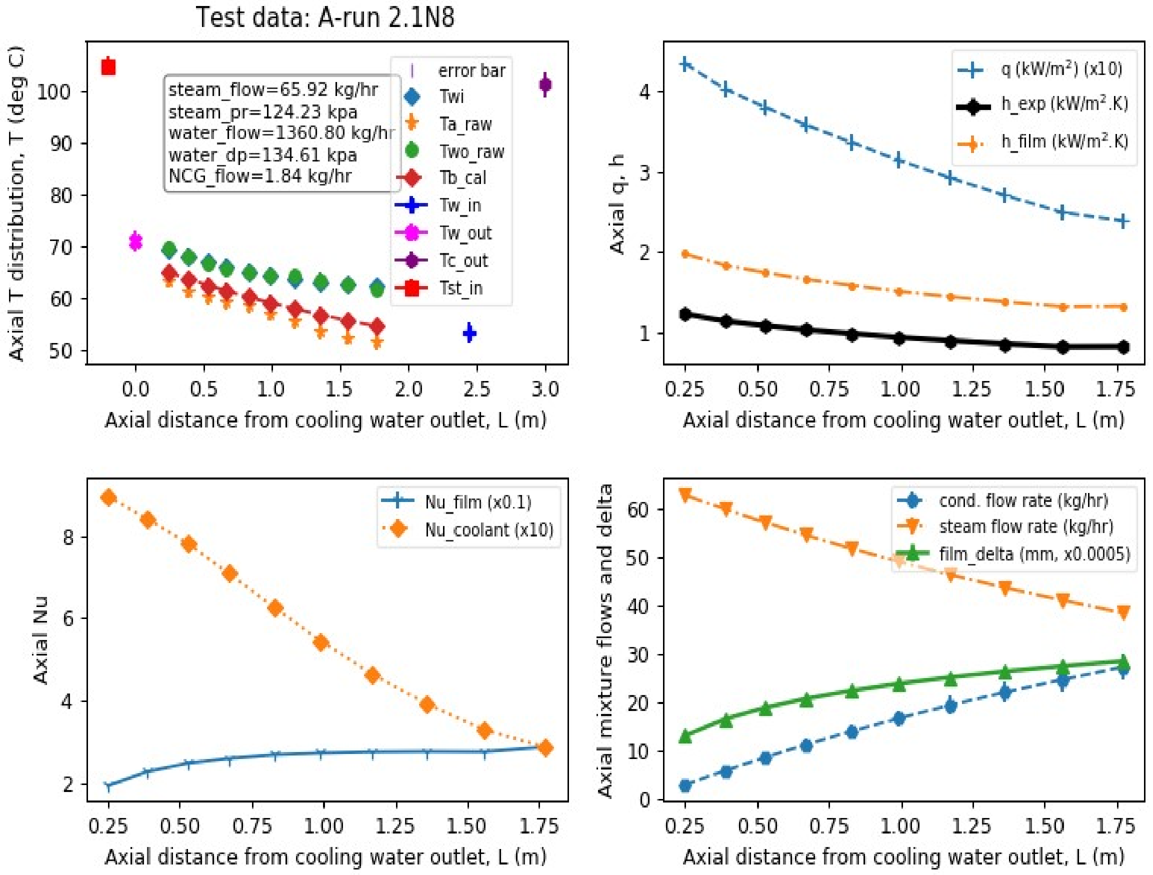

Fig. 6: Test data: A-run2.1N4 (4-in. test section; NCG: He, medium flow).

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Summary, Conclusions, and Path Forward

The condensation experiments were carried out using three scaled-down condenser tubes and various steam-NCG (i.e., He) mixture flow. The following findings, challenges, and future research directions were discussed:

- Three scaled geometries TS (i.e., 1-, 2-, and 4-in.-diameter condensing tubes) considered.
  - The length scale ratio between TS and W-SMR are 1:11, and for the area scale ratios are 1:3250, 1:1800, and 1:950.
- Test datasets were collected for an applicable range of test parameters,
  - Such as temperature, pressure, mass flow rate (i.e., steam, NCG, and coolant mass flow rates), and volume fraction.
  - Challenges to achieve same test inlet conditions for each of the TS, and comparative testing cases, due to lack of adequate control elements (i.e., mostly control valves).
- Condensation physics phenomena are exhibited in the test data and results,
  - These phenomena depend on variation in the cooling, as well as on the NCG mass fraction, pressure, and velocity.
  - Specific data reduction method is outlined with detailed UQ and uncertainty propagation modeling approaches.
  - Research into the control of test inlet conditions, adequate measurement, and a wider range of testing and data collection enable a critical understanding of
    - how consistent test data can be obtained by using representative test facilities to simulate design-specific, long-term, steady-state SMR PCCSs.
- Future research could encompass steam condensation scaled experiments with various NCG mixture amounts (e.g., air or nitrogen)
  - For a wide range of pressure and inlet/outlet boundary conditions applicable to SMR prototypic conditions.
  - In addition, uncertainty propagation, scaling factor development, and scaled-value empirical correlations would be supportive
  - Such results and findings are supportive to the reactor system design and analysis for enhancing safety margins and obtaining regulatory approvals.

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