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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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ABSTRACT

This study presents scaled experiments using steam condensation with non-condensable gas (NCG)—helium, simulating hydrogen—as these experiments are pivotal for water-cooled reactor passive containment cooling system (PCCS) design and analysis. Research into PCCSs for small modular reactors (SMRs) is especially important in light of SMR system design; however, studies in the literature reflect limitations due to test geometry and operational condition variations, without considering SMR prototypic design. To address these challenges, a scaled test facility was developed to accurately replicate SMR PCCSs. This facility includes vertical down-flow condensing test sections with 1-, 2-, and 4-in.-diameter condensing tubes, accompanied by annular water cooling. Experiments were conducted using both superheated and saturated steam, with steam mass flow rates varying from 55 to 66 kg/hr., in the presence of helium as the NCG mass flow rate ranges from 1.8 to 22 kg/hr. Test data were collected on (a) the axial temperatures of the annular cooling water; (b) the outer wall temperature of the condensers; and (c) the mass flow rate, temperature, and pressure at the test section inlets and outlets. These primary test data were used in conjunction with a standard data reduction methodology to estimate essential thermal parameters such as heat fluxes, heat transfer coefficients, and condensation rates. The effects of NCGs on steam condensation within the geometry of the scaled test sections were then presented in regard to various testing conditions.

Keywords: steam condensation, scaled experiment, non-condensable gas, steam-release accident, passive cooling

1. INTRODUCTION

Small modular reactors (SMRs) offer smaller capacities, modular construction, and enhanced safety, such as passive safety cooling. Around the world, over 80 different SMRs are currently in the design and development stage, with most being light-water-cooled [1-2], which offer both a passive safety system and a passive containment cooling system (PCCS). SMR system designs vary based on thermal capacity, cooling type (i.e., forced flow or natural circulation), and potential application (e.g., electricity generation and industrial heating). In such reactors (e.g., the Westinghouse SMR), water absorbs heat from the reactor core and transfers it to a steam generator to produce steam; the high-pressure steam's energy then spins turbines to generate electricity. 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

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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]. Steam condenses on the containment walls by releasing heat; and condensates (i.e., sub-cooled water) accumulated in containment sumps.

There are two main types of steam condensation: (a) film-wise, in which a liquid film covers the surface, and (b) drop-wise, in which condensate drops form on the surface. 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. Different reactors utilize different PCCS designs. Some large reactors use PCCSs with external heat exchangers, whereas SMRs usually incorporate suppression-type, submerged, or air-cooled PCCSs [10-12]. From a regulatory perspective, understanding the PCCS design for a specific reactor system is pivotal for reactor system design and analysis. 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. Nuclear Regulatory Commission 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]. Understanding this entire process, especially the long-term cooling phase, is essential to reactor system safety.

2. EXPERIMENTAL STUDY

To analyze the physics phenomena behind SMR PCCSs, this study presents scaled experiments regarding steam condensation in the presence of NCGs. These tests involved vertical downward steam flow and condensation within the inner surfaces of condenser tubes, coupled with annular or pool-cooling methods. Test data were collected for various steam and NCG flow rates, as well as temperature/pressure conditions.

2.1. Test Facility Description

The following are key features of the test facility [12]:

- Test section (condenser): The test sections are made of stainless steel 304. They are 8 ft. long, with specific dimensions for the steam and jacket tubes. Three different diameters (e.g., 1, 2, and 4 in.) for condensing tubes/pipes and corresponding jacket water cooling tubes/pipes (e.g., 2, 3, and 6 in.) are available, though these diameters are significantly smaller than the Westinghouse SMR prototypic containment vessel (i.e., 32 ft. [9.754 m]). The smaller scale—both in terms of length and diameter—helps reduce costs and simplify construction. The test section configuration is presented in Figure 1.
- Modular scaled configuration: The test facility, shown in Figure 1, includes three test sections mounted on a steel-frame test bench, along with other required piping, valves, and isolation components designed to withstand operational pressures and temperatures.
- Instrumentation: The test facility utilizes a total of 44 thermocouples to measure axial temperatures at the condensing tube wall and annular coolant. These thermocouples were strategically placed to minimize measurement uncertainty. The methodology entails precise temperature measurements at the steam tube outer wall and the cooling jacket tube inner wall. Conductive gel ensured optimal contact between the thermocouples and the tube surfaces. Mass flow meters measured the steam, water, and NCG mass flow rates. Thermocouples and pressure indication/measurement were used to calculate the inlet/outlet pressure and temperature of the steam, water, and NCG.

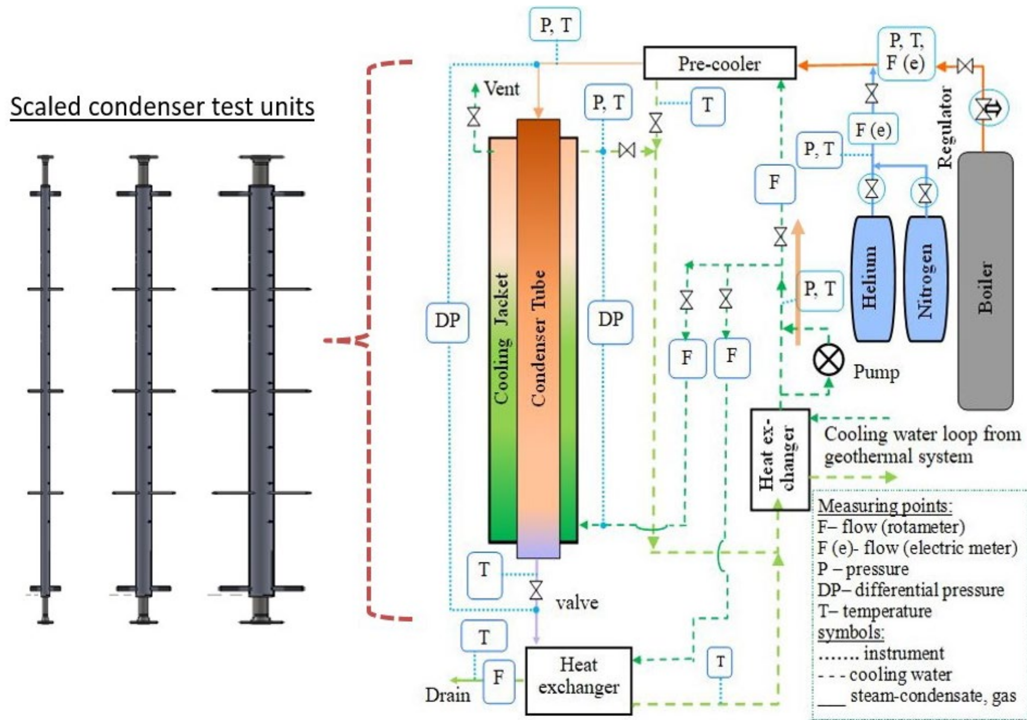

Figure 1. Final test facility instrument and control schematic [12].

The geometric information of the final design of the test sections (TS) is presented in Table I. The geometric scaling (i.e., scale ratios) are estimated in comparison with Westinghouse-SMR (W-SMR) containment vessel (CV). The length scale ratio between TS and 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]. The condenser (steam) tube and the annular (water) tubes are made of stainless steel 304, and the pipe schedules (SCH) are 10 and 40, respectively. In Table I, geometric parameters H for height, and OD for outer diameter.

Table I. Geometric information of scaled design TS and reference reactor CV [16].

TS	**Conder tubes**		**Water tubes**	**W-SMR CV**		**Length**	**Area**
No.	**OD**	**H**	**OD**	**OD**	**H**	**Scale**	
	(m)	(m)	(m)	(m)	(m)	ratio	
1	0.033	2.438	0.0603	9.754	27.13	11	3250
2	0.060	2.438	0.0889	9.754	27.13	11	1800
3	0.1140	2.438	0.1683	9.754	27.13	11	950

2.2. Testing and Test Data Reduction Methodology

The test data reduction method for CHT, outlined in Figure 2, consists of the following three primary stages of estimating parameters:

- Estimating coolant bulk temperature (T_b) and local heat flux (q''):

  The axial distribution of the coolant bulk temperature (T_b) is determined based on the coolant mass flow rate and axial temperature distribution (i.e., shape factor). The axial temperature distribution of the bulk coolant is estimated using boundary conditions derived from the inner and outer wall temperatures of the condensing tube. The local heat flux (q'') is estimated using the jacket water cooling temperature, coolant inlet/outlet temperature, and energy balance equation.

- Local HTC, blowing parameter, and film thickness:

  Using saturated steam as the working fluid, the local heat transfer coefficient (HTC) is calculated based on the estimated heat flux and condensing wall temperature. Other parameters such as interfacial shear stress, suction effect, and blowing parameter are estimated using the respective momentum transfer balance equations.

- Dimensionless parameters: Reynolds (Re) and Nusselt (Nu) numbers:

  The laminar film thickness is computed—using dimensionless parameters such as the Re and Nu numbers—from hydrodynamic analysis and incorporated into Nusselt's analysis.

- Uncertainty quantification:

  Quantification of the measurement uncertainty includes the mass flow rate, coolant and condensing tube axial temperature, inlet/outlet temperature, and steam/water pressure. Standard error propagation methods are used to estimate the total and relative errors of the measured variables.

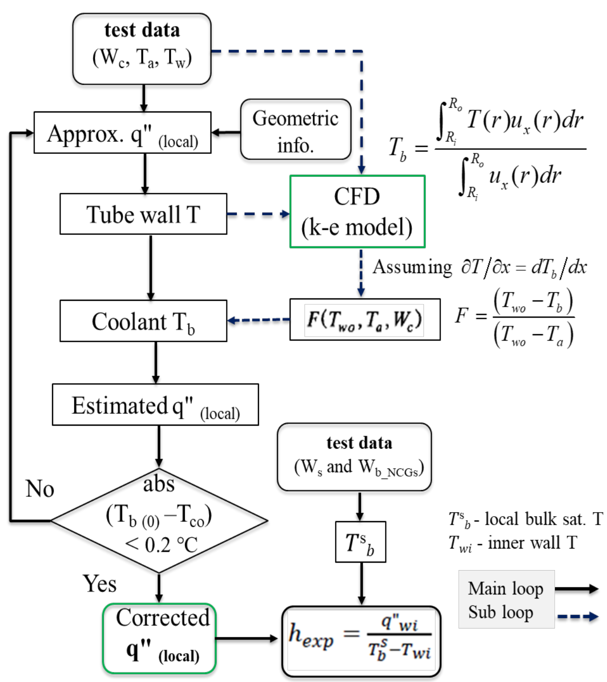

Figure 2. Local heat flux and HTC estimation [12].

Table I comprehensively presents this methodology, along with the relevant physics models, dimensionless number, scaling parameters, and uncertainty quantification (UQ) equations.

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

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.
Scaling Parameter	$\psi_s = \frac{\psi \text{ in model}}{v \text{ in prototype}}$ and $A_s = \frac{A(\text{model } 1)}{A(\text{ model } 2)}$ Where, ψ_s is the general scaling ratio, and A_s, is the flow area scale.
Uncertainty quantification	$\frac{\sigma_{exp}}{h_{exp}} = \left[\left(\frac{\sigma_{W_{cw}}}{W_{cw}}\right)^2 + \left(\frac{\sigma_{c_p}}{c_p}\right)^2 + \left(\frac{\sigma_{d_i}}{d_i}\right)^2 + \left(\frac{\sigma_{(T_c - T_w)}}{(T_{sat} - T_{wi})}\right)^2 + \left(\frac{\sigma_{(cw/dx)}}{dT_{\ cw/dx}}\right)^2\right]^{1/2}$ $\frac{\sigma_f}{f} = \left[\left(\frac{\sigma_{h_{exp}}}{h_{exp}}\right)^2 + \left(\frac{\sigma_{h_{Nu}}}{h_{Nu}}\right)^2\right]^{1/2}$ where, σ for error, dx for axial node length. Subscript sat for saturation, exp for experiment.

Experimental measured data UQ and uncertainty propagation are estimated, considering the similar approach as presented in Figure 3 [18]. The measured parameters are temperature (T), pressure (p), velocity (v), and for specific cases, steam boiler input voltage (V) and electric current (I), as presented in the blue color block. The fluid properties like density (ρ), viscosity (μ), thermal conductivity (k), and heat capacity (c_p) depend mainly on the experimental fluid temperature test condition.

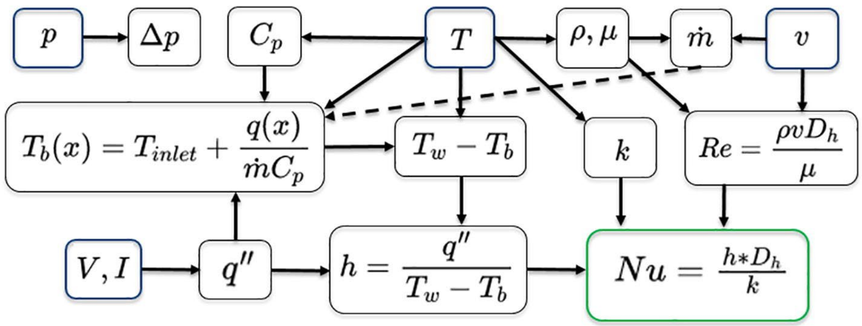

Figure 3. Uncertainty propagation from measured to derived parameters [18].

2.3. Results and Discussion

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 3, Figure 4, and Figure 5, 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. These selected test cases and levels were intended to enable a qualitative comparison of all He test cases, but not to be applicable to all test datasets.

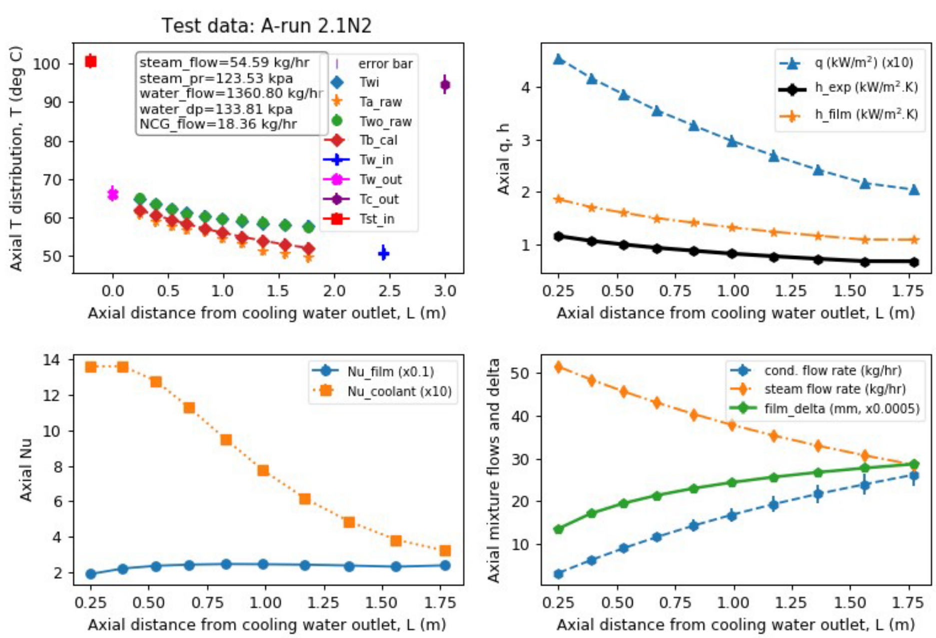

Figure 3. Test data: A-run2.1N2 (4-in. test section; NCG: He, high flow).

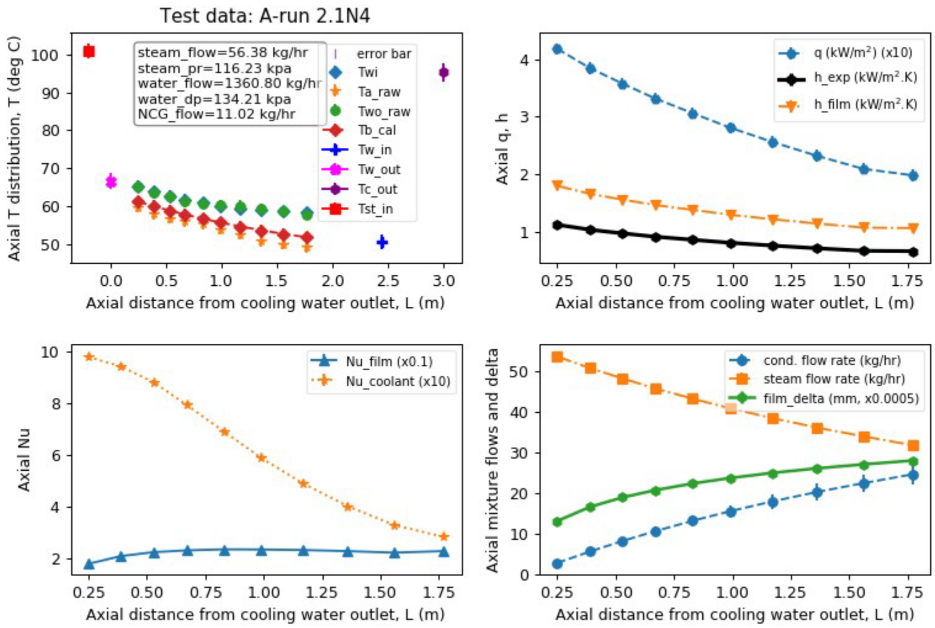

Figure 4. Test data: A-run2.1N4 (4-in. test section; NCG: He, medium flow).

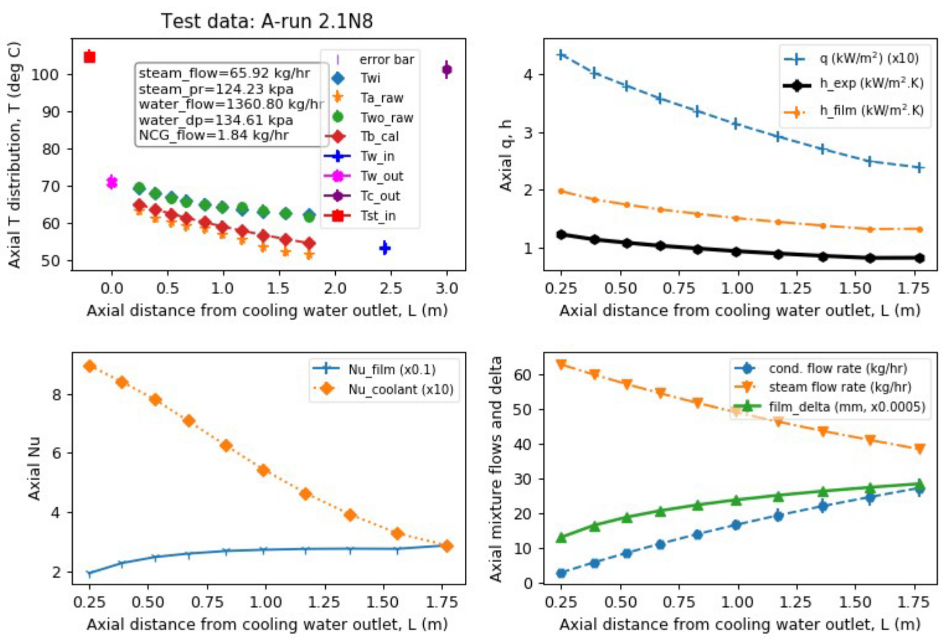

Figure 5. Test data: A-run2.1N8 (4-in. test section; NCG: He, low flow).

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

- Per the presented test data, the He flows varied over a range of approximately 5–30%. The selected tests were conducted under saturated steam conditions at approximately atmospheric pressure (100 to 128 kPa) with ambient discharge.

- The presented test data range—i.e., steam mass flow rates varying from 55 to 66 kg/hr., in the presence of helium as the NCG mass flow rate ranges from 1.8 to 19 kg/hr—and inlet conditions were helpful, as challenges in achieving identical inlet conditions for the three test sections occurred. Consistency in testing and data collection is required.
- 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. There were noticeable deviations in a few cases, due to a mismatch with the inlet conditions. Such mismatches in the test inlet conditions can be minimized by utilizing control elements (i.e., mostly control valves), which is supportive to estimating scaling distortions, and NCG effects comparisons.
- The selected tests were conducted under saturated steam conditions at approximately atmospheric pressure, preventing any possibility of gas accumulation. Additionally, 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. A series of similar tests was conducted to confirm the reproducibility of the test data for varying steam mass flow rates, pressures, and NCG mass fractions.

3. CONCLUSIONS

The condensation experiments were carried out using three scaled-down condenser tubes and various steam-NCG (i.e., He) mixture mass flow rates. Issues identified with regard to certain limitations faced by earlier experimental facilities were addressed during the design and development of this scaled modular test facility. 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, and 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. Such data reduction and UQ methods could be utilized in multiphysics and system code modeling and simulation.
- 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 certainly improve the reactor system design and analysis for enhancing safety margins and obtaining regulatory approvals.

NOMENCLATURE

If variables are extensively used in the text, a Nomenclature section would be helpful to the reader.

CHT Condensation Heat Transfer

CV Containment Vessel

NCG Noncondesable Gas

PCCS Passive Containment Cooling System

SMR Small Modular Reactor

HTC Heat Transfer Coefficient

RTD Resistance Temperature Detector

STD Standard Deviation

TS Test Sections

W-SMR Westinghouse SMR

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