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Original Article

Thermal-hydraulic behavior simulations of the reactor cavity cooling system (RCCS) experimental facility using Flownex

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A R T I C L E I N F O

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A B S T R A C T

The scaled water-cooled Reactor Cavity Cooling System (RCCS) experimental facility reproduces a passive safety feature to be implemented in Generation IV nuclear reactors. It keeps the reactor cavity and other internal structures in operational conditions by removing heat leakage from the reactor pressure vessel. The present work uses Flownex one-dimensional thermal-fluid code to model the facility and predict the experimental thermal-hydraulic behavior. Two representative steady-state cases defined by the bulk volumetric flow rate are simulated (Re = 2,409 and Re = 11,524). Results of the cavity outlet temperature, risers' temperature profile, and volumetric flow split in the cooling panel are also compared with the experimental data and RELAP system code simulations. The comparisons are in reasonable agreement with the previous studies, demonstrating the ability of Flownex to simulate the RCCS behavior. It is found that the low Re case of 2,409, temperature and flow split are evenly distributed across the risers. On the contrary, there's an asymmetry trend in both temperature and flow split distributions for the high Re case of 11,524.

1. Introduction

Electricity plays an essential role in human life. It is inherently linked with technological development and fills the energy demands of everyday needs: lighting, heating, mobility, and cooling [1]. By 2050, energy consumption needs are expected to increase by 30% and electricity production is projected to double [2]. In addition, the International Energy Agency (IEA) Net Zero Report, addressing climate change mitigation, urges the use of technologies that meet the goal of reaching zero carbon emission by 2050 [2].

Contributing to this effort, nuclear power plants have prevented more than 60 gigatons of CO_2 emissions over the past 50 years [2]. To continue this benefit, the next generation of nuclear reactors, the enhanced-featured Generation IV reactors (Gen IV) [3], aim to replace the previous generations and meet the requirements of supplying clean energy demands.

Among the Gen IV designs, the Very High-Temperature Reactors (VHTR) has capabilities that, among others, improve the net electricity efficiency and provide suitable means of hydrogen production [3]. To maintain the reactor plant components in operational condition and enhance safety levels in abnormal scenarios, the VHTR implements a passive safety system, the Reactor Cavity Cooling System (RCCS), which removes heat leakage from the reactor cavity using natural circulation.

The RCCS designs work with air or water as the cooling fluid ([4,5]). Fig. 1 represents a schematic overview of a water-cooled RCCS (WRCCS). The heat coming from the reactor pressure vessel (RPV) is transferred to the water running in the risers of the cooling panel. The heated water goes up to a tank through the chimney and is cooled by cold water inside the tank. Then, the water feeds the lower collector through the downcomer, closing the natural circulation loop.

At Texas A&M University (TAMU), Vaghetto and Hassan ([6,7]) designed and constructed a scaled WRCCS experimental facility to study its thermal-hydraulic behavior during steady-state and transient conditions. The facility is described in the following pages. The experiment findings proved the capability of heat removal of the facility and helped to understand the thermal-hydraulic phenomena that can take place within it. Furthermore, the experimental data acquired can be used to validate system codes and computer fluid dynamics (CFD) analysis.

Quintanar et al. [8] implemented updates in the TAMU WRCCS and investigated the flow and temperature distribution. They found that the temperature and flow distribution in the cooling risers are

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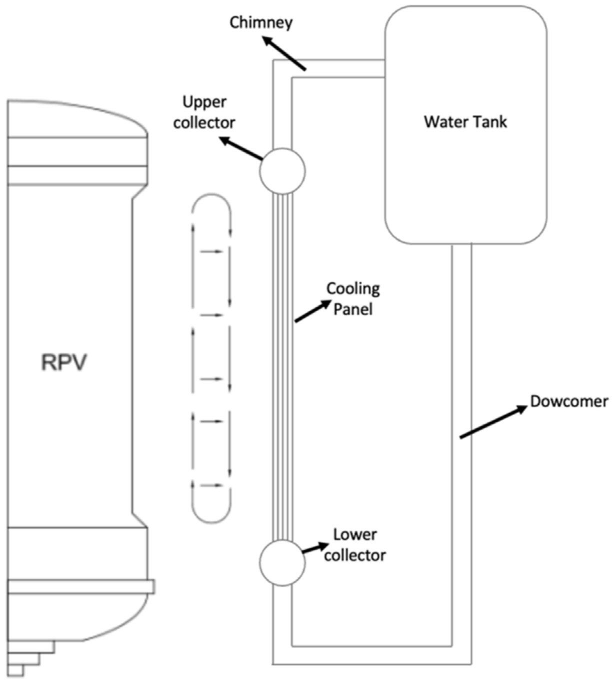


Fig. 1. Water-cooled RCCS schematic overview.

symmetric for the low Reynolds numbers (*Re*) analyzed and asymmetric for the high ones.

Holler et al. [9] performed multiple analyses and experimentation with optic fiber distributed temperature sensors (DTS) in both water and air environments. In the TAMU WRCCS, the authors acquired the temperature profile of the cooling risers with DTS and compared it against the thermocouple measurements.

With respect to the validation of computational tools, Gorman et al. [10] developed a CFD model of the test section (cooling panel) of WRCSS using ANSYS FLUENT. They ran the simulation for the steady-state condition and compared the temperature and velocity distributions against the experimental data. Pehlivan et al. [11] used RELAP5/SCDAPSIM system code [12] to model the WRCCS and simulate its behavior during normal and accidental scenarios. They found that the simulation results match the experimental ones. Following this thread, the present work aims to demonstrate the capability of Flownex Simulation Environment (SE) [13] to predict the thermal-hydraulic behavior of the TAMU WRCCS experimental facility.

Flownex is designed to be a solution for system and sub-system level simulation [14]. The software is able to design, analyze, and optimize complete networks. Also, it includes tools for constraint design, sensitivity analysis of components and system parameters. The code can model a variety of applications, such as gas, steam or combined power plants, nuclear power plant, gas turbine combustion chambers, and heat exchanger systems, among others. In the nuclear field, the extensive capabilities of Flownex merge into a tool that couples neutronics and thermal-hydraulic analysis. Other advantages of the software consist of fast processing, a friendly interface, and integration with engineering computational tools such as ANSYS, RELAP, and MCNP [15].

Rousseau et al. [15] modeled an air-cooled RCSS with two different one-dimensional system codes, Flownex and Gamma+. They found good agreement between the results from both simulation environments. Also, du Toit [16] used Flownex to investigate the effects of pipe diameter, loop length and local losses on steady-state single-phase natural circulation. The author used analytical approaches to validate the simulation results.

Here, Flownex is used to model and simulate the TAMU WRCSS facility. Two representative steady-state operational conditions, defined by the bulk volumetric flow rate through the system, are simulated (low and high Reynolds number cases, Re = 2,409 and Re = 11,524). The Flownex simulation results of the cavity outlet temperature, the temperature profile along each riser, and the volumetric flow rate split in the cooling panel, are compared with the experimental data ([8,9]) and the previous RELAP simulations [11]. These parameters are important to characterize the facility's thermal-hydraulic behavior. The flow and temperature distribution permit to assess the capability of heat removal of the RCCS and understand the response of the system for steady-state, accidental and other transient scenarios.

2. The TAMU WRCCS experimental facility

2.1. Facility description

The experimental facility modeled is a 1:23 axial scaled WRCCS [6]. Fig. 2 shows the main components of this installation. The primary loop consists of a portion of a reactor cavity (heaters and the cooling panel, consisting of nine risers), hot and cold legs, and a tank. The electrical radiant heaters increase the water temperature in the nine risers, which ultimately establishes natural circulation in the system due to buoyancy forces. The heated water travels upward and is collected by the upper manifold. Finally, it reaches the water tank through the hot leg. In the water tank, heated water is cooled through mixing with cold water supplied by a secondary loop. Then, water flows from the tank bottom outlet to the lower manifold through the cold leg, and from there is distributed among the risers. A valve placed in the tank outlet controls the system pressure drop, which in turn defines the bulk volumetric flow rate measured by the flowmeter.

A secondary loop is responsible for maintaining the tank's water temperature in a steady-state condition. Fig. 3 shows a scheme for both loops. In the secondary loop, water from the tank is circulated by a pump through a heat exchanger.

2.2. WRCCS experimental data

The main experimental data used in the simulation comes from

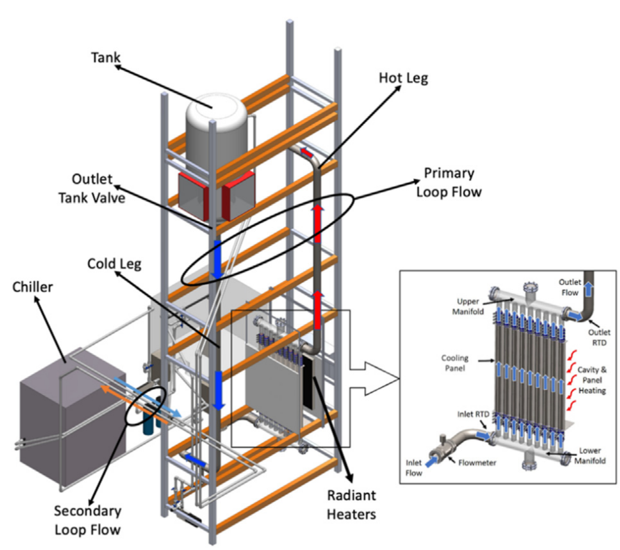


Fig. 2. Representation of the WRCCS experimental facility.

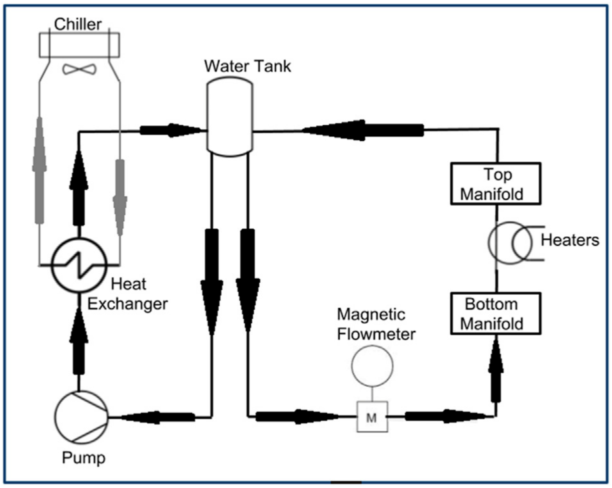


Fig. 3. Primary and secondary loop scheme of the WRCSS experimental facility [8].

the facility test section presented in Fig. 4. The test section consists of the cooling panel with nine risers, the lower and upper manifolds, and the reactor cavity inlet and outlet pipes. To record the experimental data in the test section, there is a flowmeter, a set of five thermocouples placed at different levels in each riser, and Resistance Temperature Detector (RTD) sensors at the inlet and outlet pipes.

Experiments were carried out in the WRCCS for different steady-state operational conditions, each one representing different bulk volumetric flow rates through the system ([8,9]). Table 1 shows the experimental data acquired for representative low and high Re cases (valve openings). For brevity, the water temperature readings in all thermocouple levels in each riser are not listed here. The water temperature measured between the heat exchanger and the tank (see Fig. 3) is indicated by the secondary tank inlet temperature in Table 1.

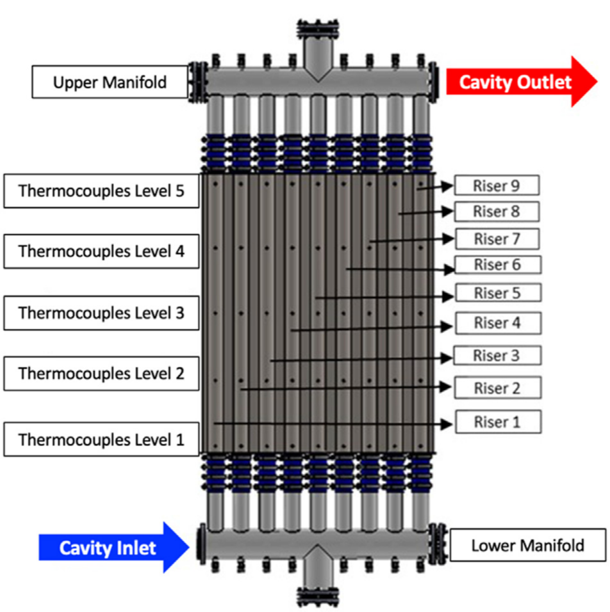


Fig. 4. Representation of the WRCCS cooling panel.

3. Flownex WRCCS model

Flownex is a system-level one-dimensional thermal-fluid code based on an implicit pressure correction solution method [17]. The code solves the steady-state and transient forms of the fundamental conservation equations of fluid dynamics and heat transfer [18].

The one-dimensional form of the continuity equation is given by:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho V)}{\partial x} = 0 \tag{1}$$

Where ρ is fluid density, t is time, x is the direction of the flow and V is the velocity. Eq. (1) states that mass in a differential control volume varies in time if there is mass entering or exiting this control volume.

The momentum equation for one direction is given by:

$$\frac{\partial(\rho V)}{\partial t} + \frac{\partial\left(\rho V^2\right)}{\partial x} = -\frac{\partial p}{\partial x} - \frac{f \rho |V| V}{2D} - \rho g \frac{\partial z}{\partial x} \tag{2}$$

Where f is the Darcy-Weisbach friction factor, D is the hydraulic diameter and g is the gravity.

The left-hand side of Eq. (2) represents the inertial terms, composed of a time derivative and convective contributions. The right-hand describes the forces acting on the differential control volume. The pressure gradient and the Darcy-Weisbach formula represent the surface forces while the remaining term is the body force, which in this case, it is due to the gravity.

Finally, the energy conservation equation, expressed in function of the specific stagnation enthalpy h_o, is given by:

$$\frac{\partial(\rho(h_o + gz) - p)}{\partial t} + \frac{\partial(\rho V(h_o + gz))}{\partial x} = \dot{Q}_h - \dot{W} \tag{3}$$

Where z is the height, $\dot{Q}_h$ is the heat provided to the control volume and $\dot{W}$ is the work done on the environment.

The specific stagnation enthalpy is defined as:

$$h_o = h + \frac{V^2}{2} \tag{4}$$

Where h is the specific enthalpy given in function of the u specific internal energy, pressure p and specific volume v:

$$h = u + pv \tag{5}$$

Flownex solution also uses built-in thermal-hydraulic relations and properties along with pre-configured library components to give information at any point of the system about temperature, pressure, mass flow rate, power, and heat transfer [15].

The component library provides a variety of options that are added to a canvas to form complex networks. The most common components are pipes, connections, valves, heat exchangers, pumps, and turbines. These components are linked through nodes, tanks, or reservoirs (linking items). The linking items connect the inlet and outlet of the component where boundary conditions can also be set. Fig. 5 shows a schematic network formed by components and nodes in Flownex.

The implicit pressure correction solution method algorithm [17] used in Flownex follows the steps described in Fig. 6 [18].

The component's parameter results are a weighted average value between its inlet and outlet [15]. Discretization of specific components can be made so that higher accuracy is achieved. For instance, a single pipe can be subdivided (discretized) and the

Table 1
Experimental parameters for WRCCS test section ([9,11]).

Parameters	Operational conditions	
Valve Opening Case (%)	25	100
Reynolds Number	2409	11524
Secondary Tank Inlet Temperature (°C)	30.8 ± 1.1[a]	30.8 ± 1.1[a]
Primary Loop Volumetric Flow Rate (lpm)	8.2 ± 0.3[a]	39.0 ± 0.6[a]
Water Inlet Temperature to Lower Manifold - Cavity In (°C)	35.8 ± 0.2[a]	36.1 ± 0.2[a]
Water Outlet Temperature from the Upper Manifold - Cavity Out (°C)	48.4 ± 0.2[a]	38.9 ± 0.2[a]
Net Power (W)	7153 ± 290[b]	7555 ± 550[b]

Note.
[a] Uncertainty values.
[b] Estimated error of the power.

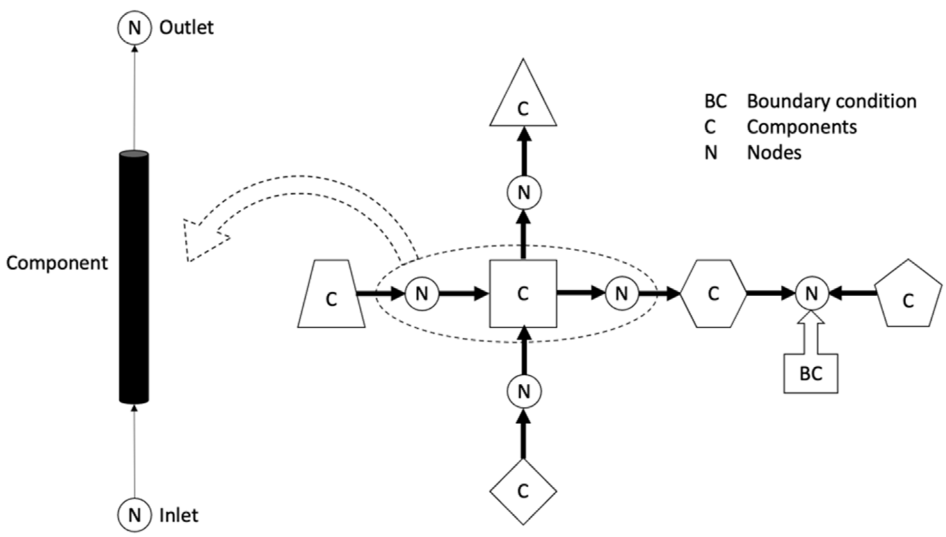


Fig. 5. Flownex schematic network.

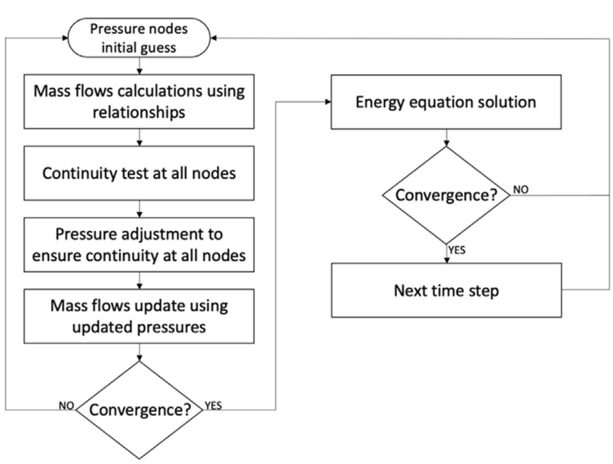


Fig. 6. Flownex solution method.

parameter result values are weight-averaged through all subdivisions.

Fig. 7 shows the Flownex network model for the WRCSS facility under study. The primary loop is modeled with an open container component (tank), a valve, pipes to form the cold and hot legs, and "T" connections and pipes for the cooling panel (risers, lower and upper manifolds). The secondary loop consists of a set of pipes. The chiller (heat sink) is modeled as a pipe with a fixed exit temperature (T_{sink}).

The model uses two input data in the secondary loop, the secondary tank inlet temperature (T_{sink}) and the secondary volumetric flow rate ($\dot{v}_2$). T_{sink} indicates the water temperature measured in the tank inlet at the secondary loop side, according to the value from Table 1. The value of $\dot{v}_2$ was adjusted so that the predicted cavity inlet temperature (T_{in}) matches the experimental one. For the primary loop inputs, atmospheric pressure (P_{atm}) was set in the tank free surface and the heat (Q_{add}) provided to the cooling panel, shown as Net Power in Table 1, was axially distributed in each riser based on a parabolic approximation of the model used in Ref. [11].

The pressure drop in the WRCCS model was set to match the bulk volumetric flow rate for each case by adjusting the secondary losses in the system. After losses for bends and junctions were applied, an adjustable valve component was used for the final tuning. It was determined that pressure losses matched experimental values with a valve opening fraction of 15% and 100% for Re = 2,409 and Re = 11,425 respectively.

4. Results and discussion

This section presents the comparison of the simulation results against experimental data and previous RELAP simulations for the steady-state cavity outlet temperature, risers' temperature profile, and flow rate split in the cooling panel. Table 2 shows the input parameters for the WRCSS model and the main simulation results. For both cases, the secondary volumetric flow rate was adjusted to achieve the T_{in} experimental value.

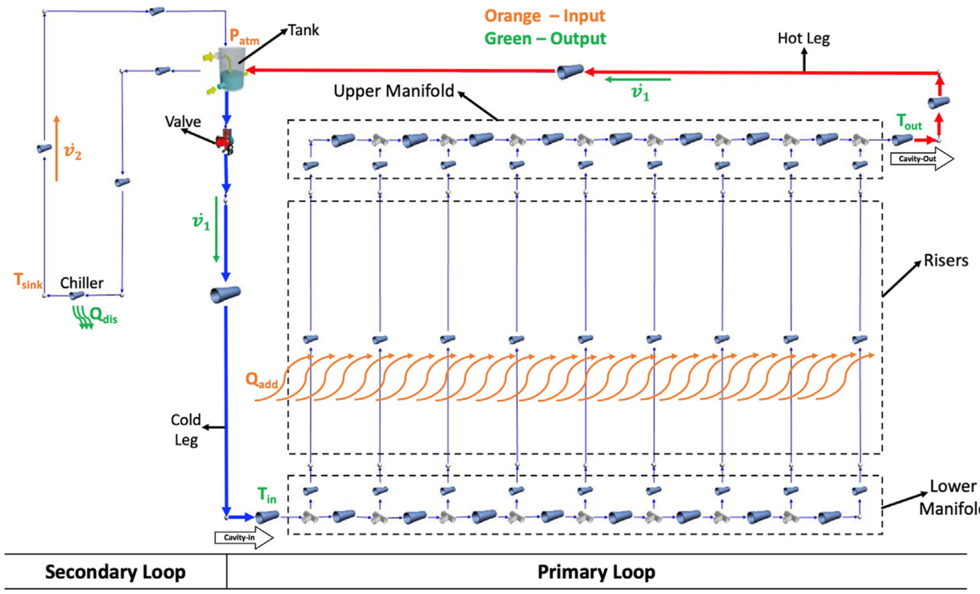


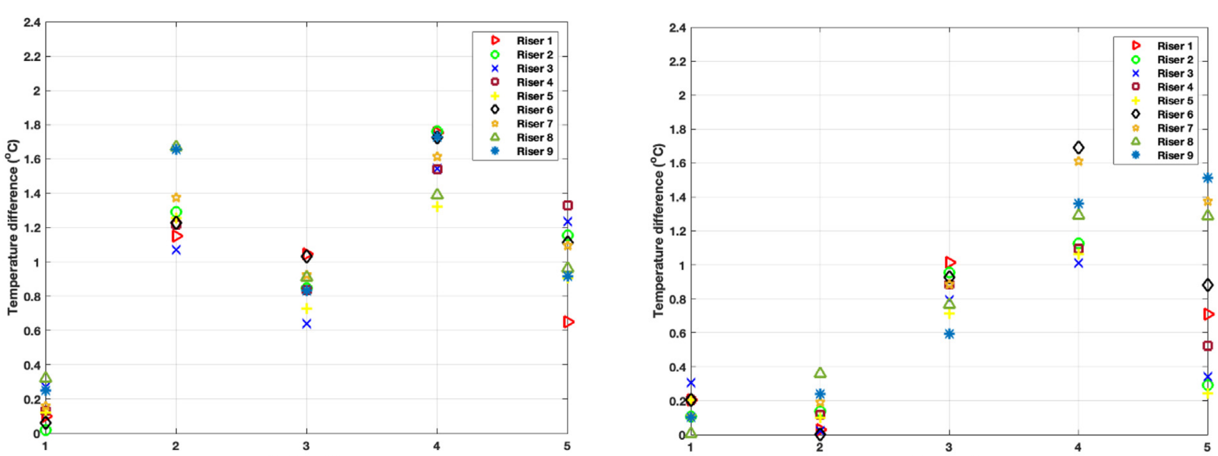
Fig. 7. WRCCS Flownex model.

Table 2
Input parameters and main simulation results from the Flownex WRCCS Model.

			Reynolds Number Case			
			Re = 2409		Re = 11,524	
			Experiment	Flownex	Experiment	Flownex
Input	Secondary Tank Inlet Temperature (°C)	T_{sink}	30.8 ± 1.1	30.8	30.8 ± 1.1	30.8
	Net Power (W)	Q_{add}	7153 ± 290	7100	7555 ± 550	7500
Result	Primary Loop Volumetric Flow Rate (lpm)	$\dot{v}_1$	8.2 ± 0.3	8.1	39.0 ± 0.6	39.4
	Inlet Cavity Temperature - Cavity In (°C)	T_{in}	35.8 ± 0.2	35.6	36.1 ± 0.2	35.9
	Outlet Cavity Temperature - Cavity Out (°C)	T_{out}	48.4 ± 0.2	48.3	38.9 ± 0.2	38.7

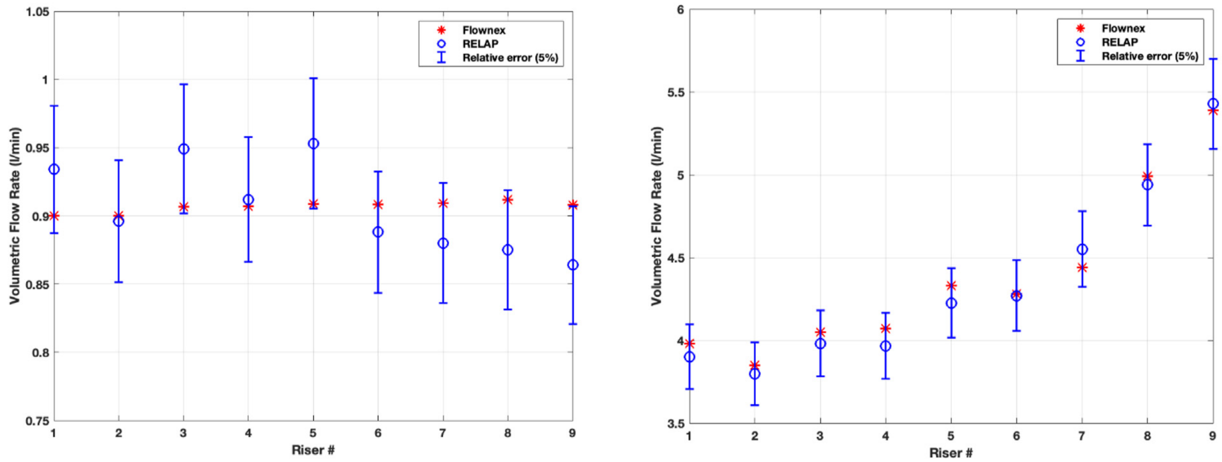
The Flownex predictions for cavity outlet temperatures are in good agreement with the experimental measurements. The difference between these values is within the uncertainty of the equipment. In an evaluation of system-level code capabilities, these results are of paramount importance because they represent the energy balance solution of the entire network for a correspondent bulk volumetric flow rate.

Fig. 8 shows the temperature difference between the thermocouple readings for all riser levels and the simulation results. The thermocouple uncertainty is 1.1 °C, hence 70% of the points are within the uncertainty of the experimental data. The temperature difference is mostly higher than 1.1 °C for the thermocouples



(a) Re = 2,409 (b) Re = 11,524

Fig. 8. Temperature difference between thermocouple readings and simulation results.



(a) Re = 2,409 (b) Re=11,524

Fig. 9. Volumetric flow rate split in the cooling panel for Flownex and RELAP simulations results.

located at level 4 of the risers in both cases. This may be due to the heat transfer profile input to the risers. The heat profile in Ref. [11] is an approximation of the heat flux imposed on the experiment. Pehlivan et al. [11] calculated the heat flux based on the thermocouple's temperature measurements in the cooling panel.

Fig. 9 compares the volumetric flow split in the cooling panel predicted by Flownex and RELAP [11]. The error bar of 5% represents the relative error between the simulation results from Flownex and RELAP (considered an acceptable value for the code simulation comparisons under study). The average relative error between both simulation results is 3% for the low Re case and 2% for the high one. The distribution of the flow split in the cooling panel (among the risers) is symmetric for Re = 2,409 and asymmetric for Re = 11,524, consistent with observations made by Quintanar et al. [8] and Holler et al. [9].

5. Conclusion

The WRCCS experimental facility was modeled and simulated for two steady-state operational conditions (Re = 2,409 and Re = 11,524 cases) using Flownex.

The comparison of the simulation results against the experimental data and previous RELAP simulations demonstrates that the flow and temperature distributions agree with previous studies ([6–11]). For Re = 11,524, Riser 9 is the coldest riser which corresponds to the highest flow rate, while Riser 1 is the hottest with low flow rates. For Re = 2,409, flow and temperature are evenly distributed in the cooling panel. The average relative error of the volumetric flow split results between RELAP and Flownex is less than 5% for both cases. The Flownex temperature predictions are within the uncertainty of the thermocouple's measurements.

The results show that Flownex is capable of predicting the behavior of the complex fluid flow network of the WRCCS under natural circulation conditions. The main advantages of system-level analysis as Flownex are its easy preparation of inputs and fast execution.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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