EXPERIMENTAL INVESTIGATION OF A SCALED REACTOR CAVITY COOLING SYSTEM WITH AIR FOR THE VHTR

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ABSTRACT

This experimental study investigates the thermal hydraulic behavior and the heat removal performance of a scaled Reactor Cavity Cooling System (RCCS) with air. A quarter-scale RCCS facility was designed and built based on the full-scale General Atomics (GA) RCCS design concept for the Modular High Temperature Gas Reactor (MHTGR). The GA RCCS is a fully passive cooling system that draws in air to use as the working fluid for decay heat removal. The system relies on radiative and convective heat transfer from the reactor pressure vessel to the air-cooled riser tubes and ultimately discharges the heated air into the atmosphere.

A specific set of scaling laws were used to preserve key thermal hydraulic aspects and to maintain similarity among various scales. The air RCCS facility at the University of Wisconsin-Madison (UW-Madison) is a quarter-scale reduced length experiment standing over 13 meters in height and housing six riser ducts that represent a 9.5° sector slice of the full-scale GA air RCCS concept. Radiant heaters were used to simulate the heat radiated from the reactor pressure vessel. The maximum power that can be achieved with the radiant heaters is 40 kW at a corresponding peak heat flux of 25 kW/m^2.

The quarter-scale air RCCS at UW-Madison was run under different heat loading cases and operated successfully across 12 test runs. The results presented in this paper were performed over a range of initial and boundary conditions. Instabilities were observed in some experiments; however, the air RCCS system shows potential for a high level of performance and is well suited as a heat removal system during an accident scenario.

Keywords: Passive safety, Natural circulation, Scaled experiments, Flow instabilities

1. INTRODUCTION

Passive heat removal systems are an integral safety component under consideration for long term removal of decay heat in the next generation of advanced nuclear reactors[1]. Passive cooling systems rely on fundamental physics in nature to remove heat from the system and do not employ fans, pumps, or other active components that require electrical power. In the event of an accident scenario, no human intervention is needed to ensure proper cooling for heat removal to an ultimate heat sink. In particular, this experimental investigation focuses on a quarter-scale experiment of the Reactor Cavity Cooling System (RCCS) designed by General Atomics (GA) for the Modular High Temperature Gas Reactor (MHTGR). The RCCS draws in air to use as the cooling fluid to remove heat radiated from the reactor pressure vessel (RPV) to the air-cooled riser tubes and discharges the heated air into the atmosphere as the ultimate heat sink[2]. Fundamentally, the air RCCS is an open air natural circulation loop as seen in Figure 1. The RCCS offers a clear advantage compared to forced cooling systems in that it does not require electrical power and can in theory operate indefinitely in an accident scenario. The GA air RCCS design concept must remove 700kW$_t$ during normal operations.[3] In the event of an accident where active cooling systems are incapacitated, the GA air RCCS must remove 1.5 MW$_t$ and also accommodate for peak wall heat flux values of 10 kW/m^2.[4] A design criterion of the RCCS states that the outlet should not be above 152°C when the inlet is at 22°C (ΔT =130°C). The full-scale GA RCCS prototype employs 227 riser ducts.[5] In order to gauge the potential of the RCCS as a viable long-term core cooling strategy, the thermal hydraulic behaviour will be investigated via a scaled experiment at UW-Madison. A quarter-scale RCCS facility was designed and built based on the full-scale GA RCCS design concept[3]. Scaling laws were used to preserve key thermal hydraulic aspects and to maintain similarity among various scales[4].

Table 1 - Scaling parameters.

Parameter	GA RCCS	UW ¼ Scale	Scaling Similarity
Total RCCS Height	55.2 m	13 m	ℓ_R
Heated Riser Section	1103 m	2.8 m	ℓ_R
Riser Duct Count	227	6	-
Max. Decay Heat	1.5 MW	19.82 kW	$\ell_R^{-0.5}$
Peak Heat Flux	10 kW/m^2	20 kW/m^2	$\sqrt{\ell_R}$

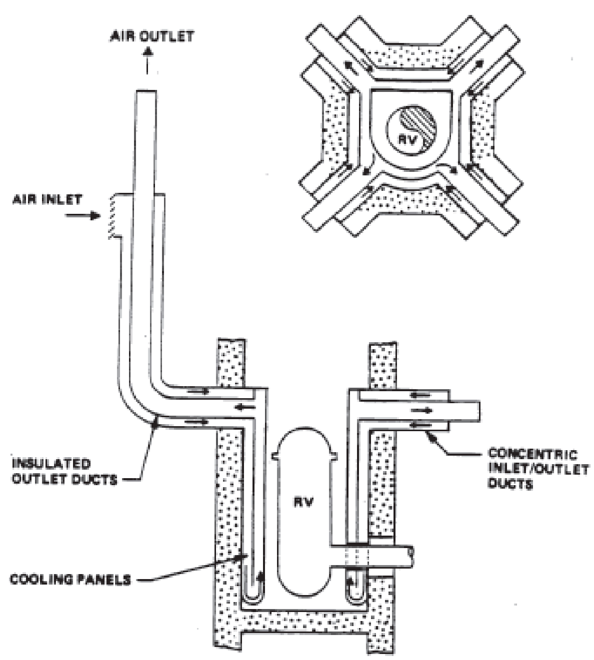

Figure 1 - Cavity plan view of RPV and RCCS.[2]

2. QUARTER-SCALE RCCS FACILITY

The air RCCS facility at the University of Wisconsin-Madison (UW-Madison) is a quarter-scale reduced length experiment standing over 13 meters in height and housing six riser ducts that represent a 9.5° sector slice of the full-scale GA air RCCS concept[3]. Black heat resistant paint was applied to the six riser ducts to maintain a constant surface emissivity of approximately 0.8. Radiant heaters were used to simulate the heat radiated from the reactor pressure vessel. The maximum power that can be achieved with the 32 radiant heaters is 40 kW at a corresponding peak heat flux of 25 kW/m^2. Scaling with similarity parameters was necessary to determine the power required for the quarter-scale facility to simulate the full-scale GA RCCS decay heat load. Details of our scaling studies and design requirements can be found in earlier works by the authors.[3]

The quarter-scale RCCS experiment consists of three important components: inlet piping/plenum, heated cavity (which contains the six riser ducts), and the outlet plenum/exhaust ducts. The inlet piping and plenum is the entry point for air drawn from the environment by the air RCCS. Electrical resistance heaters inside the heated cavity simulate the reactor pressure vessel of the reactor and radiate heat to the six riser ducts. The outlet plenum provides a volume to allow mixing before the heated air returns to the outside environment via two exhaust ducts. Insufficient mixing could lead to stratification of the flow and hamper heat removal performance.[6]

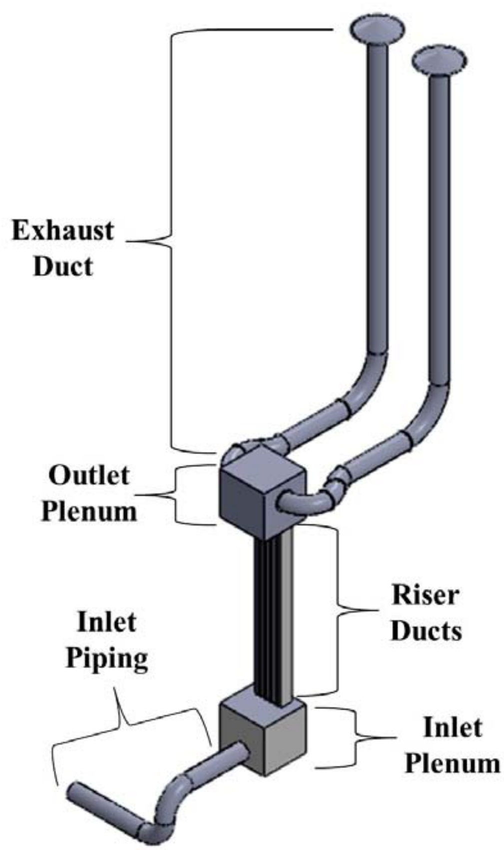

Figure 2 – Solid model rendering of UW quarter-scale air RCCS.

Instrumentation was placed in the air RCCS facility to control the heating zones and to record temperature and velocity measurements at certain locations to better understand the thermal hydraulic phenomena. Four power controllers were used to provide well defined true RMS power to the electrical resistance heaters inside the heated cavity. The heaters were arranged in four-column heating zones to allow for different power shaping. Temperature and velocity measurements were placed at key locations in the quarter-scale RCCS as seen in the Figure A.1 (Appendix). An air velocity transducer was installed at the inlet piping in order to establish velocity profiles. Type-K thermocouple probes were used to measure the air temperature throughout the facility. In order to measure the surface temperature of the risers, type-K thermocouple wire was welded to the metal surface.

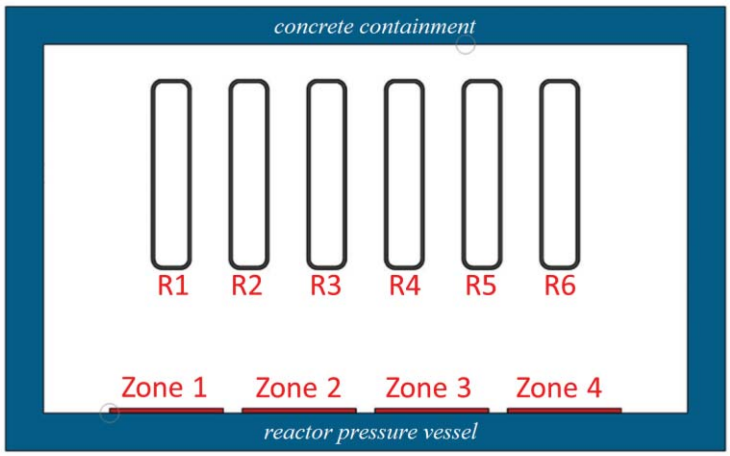

Figure 3 – Heated cavity section view.

3. FORCED FLOW TESTING

Four experiments were carried out under forced flow conditions to ensure that the air RCCS facility produced repeatable data. An inline duct fan was placed at the entry of the inlet piping and kept at a constant duty cycle for all four tests. A total of 4 tests were run at two different powers; 19.82 kW and 37.93 kW, or 6.42 and 12.29 kW/m^2, respectively. The power was equally distributed among the four heating zones. The quarter-scale RCCS produced repeatable results which are shown in Table 2. The thermal power calculated with the experimental data was lower than the electrical heater input due to heating losses, which averages 80% for the cases presented. The differential system temperature (ΔT across the heated section) for all tests (see Figure 4) was calculated as the difference between the inlet duct air temperature and the average outlet duct air temperature. Figure 5 shows the average riser air temperature at steady state conditions.

Table 2 – Forced flow test results (FS: Front Surface).

Test	Power (kW)	Heat Flux kW/m^2	ΔT (Δ°C)	$\dot{m}_{total}$ (kg/s)	$\dot{m}_{total}c_p\Delta T$ (kW)	Avg. Riser FS Temp. (°C)
1	19.82	6.42	41.50	0.38	15.76	125.03
2			41.13	0.39	15.93	127.26
3	37.97	12.29	76.12	0.38	29.35	210.03
4			75.08	0.39	29.38	212.98

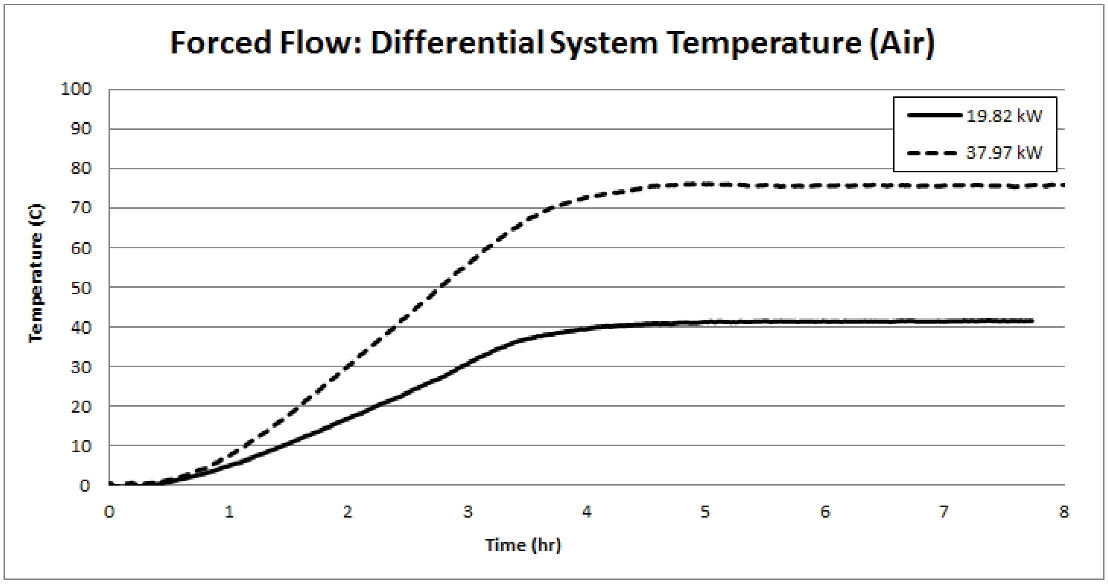

Figure 4 – Differential system temperature (air) for forced flow (Uncertainty: ± 0.7°C).

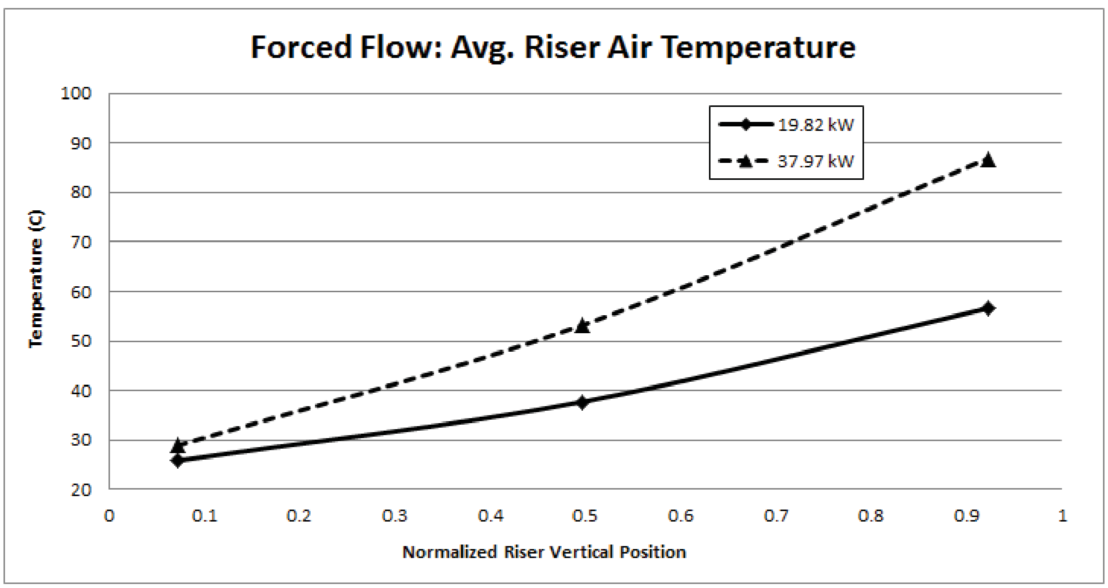

Figure 5 - Riser air temperatures for forced flow (Uncertainty: ± 0.7°C).

4. NATURAL CIRCULATION TESTING

Natural circulation test were carried out without the inline duct fan. Tests were carried out at two different heat flux conditions (constant heat flux and asymmetric heat flux) and different power levels. Power was equally distributed to all four heater zones for constant heat flux. For an asymmetric heat flux condition, heater zones 3 and 4 were turned off and power was equally distributed to heater zones 1 and 2 (see Figure 3).

4.1 Constant Heat Flux Power Testing

Testing under constant heat flux conditions were carried out at two powers (19.82 kW and 37.97 kW). Table 3 lists the results for constant heat flux testing. The power calculated with the experimental data was lower than the heater input due to heating losses. Figure 6 shows the average riser air temperature at steady state conditions.

Table 3 – Constant heat flux test results (FS: Front Surface).

Test	Power	Heat Flux	ΔT	$\dot{m}_{total}$	$\dot{m}_{total}c_p\Delta T$	Avg. Riser FS Temp.
	(kW)	kW/m^2	(Δ°C)	(kg/s)	(kW)	(°C)
5	19.82	6.42	90.28	0.16	14.39	237.33
6			90.38	0.15	13.90	233.14
7	37.97	12.29	141.63	0.18	25.60	363.93
8			141.71	0.18	25.43	365.13

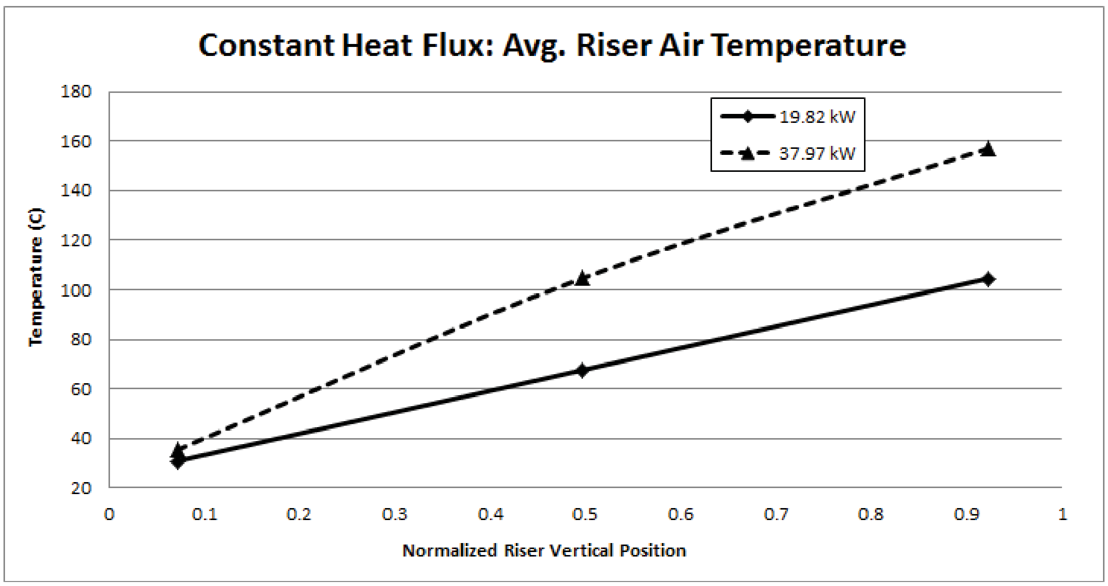

Figure 6 - Riser air temperatures for forced flow (Uncertainty: ± 0.7°C).

4.1.1 Constant Heat Flux Testing at 19.82 kW

Test 5 and Test 6 were run at 19.82 kW under a constant heat flux condition. The inlet piping and exhaust duct air temperatures for Test 5 and Test 6 can be seen in Figure 7 and Figure 8, respectively. Test 6 experienced a sharp drop in air temperature for one of the exhaust ducts between the fifth and sixth hour of the experiment. The temperature data suggests a reversal in flow direction for one the exhaust ducts that can be attributed to sharp changes in the ambient meteorological conditions. Shortly after the seventh hour of the test, the air temperature in the exhaust duct rises and the flow reversal ends without any operator intervention. This behaviour can be attributed to the inherently sensitivity of natural circulation systems, where even minor perturbations of the test boundary conditions can have system wide influences. Tests performed on a similar ½ scale facility at Argonne National Lab suggest similar behaviour when abrupt shifts occur in either the wind direction and/or wind speed. Both test facilities thus experience similar instabilities – one exhaust chimney is redefined as a fresh air intake while the other serves as the sole hot air exhaust. Mainly observed at low powers (when the driving chimney effect is less developed), this behaviour is of great interest and must be further studied to fully understand the RCCS performance under the full range of potential accident conditions.

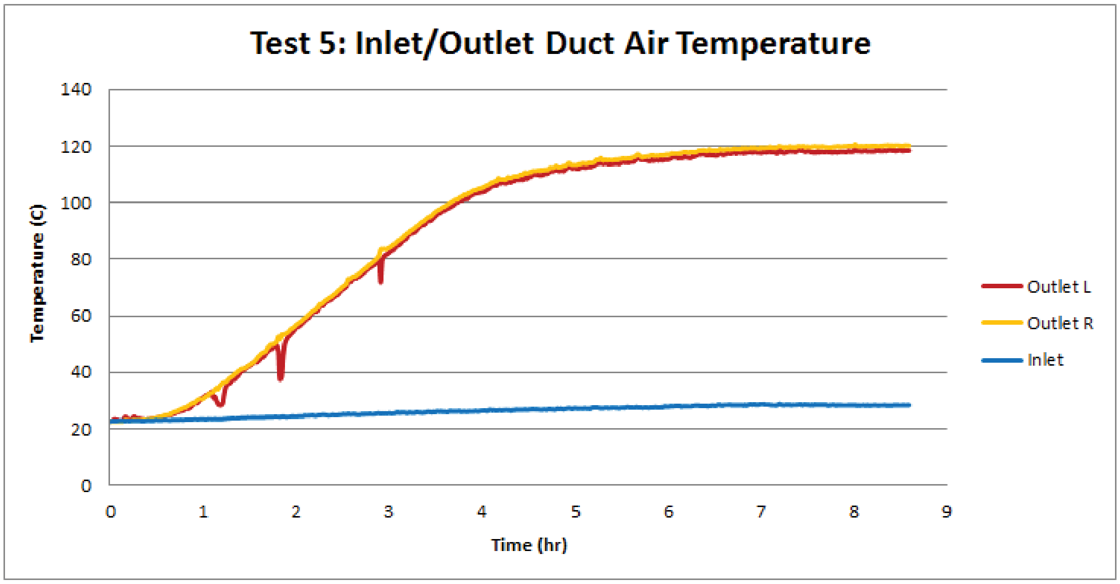

Figure 7 – Inlet and exhaust duct air temperature for Test 5 (Uncertainty: ± 0.7°C).

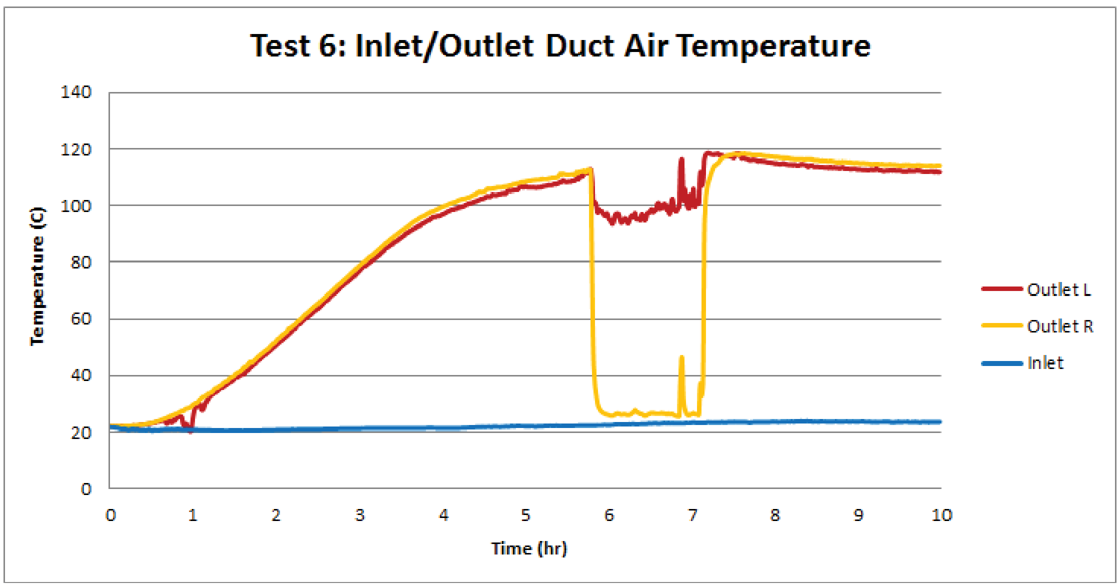

Figure 8 – Inlet and exhaust duct air temperature for Test 6 (Uncertainty: ± 0.7°C).

4.1.2 Constant Heat Flux Testing at 37.97 kW

Test 7 and Test 8 were run at 37.97 kW under a constant heat flux condition. The inlet and outlet duct air temperatures for Test 7 and Test 8 can be seen in Figure 9 and Figure 10, respectively. Both tests at 37.97 kW were stable and no sharp fluctuations in temperature were observed.

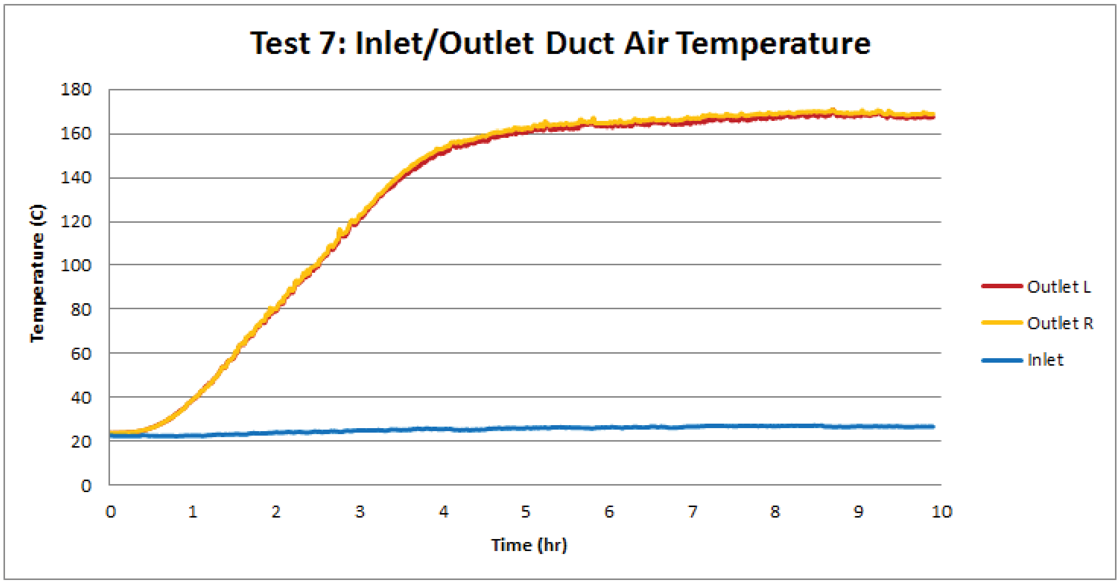

Figure 9 – Inlet and exhaust duct air temperature for Test 7 (Uncertainty: ± 0.7°C).

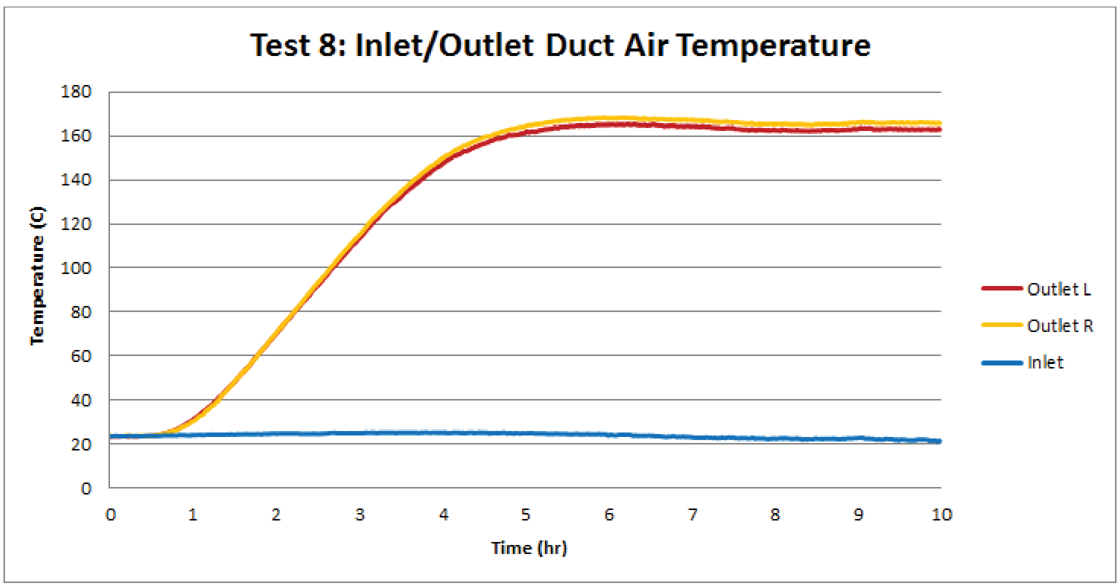

Figure 10 – Inlet and exhaust duct air temperature for Test 8 (Uncertainty: ± 0.7°C).

4.2 Asymmetric Heat Flux Testing

Testing under asymmetric heat flux conditions was carried out at two powers (9.91 kW and 18.99 kW). Heater zones 3 and 4 were turned off and power was equally distributed to heater zones 1 and 2. Table 4 lists the results for asymmetric heat flux testing. The power calculated with the experimental data was lower than the heater input due to heating losses. Figure 11 shows the average riser air temperature at steady state conditions.

Table 4 – Asymmetric heat flux test results (FS: Front Surface).

Test	Power (kW)	ΔT (Δ°C)	$\dot{m}_{total}$ (kg/s)	$\dot{m}_{total}c_p\Delta T$ (kW)	Avg. Riser FS Temp. (°C)
9	9.91	55.16	0.13	7.52	144.03
10		62.18	0.12	7.49	159.71
11	18.99	82.08	0.16	13.58	207.80
12		85.38	0.15	12.97	236.03

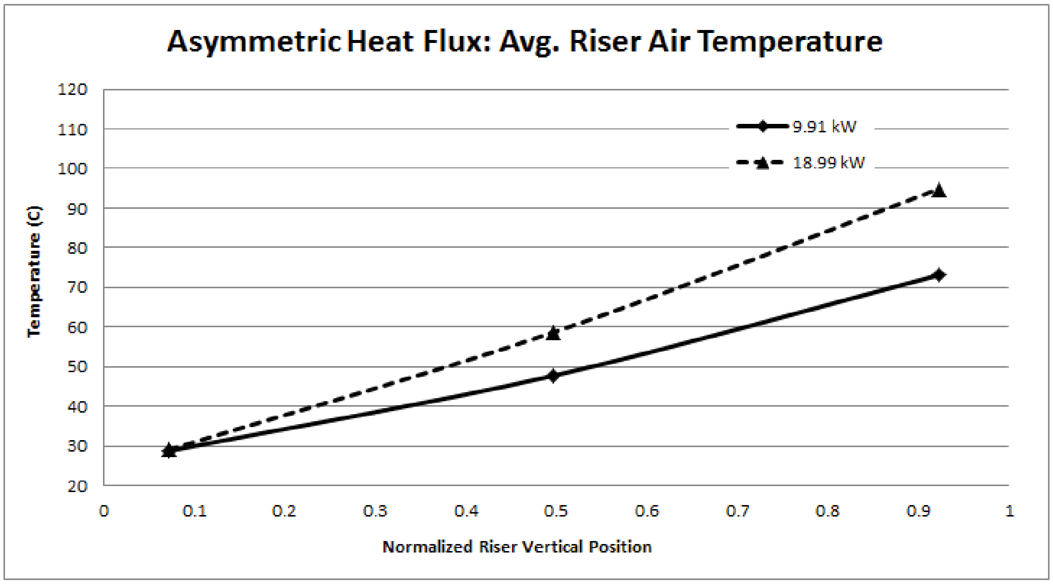

Figure 11 - Riser air temperatures for forced flow (Uncertainty: ± 0.7°C).

4.2.1 Asymmetric Heat Flux Testing at 9.91 kW

Test 9 and Test 10 were run at 9.91 kW under an asymmetric heat flux condition. The inlet and exhaust duct air temperatures for Test 9 and Test 10 can be seen in Figure 12 and Figure 14, respectively. Test 9 experienced a sharp drop in air temperature for one of the exhaust ducts at around the fourth hour of the experiment in which the wind direction transitions from south west to south east and eventually rises at around the sixth hour. Test 10 experienced multiple and alternating temperature fluctuations in both exhaust ducts. In between the eighth and ninth hour, an inline duct fan was placed at the inlet piping for fifteen minutes and then removed. After the fan was removed, the temperatures stabilized for the remainder of the test. This may suggest that developing a start-up procedure in which an inline duct fan is initially used to achieve the desired flow path could be beneficial.

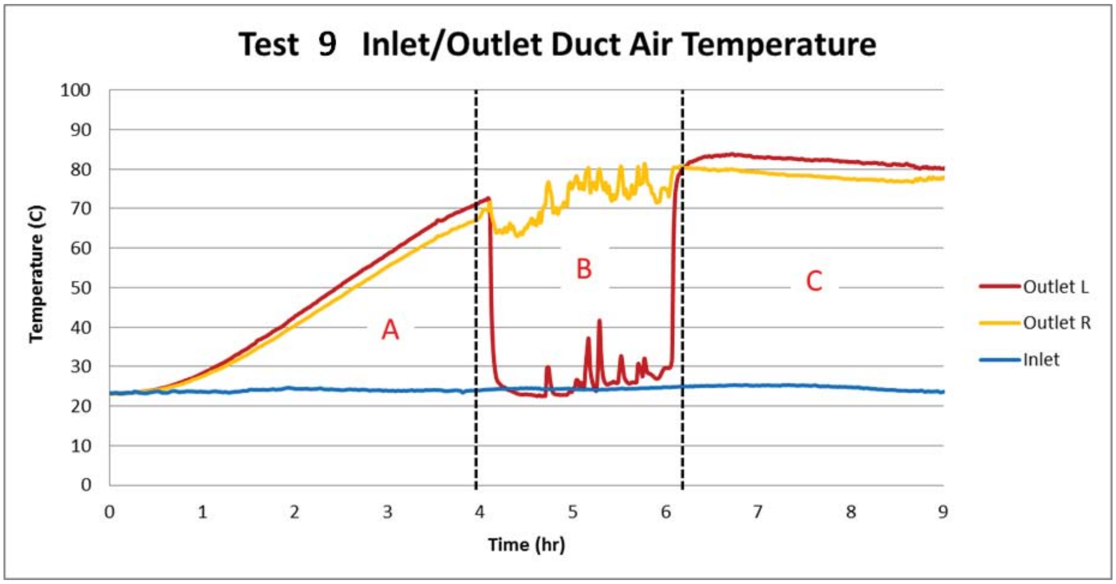

Figure 12 – Inlet and exhaust duct air temperature for Test 9 (Uncertainty: ± 0.7°C).

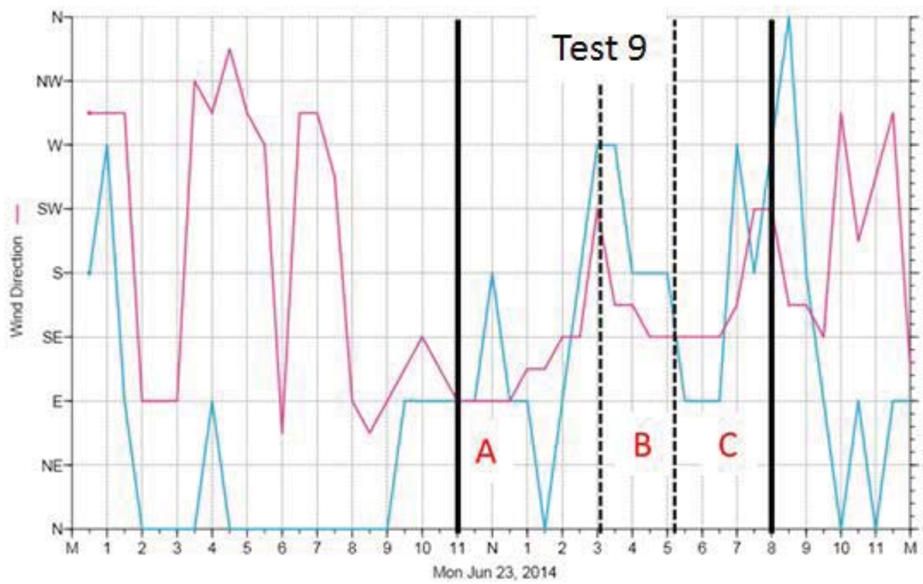

Figure 13 – Outside wind direction and speed for Test 9.

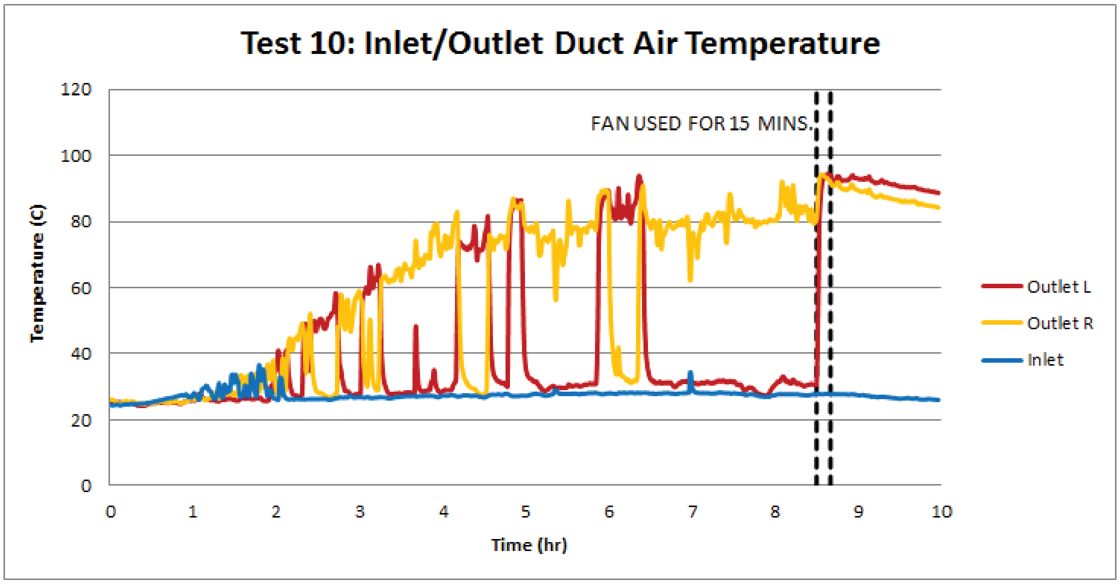

Figure 14 – Inlet and exhaust duct air temperature for Test 10 (Uncertainty: ± 0.7°C).

4.2.2 Asymmetric Heat Flux Testing at 18.99 kW

Test 11 and Test 12 were run at 18.99 kW under an asymmetric heat flux condition. The inlet and exhaust duct air temperatures for Test 11 and Test 12 can be seen in Figure 15 and Figure 17, respectively. Temperature fluctuations were observed in both tests in a similar manner to the asymmetric heat flux testing at 9.91 kW and constant heat flux testing at 19.82 kW. Weather data for Test 11 shows fluctuations in wind direction and speed that correspond to the temperature data.

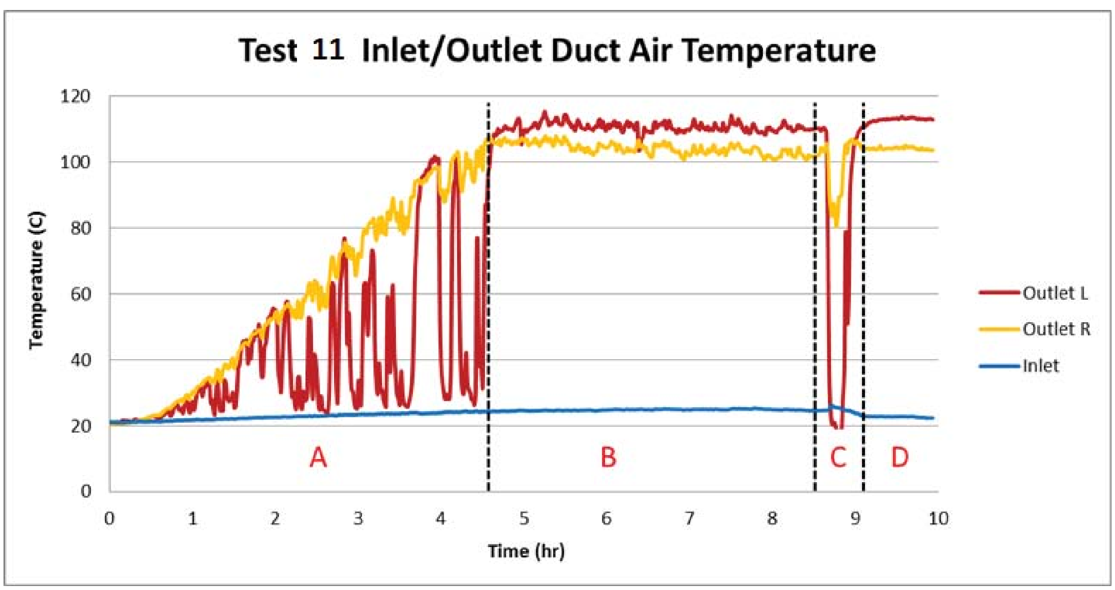

Figure 15 – Inlet and exhaust duct air temperature for Test 11 (Uncertainty: ± 0.7°C).

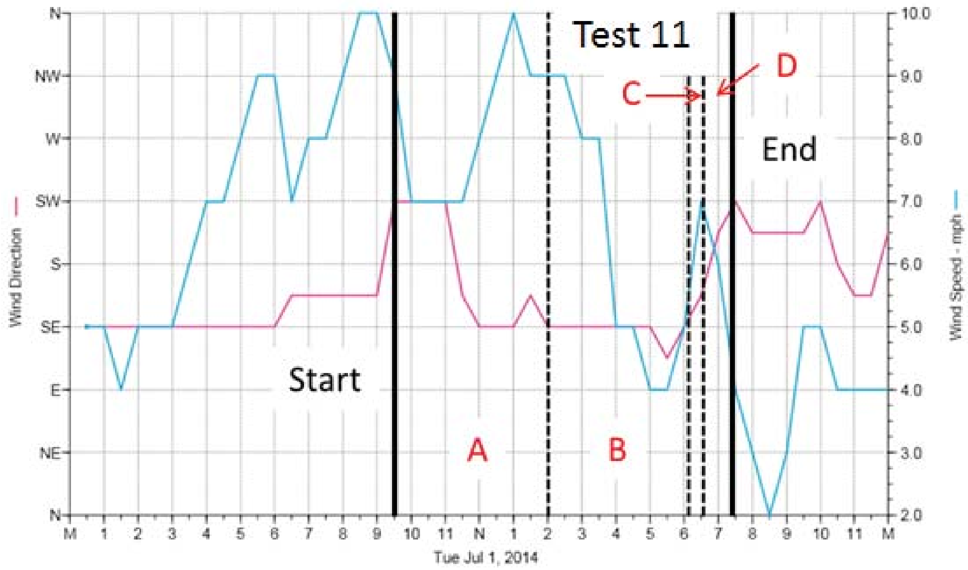

Figure 16 - Outside wind direction and speed for Test 9.

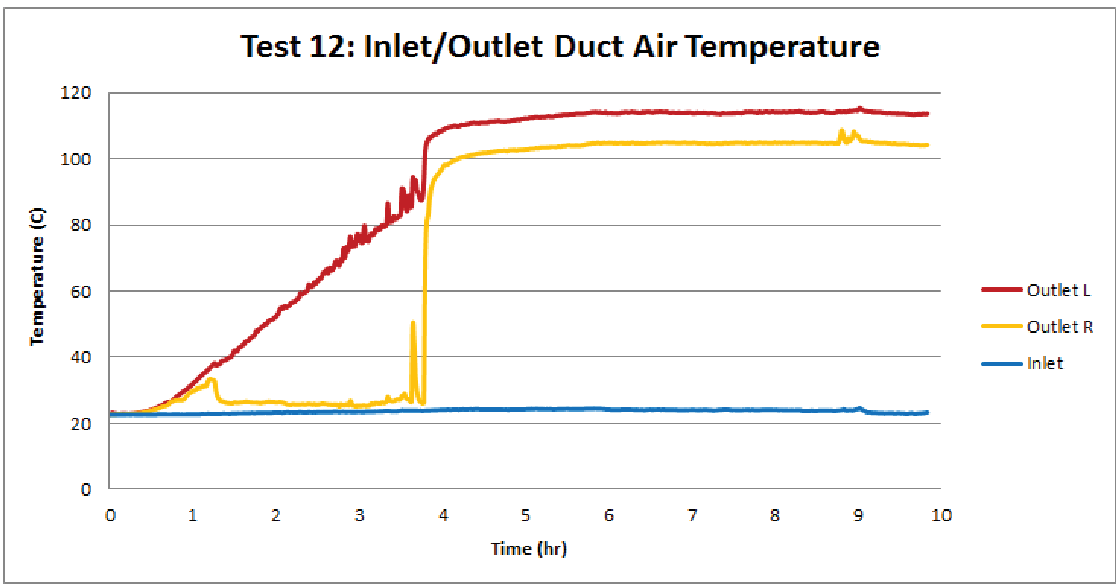

Figure 17 – Inlet and exhaust duct air temperature for Test 12 (Uncertainty: ± 0.7°C).

5. CONCLUSION

A quarter-scale Reactor Cavity Cooling System (RCCS) facility was used for an experimental investigation of the thermal hydraulic behavior of a passive cooling system with air based on the full-scale General Atomics (GA) RCCS design concept for the Modular High Temperature Gas Reactor (MHTGR). Scaling laws preserved key thermal hydraulic aspects and maintained similarity amongst scales. The air RCCS facility built at the University of Wisconsin-Madison (UW-Madison) is a quarter-scale reduced length experiment standing over 13 meters in height and housing six riser ducts that represent a 9.5° sector slice of the full-scale GA air RCCS concept. Radiant heaters simulated the heat radiated from the reactor pressure vessel . Testing was performed under different heat loading cases and operated successfully across 12 test runs.

Figure 18 shows the averaged system differential temperature for all tests. Temperature instabilities in the outlet ducts were observed in some experiments, particularly at lower powers. Further work on the air RCCS should focus on flow instabilities in the outlet ducts, possible causes, and mitigation of instabilities through design efforts such as increasing the exhaust height relative to the inlet and operational procedures such as using forced flow at start-up to develop the desired flow path. The air RCCS system shows potential for a high level of performance and may be well suited as a heat removal system during an accident scenario.

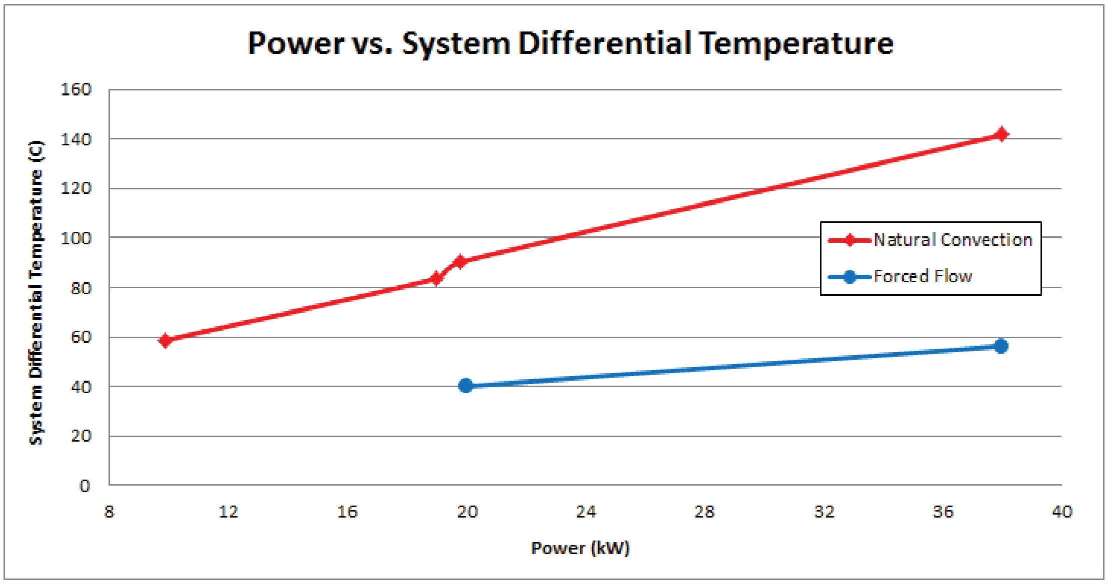

Figure 18 – System differential temperatures for all test conditions.

6. ACKNOWLEDGEMENTS

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8. APPENDIX

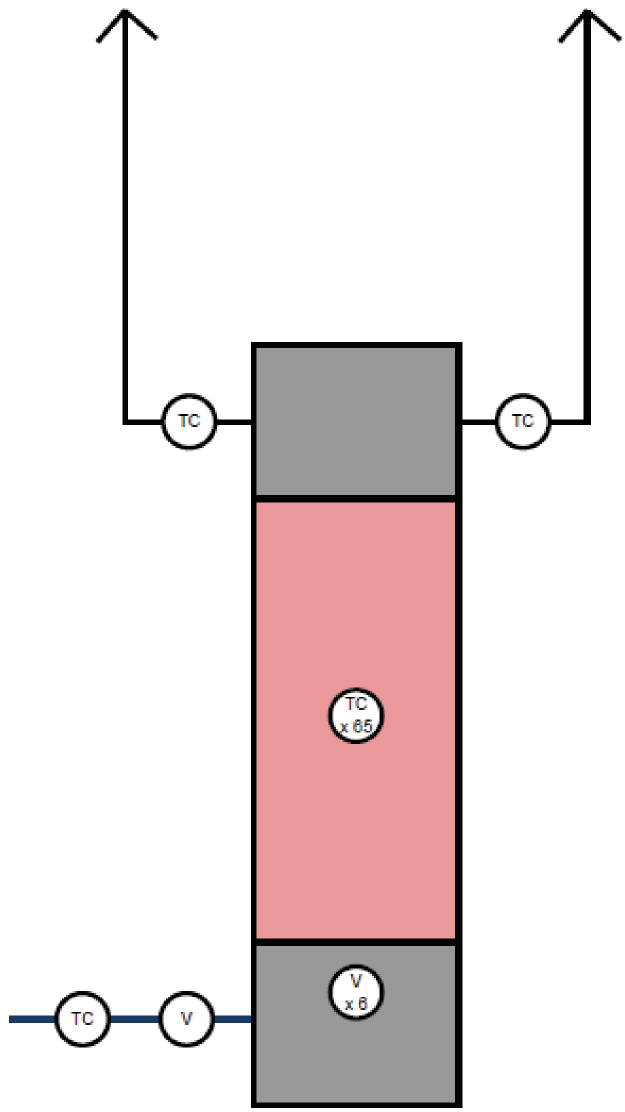

Figure A.1 – RCCS instrumentation schematic.