

System Code Analysis of Radiative and Convective Heat Transfer in the STELLA-2 Reactor Vessel Cooling System Using MARS-LMR and GAMMA+

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1. Introduction

Sodium-cooled fast reactors (SFRs) have been considered as one of the promising Generation IV reactor concepts because of their high thermal efficiency and inherent safety characteristics. In a pool-type SFR, decay heat can be rejected through the reactor vessel, ultimately to the surroundings by a reactor vessel cooling system (RVCS). The RVCS utilizes the large surface area of the reactor vessel and air cooling, and therefore plays an important role in maintaining reactor safety during accidental conditions [1].

To investigate the heat removal performance of the RVCS, preliminary performance tests were conducted using the STELLA-2 integral effects test facility under various primary heat transport system (PHTS) temperature, sodium flow, and RVCS air flow conditions [1]. The measured results showed that the RVCS heat removal rate increased with the air flow rate and PHTS temperature, but detailed interpretation of the internal heat transfer mechanisms remained limited.

A system-level analysis therefore requires properly representing the relevant heat transfer mechanisms between the reactor vessel and the surrounding cooling structures, including thermal radiation across that annular gap. Since SFRs operate at higher temperatures than conventional light-water reactors, where radiative heat transfer has been shown to be significant in narrow vessel-to-containment gaps [2], its contribution should be considered together with convection when modeling the RVCS.

In this study, the STELLA-2 RVCS performance tests were analyzed using the MARS-LMR and GAMMA+ system codes with radiative and convective heat transfer models. The calculated RVCS heat removal rates were compared with the experimental data to validate the system-code predictions and to investigate the heat transfer characteristics of the STELLA-2 RVCS.

2. Methodology

2.1 STELLA-2 RVCS and Test Conditions

The STELLA-2 RVCS consists of an air jacket surrounding the model reactor vessel (MRV), forming inner and outer annular flow passages (96 mm and 100 mm gaps) separated by a thin wall, with cooling air supplied by two inlet blowers (Fig. 1). The geometric parameters for the system code models were obtained

from the STELLA-2 design specifications and the previous performance test [1,3], consistent with prior MARS-LMR system-code analyses of STELLA-2 [4].

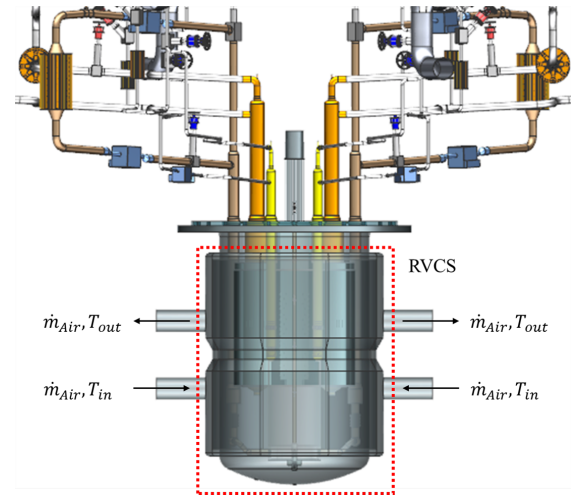


Fig. 1. STELLA-2 RVCS air jackets and air flow directions.

Calculations were performed for the steady-state HF test conditions reported in [1]. Two test groups, 350-HF and 450-HF, were analyzed with RVCS air flow rates ranging from approximately 0.05 to 0.63 kg/s. The net RVCS heat removal rate was evaluated in two ways: Q_{oper} , obtained by subtracting the standby heat loss from the electric core heater power, and Q_{Air} , independently evaluated from the air-side energy balance using the measured total RVCS air mass flow rate (sum of the two inlet flows [1]) and the representative inlet/outlet air temperatures. The resulting experimental values, summarized in Table I, were used for comparison with the system-code calculations.

Table I: Experimental RVCS heat removal rates used for system-code analyses [1].

Case	$\dot{m}_{Air}$ [kg/s]	Q_{oper} [kW]	Q_{Air} [kW]
350-HF	0.13	24.5	29.4
	0.29	35.0	48.2
	0.46	48.9	62.0
	0.63	62.7	72.5
450-HF	0.05	20.9	15.8
	0.28	52.2	69.4
	0.44	80.0	88.1
	0.62	104.4	106.4

2.2 System Code Modeling (MARS-LMR & GAMMA+)

Figure 2 shows the nodalization schemes for the two codes, constructed to represent the major heat transfer paths through the MRV, the inner and outer RVCS air channels, and the separator wall, using the same geometric and thermal boundary conditions wherever applicable. Since the test objective was to evaluate heat transfer from the MRV to the RVCS rather than to reproduce the detailed primary-side behavior, a fixed sodium-side temperature boundary condition was imposed on the MRV. This treatment is justified by the high thermal conductivity of liquid sodium together with the fast primary flow under the HF condition, which maintains nearly uniform vessel wall temperature under the steady-state test conditions; the measured sodium temperature closest to the vessel wall was therefore adopted as the prescribed boundary temperature. The measured RVCS air mass flow rate and inlet temperature were applied as air-side boundary conditions. Heat removed from the MRV was evaluated through two paths: Q_{Air} , removed by the RVCS air flow, and Q_{wall} , lost from the outer insulation surface to the ambient air, with $Q_{Total} = Q_{Air} + Q_{wall}$, consistent with the treatment of unintended heat loss paths in prior STELLA-2 system-code study [5].

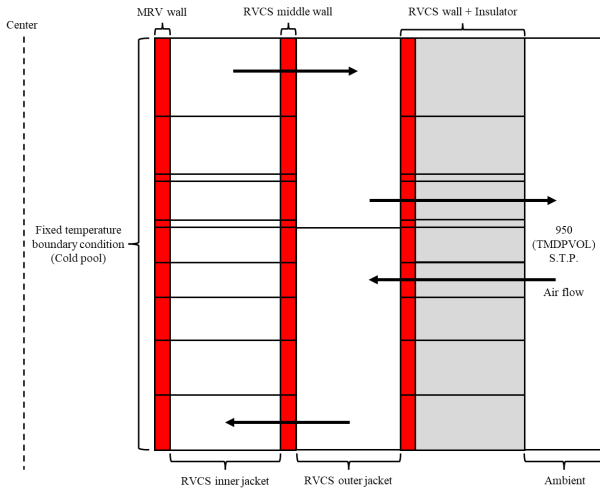


Fig. 2. Nodalization of the STELLA-2 RVCS (not to scale).

The treatment of convective heat transfer differs between the two codes. In MARS-LMR, the Churchill-Chu correlation yielded the largest predicted Nusselt number relative to the forced-convection correlation across the entire investigated air flow range and was therefore selected throughout. GAMMA+ likewise adopts Churchill-Chu as the free-convection correlation, but combines it with the forced-convection Nusselt number using a cubic superposition relationship for vertical channels in the laminar mixed-convection regime [6, 7], so that the relative weight of the forced-convection term grows with the RVCS air flow rate. To provide a consistent basis for comparison, GAMMA+ calculations were first performed using only the Churchill-Chu correlation, and the mixed convection

option was additionally evaluated for its influence on the predicted RVCS heat removal performance.

2.3 Radiative Heat Transfer Modeling

Radiative heat transfer between the MRV and the surrounding structures was modeled in both codes using surface emissivity and geometric view factors, following the standard two-surface gray body radiation network [8], expressed as

$$(1) Q_{rad} = \frac{\sigma(T_i^4 - T_j^4)}{\frac{1 - \varepsilon_i}{A_i \varepsilon_i} + \frac{1}{A_i F_{ij}} + \frac{1 - \varepsilon_j}{A_j \varepsilon_j}}$$

where ε , A , and F_{ij} denote the surface emissivity, radiating area, and view factor from surface i to j , respectively. Since the surface emissivity of the STELLA-2 RVCS could not be directly measured, a uniform effective emissivity of 0.4 was applied to all radiating surfaces in both models, estimated from the measured temperature data together with literature emissivity values for relevant structural materials [9].

Using the same axial nodalization as the thermal-hydraulic model (Fig. 2), the view factors between all radiating surface pairs were calculated analytically using established solutions for concentric and coaxial cylindrical surfaces [10, 11]. The resulting view factor matrix, verified to satisfy the reciprocity and enclosure relations, was applied identically to both code models.

3. Results and Discussion

3.1 Comparison of RVCS Heat Removal Rates

The calculated RVCS heat removal rates were compared with the experimental Q_{Oper} and Q_{Air} values (Table I): the calculated Q_{Air} was compared with the experimental Q_{Air} , while the calculated Q_{Total} ($= Q_{Air} + Q_{wall}$) was compared with Q_{Oper} . Both the experimental and calculated results showed an increase in the RVCS heat removal rate with increasing air flow rate, and a higher heat removal rate at the higher PHTS temperature.

Figs. 3 and 4 compare the MARS-LMR and GAMMA+ predictions without the mixed convection treatment against the experimental data at PHTS temperatures of 350°C and 450°C, respectively. The two codes produced consistent predictions across the investigated air flow range at both PHTS temperatures, with a maximum relative difference of 5.3%, confirming consistent predictions under comparable one-dimensional modeling assumptions and convective heat transfer treatment.

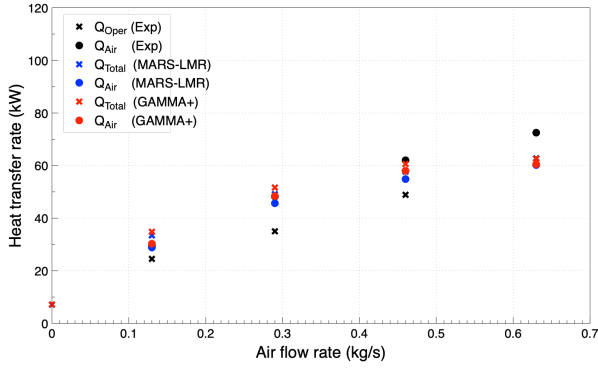


Fig. 3. Comparison of experimental and system-code RVCS heat removal rates at a PHTS temperature of 350°C.

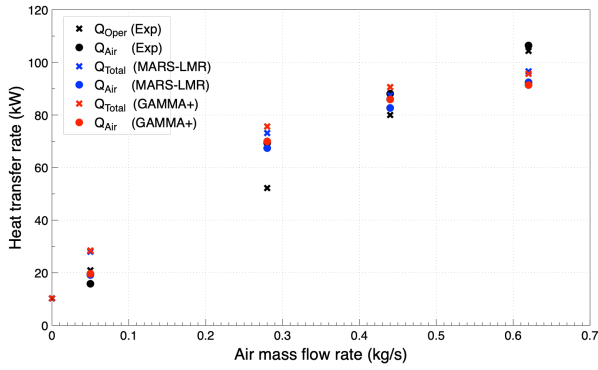


Fig. 4. Comparison of experimental and system-code RVCS heat removal rates at a PHTS temperature of 450°C.

Figs. 5 and 6 show the influence of the mixed convection treatment in GAMMA+ at PHTS temperatures of 350°C and 450°C, respectively. At low air flow rates, the predictions with and without the mixed convection treatment were nearly identical, but the difference grew with increasing air flow rate, reaching up to 5.2%, reflecting the increasing significance of the forced-convection component in the GAMMA+ heat transfer model. The mixed convection results showed closer agreement with the experimental data across the investigated range.

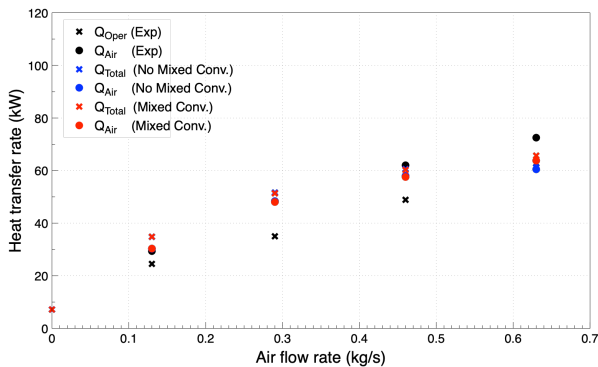


Fig. 5. Effect of mixed-convection treatment on the predicted RVCS heat removal rates at a PHTS temperature of 350°C using GAMMA+.

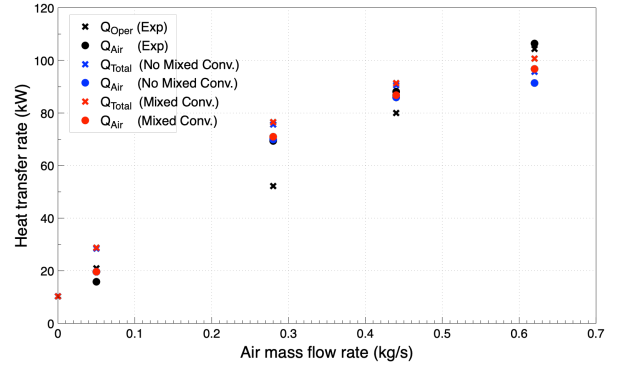


Fig. 6. Effect of mixed-convection treatment on the predicted RVCS heat removal rates at a PHTS temperature of 450°C using GAMMA+.

3.2 Analysis of Heat Transfer Mechanisms

The mixed convection treatment provides a more physically complete representation of the RVCS air channels. As shown in Figs. 7 and 8, radiative heat transfer accounted for a substantial portion of the total heat removal at both PHTS temperatures, and was the dominant mechanism at low air flow rates at 350°C, while at 450°C it remained dominant throughout the investigated air flow range. As the air flow rate increased, the convective contribution grew and the flow regimes shifted from natural toward mixed convection without reaching a purely forced convection regime even at the highest flow rates investigated. Consequently, the relative contribution of radiation decreased with increasing air flow rate, falling below the convective contribution at higher flow rates at 350°C, while remaining dominant throughout at 450°C. Because radiative heat transfer represents such a substantial fraction of the total, changes in the convective heat transfer treatment (Section 3.1) do not translate proportionally into changes in the total RVCS heat removal rate, explaining the limited sensitivity observed between the GAMMA+ predictions with and without mixed convection.

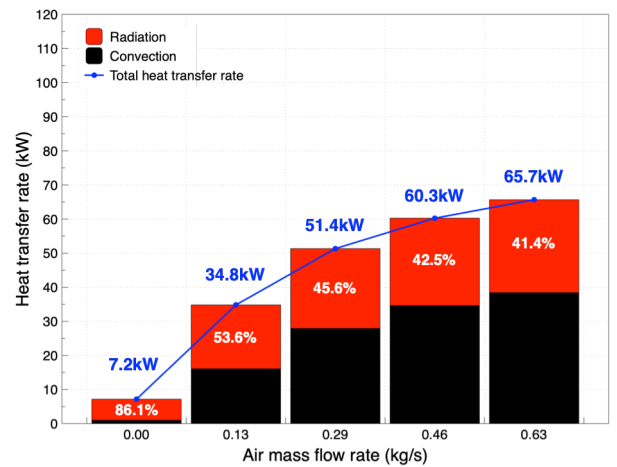


Fig. 7. Radiation and convection contributions to total heat removal rate at a PHTS temperature of 350°C.

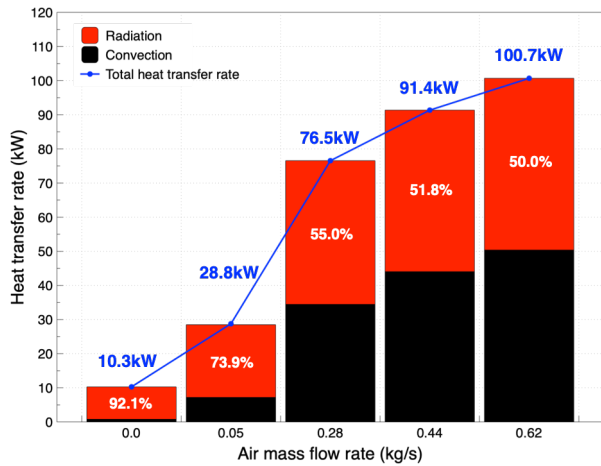


Fig. 8. Radiation and convection contributions to total heat removal rate at a PHTS temperature of 450°C.

4. Conclusions

The heat removal characteristics of the STELLA-2 RVCS were analyzed using the MARS-LMR and GAMMA+ system codes with radiative and convective heat transfer models under the 350-HF and 450-HF conditions. The calculated heat removal rates showed trends consistent with the experimental results, increasing with both RVCS air flow rate and PHTS temperature, and the two codes produced consistent predictions (within 5.3%) under comparable convective heat transfer treatments. The heat transfer mechanisms analysis further showed that radiative heat transfer contributed substantially to the overall heat removal, dominating at low air flow rates which limited the sensitivity of the total heat removal rate to the choice of convective heat transfer treatment.

The modeling approach will be extended to transient operating conditions and multi-dimensional GAMMA+ analyses, along with a sensitivity analysis of surface emissivity to quantify its influence on the predicted RVCS heat removal performance.

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REFERENCES

- [1] Baik, S., Shin, Y.-H., Yoon, J., Jun, I.S. & Lee, J. (2026). Preliminary Performance Test of STELLA-2 Reactor Vessel Cooling System. In: *Transactions of the Korean Nuclear Society Spring Meeting* (pp. 1-4).
- [2] Byeon, G., Jeong, B., Kim, N., Song, J., & Kim, S. J. (2026). Experimental validation of predominant radiative heat loss through a metal containment vessel of small modular reactors under normal operation. *Progress in Nuclear Energy*, 196, 106330.
- [3] Eoh, J. (2015). Engineering Design of Sodium Thermal-hydraulic Integral Effect Test Facility (STELLA-2). KAERI SFR Design Report, SFR-720-TF-462-002Rev. 00, 17-18.

- [4] Shin, Y. H., Baik, S., Lee, Y. B., Yoon, J., Kim, H., & Lee, J. (2026). Integral effects tests and system thermal-hydraulics code analyses on the decay heat removal systems of the STELLA-2 facility. *Nuclear Engineering and Technology*, 104462.
- [5] Lee, J., Lee, Y. B., Shin, Y. H., & Yoon, J. (2025). Heat rejection effect study on large-scale sodium test facility STELLA-2. *Nuclear Engineering and Technology*, 57(4), 103280.
- [6] Chung, B. D., Bae, S. W., Lee, S. W., Yoon, C., Hwang, M. K., Kim, K. D., & Jeong, J. J. (2010). MARS Code Manual Volume V: Models and Correlations (No. KAERI/TR-3872/2009). Korea Atomic Energy Research Institute, Daejeon (Korea, Republic of).
- [7] Lim, H. S. (2021). GAMMA+ 2.0 volume II: theory manual. Korea Atomic Energy Research Institute Report, KAERI/TR-8662.
- [8] Howell, J. R., Menguc, M. P., & Siegel, R. (2010). Thermal radiation heat transfer. CRC press.
- [9] Hunnewell, T. S., Walton, K. L., Sharma, S., Ghosh, T. K., Thompson, R. V., Viswanath, D. S., & Loyalka, S. K. (2017). Total hemispherical emissivity of SS 316L with simulated very high temperature reactor surface conditions. *Nuclear Technology*, 198(3), 293-305.
- [10] Leuenberger, H., & Person, R. A. (1954). Compilation of radiation shape factors for cylindrical assemblies (No. PAPER56A144).
- [11] Rea, S. N. (1975). Rapid method for determining concentric cylinder radiation view factors. *AIAA Journal*, 13(8), 1122-1123.