

Simulation of natural convective flow in an experimental reactor cavity cooling system facility

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ABSTRACT

The very high temperature reactor (VHTR) has many safety features. One of these features is the reactor cavity cooling system (RCCS). This system is intended to remove decay heat from the reactor cavity during upset conditions. The Korea Atomic Energy Research Institute (KAERI) constructed a facility that represents a ¼ scale model of the RCCS of a VHTR. The preliminary testing on the facility has been completed and a simulation model has been set up for the facility, using the program GAMMA+. This study aims to simulate the facility using the 1D CFD program Flownex SE for comparison with the results obtained with GAMMA+. Since the fundamental equations used in both programs are the same, the results show a high degree of correlation. The Flownex simulation was set up as close as possible to the GAMMA+ model by using the same geometry and initial- and boundary conditions. The surface temperatures and the mass flow rate in the riser duct system were used as a measure to determine the level of agreement between the two programs. The results obtained by using the two programs show very good agreement.

KEYWORDS

Reactor cavity cooling system, experimental facility, thermal radiation, natural convection, mixed convection.

INTRODUCTION

The very high temperature reactor (VHTR) has many safety features. One of these features is the reactor cavity cooling system (RCCS). Korea has chosen the 200 MWth PMR (PMR200) General Atomic prismatic core VHTR reactor as the candidate reactor for the Nuclear Hydrogen Development and Demonstration (NHDD) project. The inlet temperature to the core is considered to be 490°C and the outlet temperature from the core to be 950°C [1]. Apart from removal of the residual and decay heat, it also requires the proper cooling of the reactor cavity under normal operating conditions. The RCCS is the only safety-related system for the residual and decay heat removal and its performance impacts directly on the maximum temperatures of the fuel, reactor pressure vessel (RPV) and concrete during off-normal conditions. The General Atomic air-cooled RCCS design concept, which is a completely passive system, has not yet been deployed in a VHTR. The Korea Atomic Energy Research Institute (KAERI) constructed a facility that represents a ¼ scale model of the RCCS of a VHTR. The natural cooling experimental facility (NACEF) has been simulated by using the code GAMMA+ [2]. This study aims to compare the results obtained by using GAMMA+ with the results obtained by using Flownex.

DESCRIPTION OF THE NACEF

Figure 1 is a representation of the NACEF. Air enters at the bottom through two inlet pipes and then enters the inlet plenum, from where it is directed into six riser tubes. The risers run vertically through the cavity, where a ceramic heater is installed. After exiting the riser tubes, the air enters the outlet plenum which directs it into the two chimneys.

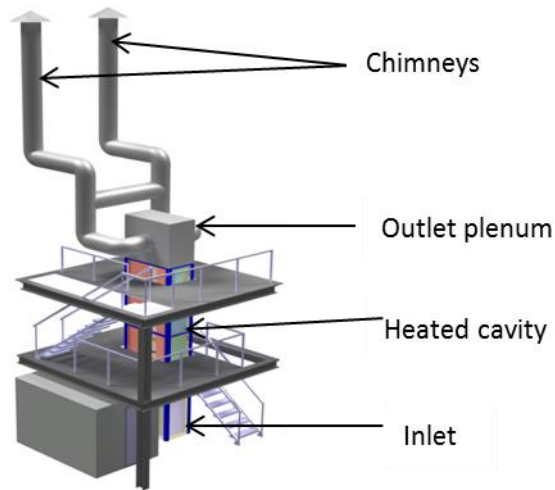


Figure 1. The natural cooling experimental facility (NACEF). [3]. Note the highlighted heated section.

Figure 2 shows a cross sectional view of the heated cavity. The ceramic heater provides a maximum power of 52 kW. A stainless steel plate is mounted at the front and rear of the cavity. The side walls are made of Calcium-Silicate. Various layers of insulation minimize heat loss to the environment.

The cavity contains six riser tubes as shown in Figure 2.

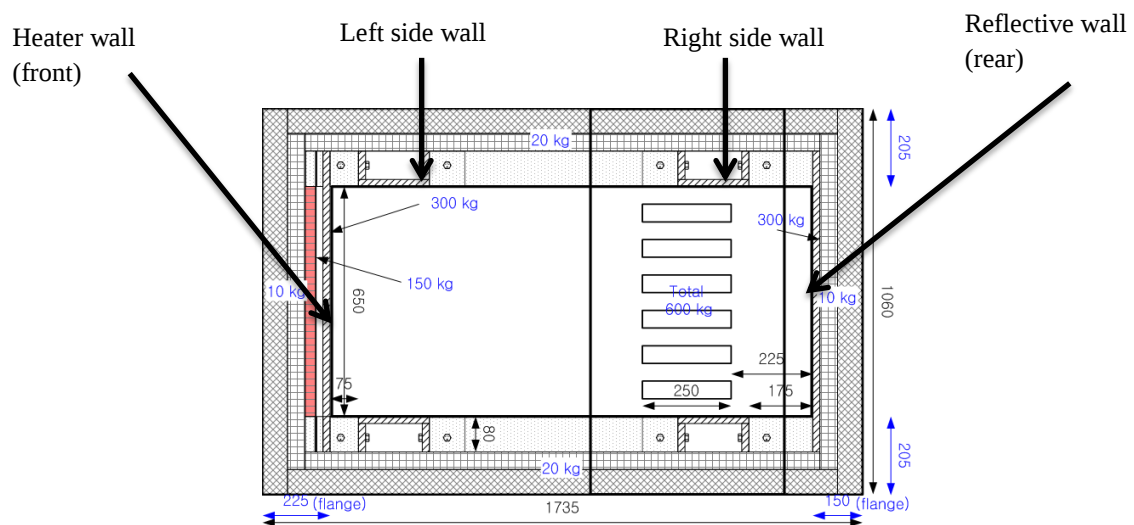


Figure 2. Cross sectional view of the heated section in the NACEF. Adapted from [2].

DESCRIPTION OF MODEL

The six riser tubes (Figure 2) were grouped together as follows: The two tubes closest to the side walls were modelled as a single tube (referred to as the outer tubes) and the four remainder tubes were modelled as a single tube (referred to as the inner tubes). The inner and outer tubes are ultimately simplified to a single representative tube.

The side walls were segmented so as to form two surfaces, as shown in Figure 2. The opposing walls are grouped together into a single surface. The result is two model surfaces, i.e. the left side wall and the right

side wall. The cavity walls were assigned a thickness of 30 mm for the purposes of the simulation. The outside surfaces of the left and right side wall and the reflective wall are considered to be adiabatic. The solid parts of the model were specified as stainless steel.

The flow regime in the riser tubes was found to be mixed convection. The Nusselt number for upward flow was therefore calculated by interpolating between the free convection and forced convection Nusselt numbers [4]:

$$Nu_{mixed} = (Nu_{forced}^3 - Nu_{free}^3)^{\frac{1}{3}} \quad (1)$$

Where Nu_{mixed} , Nu_{forced} and Nu_{free} are the mixed, forced and free convection Nusselt numbers respectively.

The convection coefficient was then calculated by [5]:

$$h_{mixed} = \frac{Nu_{mixed} * k}{D_h} \quad (2)$$

Where h_{mixed} is the convection heat transfer coefficient in $W m^{-2} K^{-1}$, k is the thermal conductivity in $W m^{-1} K^{-1}$ and D_h the hydraulic diameter in m. All the fluid properties required to calculate the Nusselt numbers and the heat transfer coefficient are based on the film temperature, taken as the average of the wall and bulk fluid temperatures

GAMMA+ MODEL

GAMMA+ (General Analyzer for Multi-component and Multi-dimensional Transient Application) is a simulation code intended for use in the simulation of phenomena in high temperature gas cooled reactors. It is capable of predicting chemical reactions and thermal hydraulic phenomena [6]. Some benchmark tests have been done with the aim of validation of the code [7]. It has also been compared with Flownex in a code-to-code comparison, in which the results showed good agreement [8].

The GAMMA+ model of the NACEF is shown in Figure 3. The GAMMA+ model consists of fluid regions (F1 in Figure 3) and solid regions (W2, W3 in Figure 3). The fluid regions are made up of control volumes referred to as fluid blocks, which are connected by the junction blocks. The flow in one of the chimneys is choked, such that the mass flow rate is zero in the said chimney. The thermal radiation heat transfer in the cavity and within the riser tubes is accounted for in the model. The boundary conditions are applied as shown (BC in Figure 3). The heater, the cavity walls and the risers are all divided into 20 vertical increments of equal length.

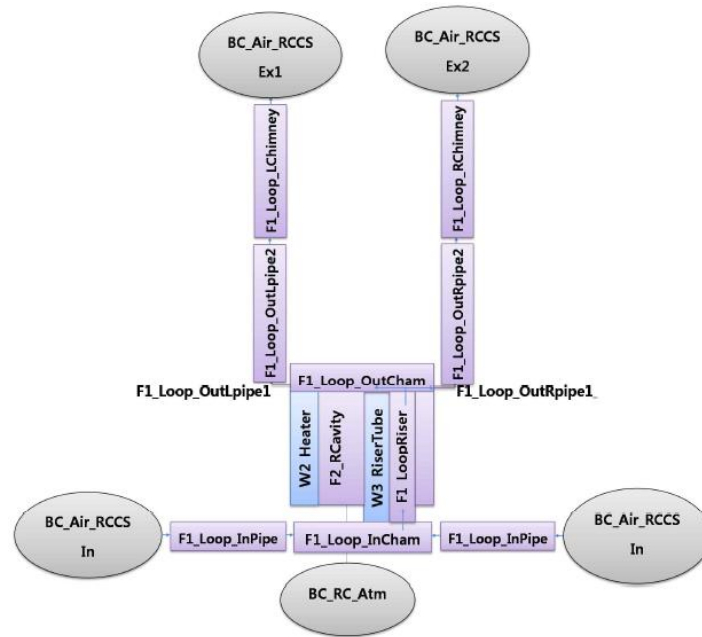


Figure 3. GAMMA+ model of the NACEF [2].

FLOWNEX MODEL

Flownex is a systems CFD code that is capable of solving thermal-fluid systems consisting of heat transfer, combustion, mechanical components etc. [9].

The inlet of the system as modelled in Flownex is shown in Figure 4. The temperature and pressure boundary conditions as stated in Table 4 are applied as shown in Figure 4.

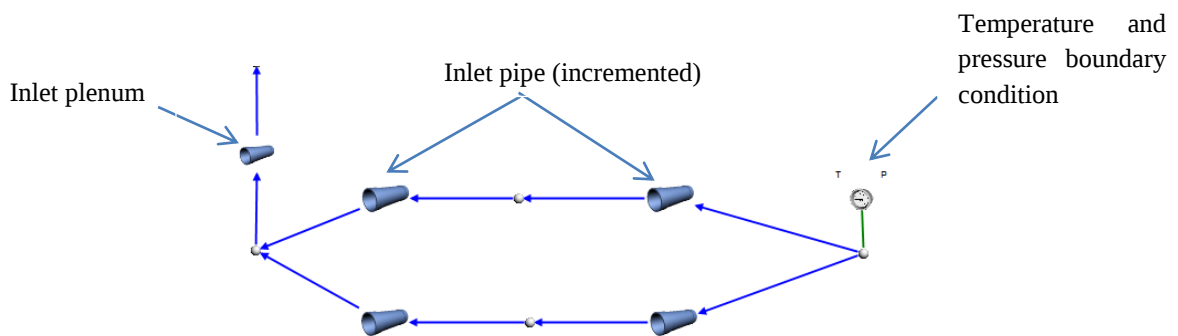


Figure 4. Inlet of the NACEF as modelled in Flownex.

The pipe network in Figure 4 connects to the riser tube, of which a single increment is shown in Figure 6. As in the GAMMA+ model the riser tube consists of 20 increments of equal length.

The flow element (Figure 6) models the momentum transfer of the air as it rises through the tube. The convection elements account for the convection heat transfer on the cavity walls, as well as, the inner and outer surfaces of the riser tubes. The conduction elements account for the conduction through the stainless steel walls. The compound components are defined by the user. In this case these components model radiative heat transfer. The compound components are illustrated in Figure 8 and Figure 9.

The scripting components calculate the convection heat transfer coefficient for the air in the riser tubes. The mixed convection theory described in equations (1) and (2) was programmed into the scripts. The GAMMA+ model contains similar theory to solve mixed convection flow. The convection heat transfer

coefficients for the cavity walls and the riser tube outer walls could not be calculated in Flownex. The coefficients calculated in GAMMA+ were therefore used.

The axial conduction in all the walls, not shown in the figure, (as function of elevation of the cavity) has also been accounted for. The tangential conduction heat transfer between the riser tubes' walls was also accounted for.

The descriptions for the Flownex components used in Figure 6 are shown in Figure 5.

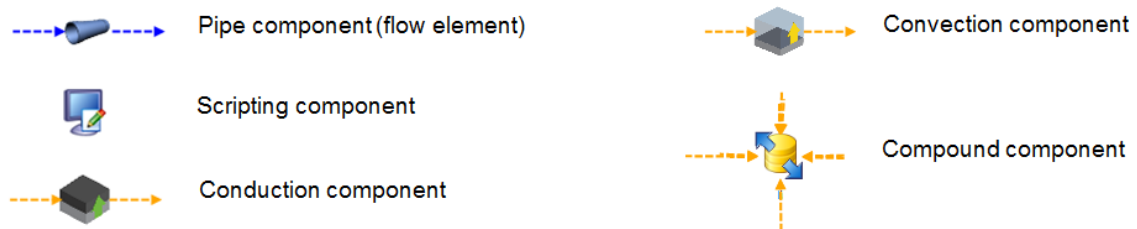


Figure 5. Description of the components used in Figure 6.

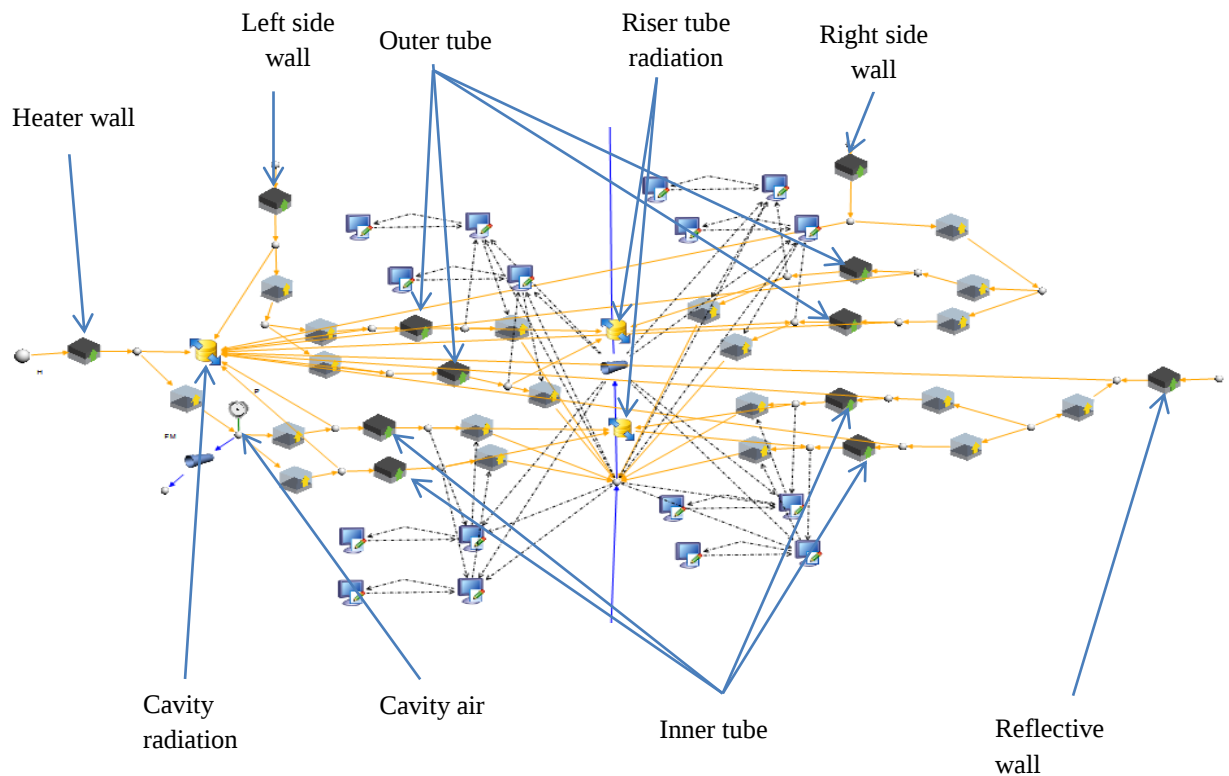


Figure 6. A single increment of the riser tube, as modelled in Flownex.

The chimneys, as modelled in Flownex, are shown in Figure 7. Flow in the right chimney was choked in accordance with the GAMMA+ model. The pipe increments were given the same lengths as to correspond exactly with the GAMMA+ model.

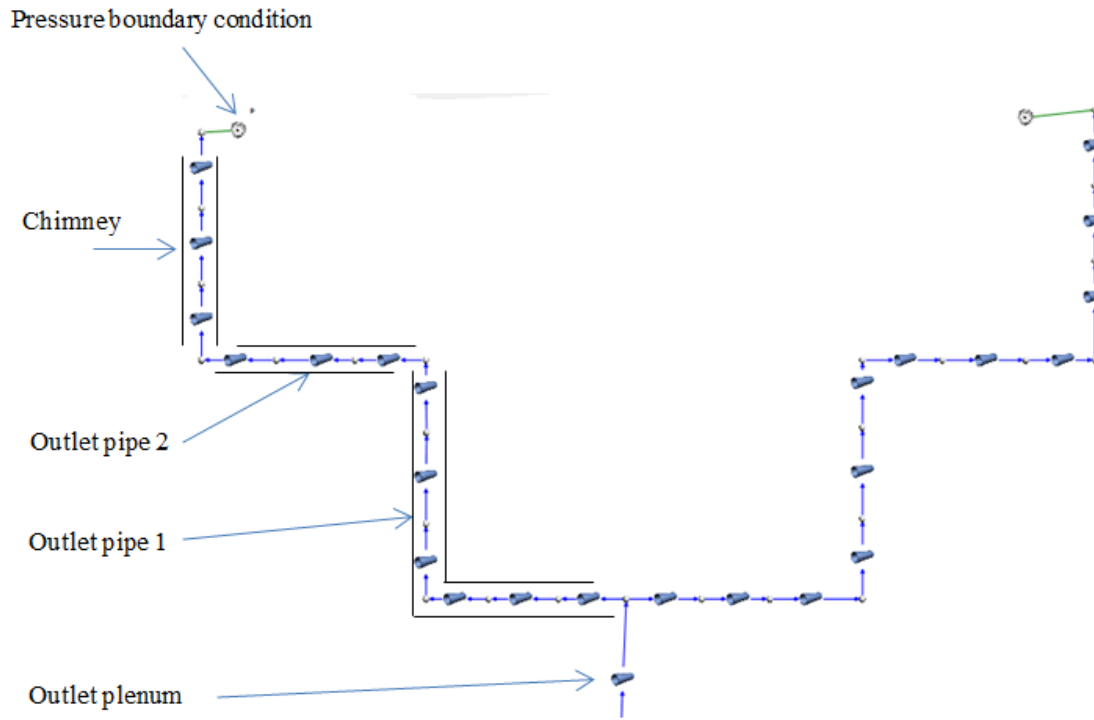


Figure 7. Outlet chimneys of the NACEF as modelled in Flownex.

The thermal radiation heat transfer in Flownex is accounted for by using surface and spatial radiation heat transfer elements. The network accounting for the thermal radiation heat transfer between the cavity surfaces is shown in Figure 8. The radiation view factor matrix for the cavity surfaces that was used in both Flownex and GAMMA+ is shown in Table 2:

Table 2. Radiation view factor matrix [10].

	Heater wall	Left side wall	Right side wall	Reflective wall	Outer tube front surface	Outer tube side surface	Outer tube rear surface	Outer tube side surface	Inner tube front surface	Inner tube rear surface	Inner tube side surface	Inner tube side surface
Heater wall	0.00E+00	7.31E-01	3.24E-02	3.34E-02	4.00E-02	3.18E-04	0.00E+00	2.63E-02	8.90E-02	0.00E+00	1.27E-02	3.53E-02
Left side wall	2.58E-01	5.15E-01	1.04E-02	2.35E-04	3.65E-02	2.56E-02	0.00E+00	1.16E-02	6.83E-02	0.00E+00	4.22E-02	3.20E-02
Right side wall	2.22E-02	2.03E-02	1.25E-01	2.31E-01	0.00E+00	4.70E-01	3.49E-02	3.66E-03	0.00E+00	3.59E-02	4.11E-02	1.49E-02
Reflective wall	3.34E-02	6.65E-04	3.38E-01	6.15E-02	0.00E+00	3.91E-03	8.86E-02	6.07E-02	0.00E+00	2.26E-01	7.49E-02	1.13E-01
Outer tube front surface	2.60E-01	6.72E-01	0.00E+00	0.00E+00	6.81E-02	0.00E+00	0.00E+00	0.00E+00	0.0	0.00E+00	0.00E+00	0.00E+00
Outer tube side surface	4.13E-04	9.42E-02	8.92E-01	5.09E-03	0.00E+00	8.49E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Outer tube rear surface	0.00E+00	0.00E+00	3.31E-01	5.76E-01	0.00E+00	0.00E+00	9.35E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Outer tube side surface	3.42E-02	4.27E-02	6.94E-03	7.89E-02	0.00E+00	0.00E+00	0.00E+00	2.11E-02	0.00E+00	0.00E+00	8.16E-01	0.00E+00
Inner	2.89E-	6.29E-	0.00E	0.00E+	0.00E+00	0.00E+	0.00E+	0.00E+	8.20E-	0.00E+	0.00E+	0.00E+

tube front surface	01	01	+00	00		00	00	00	02	00	00	00
Inner tube rear surface	0.00E+00	0.00E+00	1.70E-01	7.34E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.56E-02	0.00E+00	0.00E+00
Inner tube side surface	8.22E-03	7.77E-02	3.89E-02	4.87E-02	0.00E+00	0.00E+00	0.00E+00	4.08E-01	0.00E+00	0.00E+00	1.08E-02	4.08E-01
Inner tube side surface	2.29E-02	5.90E-02	1.41E-02	7.34E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.08E-01	4.23E-01

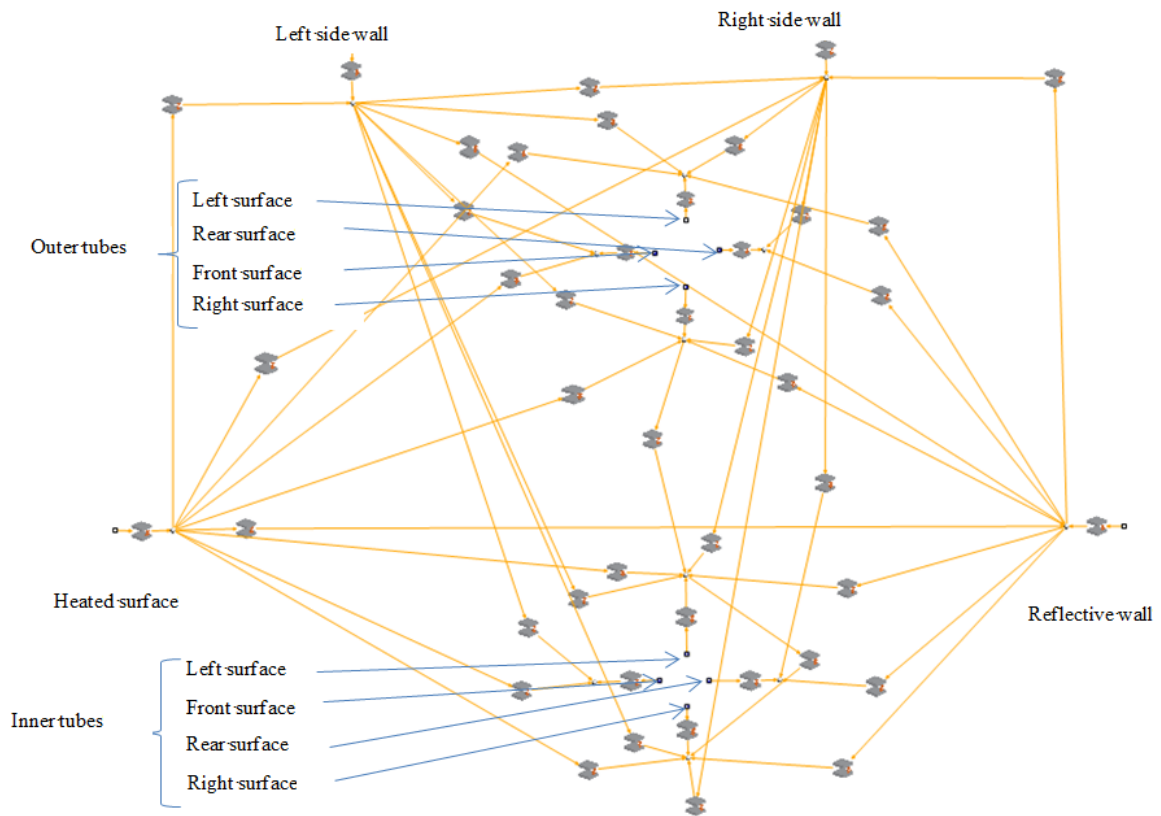


Figure 8. Flownex compound component describing the radiative heat transfer in the cavity.

The radiation heat transfer between the riser tube inner surfaces was modelled using the network as shown in Figure 9. The radiation view factor matrix for the riser tube inner surfaces used in both Flownex and GAMMA+ is shown in Table 3:

Table 3. Thermal radiation view factors for the riser tube inner surfaces [8].

Surface	Front	Side	Side	Rear
Front	0	0.45049	0.45049	0.09902
Side	0.090098	0	0.819804	0.090098
Side	0.090098	0.819804	0	0.090098
Rear	0.09902	0.45049	0.45049	0

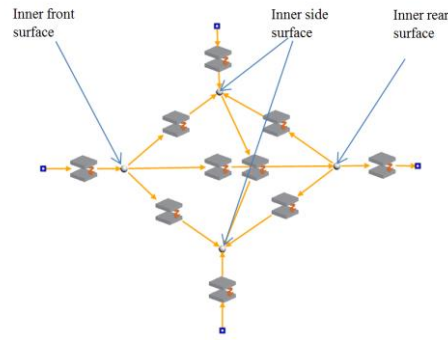


Figure 9. Radiative heat transfer network for the riser tube inner surfaces.

The boundary conditions for the model are given in Table 4. The inlet pressure was chosen to reflect purely hydrostatic flow.

Table 4. The boundary conditions for the model.

Inlet temperature	24° C
Inlet pressure	101.46 kPa
Outlet pressure	101.3 kPa
Heater flux	4.34 kW/m ²
Heater wall emissivity	0.75
Riser tube surface emissivity	0.8
Side walls emissivity	0.1

RESULTS

The air temperature is plotted as function of the elevation in the riser tube in Figure 10. The results obtained by Flownex and GAMMA+ are compared in the figure. The average difference between the results is 0.24%. The air temperature shows a gradual increase with an increase in elevation.

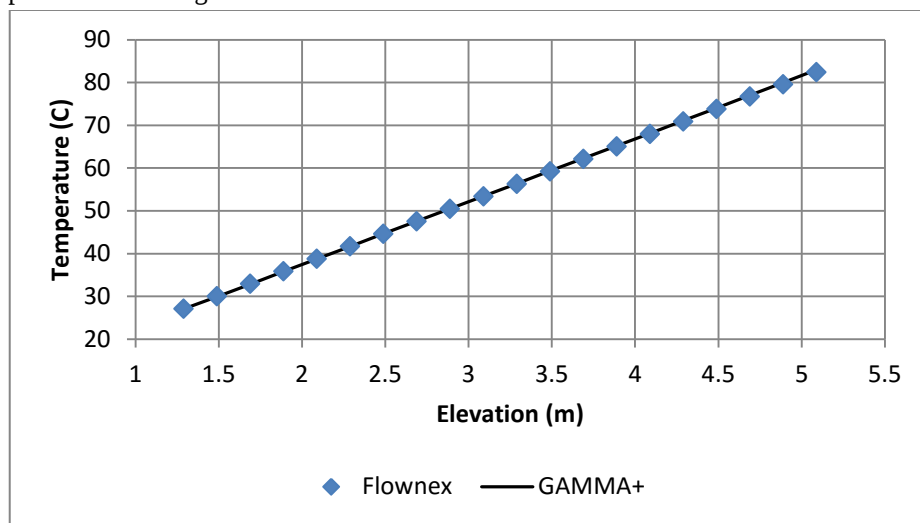


Figure 10. Riser tube air temperature as a function of elevation.

The heater wall and reflective wall temperatures calculated by GAMMA+ and Flownex are compared in Figure 11. The difference between the results is 0.23% and 1.39% respectively. The wall temperatures show an increase with an increase in elevation.

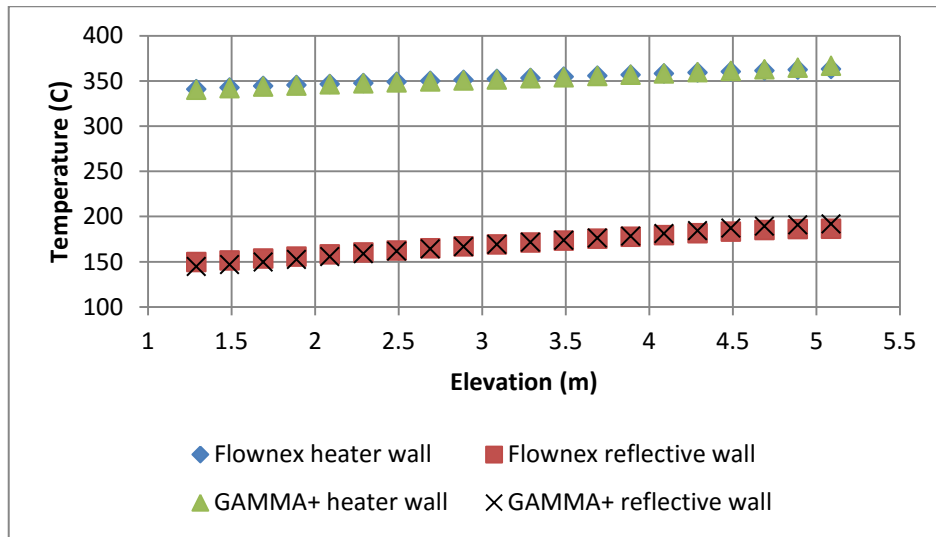


Figure 11. Heater- and reflective wall temperature as a function of elevation.

The left-side wall and right-side wall temperatures are compared in Figure 12. The average difference between the results is 0.69% and 0.9% respectively. The results show the largest deviation at the highest elevation.

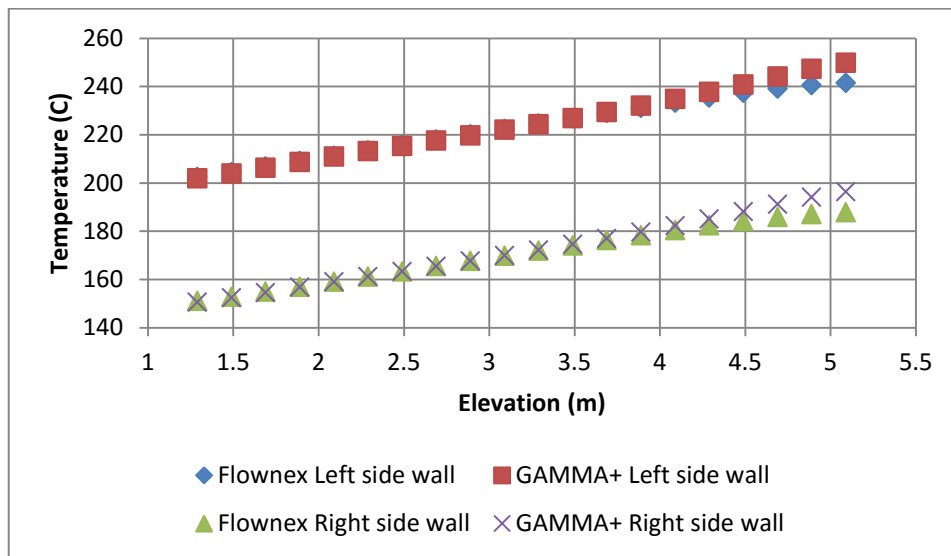


Figure 12. Left-side- and right side wall temperature as a function of elevation.

The convection heat transfer coefficient, as calculated in GAMMA+ and Flownex is compared in Figure 13. The average difference is 0.49%. The convection heat transfer coefficient at the lowest elevation is higher than the second; where after a gradual increase is experienced with an increase in elevation. The reason for this occurrence is as follows: in the first increment, the effect of the free convection is comparatively small. This means that equation 1, results in a higher Nusselt number and consequently a higher convection heat transfer coefficient is calculated in equation 2. There are two unheated increments of the riser tube below the lowest elevation in Figure 13. Some of the heat from the first increment escapes downward into the unheated section of the riser tube, by mechanism of conduction. This results in a lower wall temperature, which in turn influences the Nusselt number and subsequently the convection heat transfer coefficient. From the second elevation, the effect of the free convection is larger, resulting in a smaller coefficient to be calculated. For the rest of the tube, both the forced convection and free convection have a gradually increasing influence on the Nusselt number.

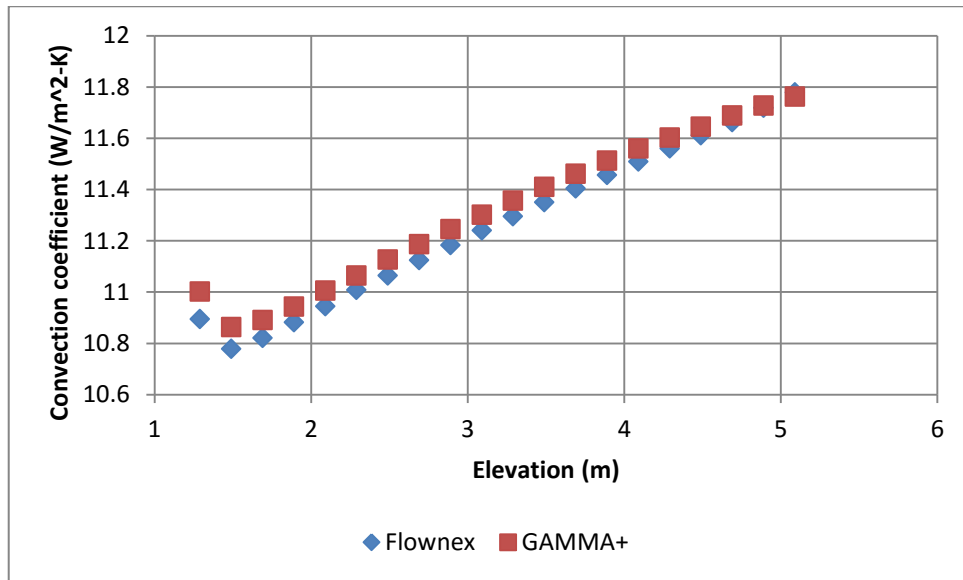


Figure 13. Convection heat transfer coefficient as a function of elevation.

The Flownex model calculated a mass flow rate of 0.192 kg/s in the riser tube. The GAMMA+ model calculated a mass flow rate of 0.189 kg/s. The mass flow rates show good agreement, with a difference of 1.77% between the codes.

The differences between the GAMMA+ and Flownex results can be explained as follows: GAMMA+ represents the cavity air by four sub fluid-blocks (connected control volumes) per increment, while Flownex uses a single node (control volume) per increment to represent the cavity air. The Flownex model calculates an average value for the air temperature in the cavity, while GAMMA+ can account for local air temperatures, as well as air circulation. The fluid properties calculated by GAMMA+ and Flownex are also slightly different due to the fact that they employ different correlations to obtain the values of the properties.

CONCLUSION

The reactor cavity cooling system is a safety feature built into the high temperature gas-cooled reactor. The system is intended to remove decay heat under upset conditions. The natural cooling experimental facility (NACEF) is a scale model of a RCCS. The NACEF was simulated by using Flownex and the results were compared with the results obtained by GAMMA+. There is very good agreement between the results. The reasons for the differences have been discussed.

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