ANALYSIS OF PASSIVE REACTOR CAVITY COOLING SYSTEM FOR A 600 MWTH HTGR USING MELCOR CODE

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ABSTRACT

High Temperature Gas-Cooled Reactor (HTGR) is one of Generation-IV reactor concept which is being developed to generate high temperature heat for other industrial processes and hydrogen production. Since one of the most important requirements for HTGR is passive safety, most HTGR designs typically use passive reactor cavity cooling system (RCCS) designed to remove all the core afterheat without the use of any active safety systems during all postulated accidents. On the researches of the HTGR licensing technologies in Korea Institute of Nuclear Safety (KINS), MELCOR code is under consideration as a safety evaluation tool for HTGR, which is used for thermal-fluid and accident analysis, including fission products transport release. The latest version of this code, MELCOR 2.1 has been modified for the Next Generation Nuclear Plant (NGNP) by the U.S. Nuclear Regulatory Commission (NRC). In this study, the MELCOR 2.1 input model of HTGR with RCCS was developed for the design of 600 MWth HTGR which is based on General Atomics’ Gas Turbine-Modular Helium Reactor (GT-MHR) to assess the ability of MELCOR to predict the RCCS performance. The characteristics of HTGR were modelled including conduction and radiation heat transfer in RCCS and between fuel and/or reflector blocks and insulation effect of RCCS downcomer, etc. The normal operation and depressurization accident conditions were analysed using the developed input model to evaluate the applicability of MELCOR code in HTGR with RCCS.

1 INTRODUCTION

High temperature gas-cooled reactor (HTGR) has the most outstanding safety characteristics among other Generation-IV reactors. The HTGR design is characterized by 1) the use of refractory triple isotropic layers coated fuel particles (TRISO CFP) which retain the fission products and then provides a unique robustness of the first barrier for the fission products, 2) the use of inert, single phase helium gas as coolant and of graphite with high temperature stability and long response times as moderator, and 3) passive core cooling and decay heat removal by natural process, etc.

For passive removal of decay heat, the core power density and the annular core configuration have been designed so that the decay heat can be removed by conduction to the pressure vessel and transferred by radiation from the vessel to the reactor cavity cooling
system (RCCS) without exceeding the fuel particle temperature limit. The RCCS which mainly contributes to the securement of passive safety characteristics of HTGR is typically safety grade system designed to remove all of the core decay heat[1]. Although the RCCS which is the only safety-grade system of HTGR appears to be highly reliable and passive with simplicity, the adequacy of the RCCS design for plant licensing should be reviewed to ensure stable operation of the system within appropriate design limits. It could be efficiently performed with use of system-level analysis code.

The safety analysis tools of HTGR can be developed in two ways - development of new HTGR-specific codes or revision of existing codes. The Korea Institute of Nuclear Safety (KINS) is under consideration of using existing analytic tools to the extent feasible with appropriate modifications for the intended purpose. Thus it is being considered to assess the applicability of several safety analysis codes. The MELCOR code has been used for light water reactor (LWR) safety analysis, which is capable of performing thermal-fluid and accident analysis, including fission-product transport and release[2]. Recently, this code is being modified for the HTGR by the U.S. Nuclear Regulatory Commission (NRC) for Next Generation Nuclear Plant (NGNP) project.

In this study, the safety issues which may have a major impact on the licensing of RCCS design were identified. The MELCOR input model for HTGR RCCS was developed and its analytic capability for normal operation and accident condition was analysed to assess the capability of MELCOR code to predict the performance of RCCS.

2 SAFETY ISSUES OF RCCS

The RCCS, the only safety-related system for the safety function of core heat removal in HTGR design, provides a passive means of removing core residual heat during accident conditions when the main heat transport system (HTS) and shutdown cooling system (SCS) are unavailable. The RCCS receives heat transferred from the un-insulated reactor vessel by thermal radiation and natural convection. RCCS components include cooling panels that surround the reactor vessel, inlet/outlet structures that are located above grade and a concentric duct system with the annular, outer flow path acting as the cold leg and the inner flow path acting as the hot leg. Natural convection airflow is established through the RCCS circuit through a balance of buoyancy and gravitational forces. Figure 1 schematically shows the operation of RCCS and the RCCS integrated into the reactor building [3].

![Figure 1: Schematics of RCCS Operation (left) and Reactor Building (right)](image)
The passive characteristics of the RCCS design has resulted in safety issues related to its licensing. The major safety issues on the heat removal function of RCCS were explained from regulatory aspect.

2.1 Heat Transport Characteristics

Core afterheat and effective thermal conductivity are the dominant factors affecting the maximum fuel and vessel temperature in especially limiting events such as depressurized-loss of forced cooling (D-LOFC). Therefore, afterheat curve and thermal conductivities of fuel and reflector regions shall be reliably confirmed. About 90% of heat directed from reactor pressure vessel (RPV) to hot riser panel of RCCS is transported by radiation. Thus the effective thermal emissivity of vessel and panel should be precisely predicted. The effect of coating on the surface of RPV and hot riser panel of RCCS also should be investigated which could have an influence on the emissivity.

The water vapour generated by any pipe ruptures in reactor cavity could reduce the radiation heat transfer. Water vapour had more influence on the temperature increase of RPV rather than that of fuel in particular\cite{4}. Therefore, the effect of water vapour in reactor cavity shall be taken into consideration in long-term D-LOFC condition in which the integrity of RPV may not be maintained. Inner side of RCCS downcomer is insulated to prevent the preheating of air before it flows into hot riser. However, the insulation of downcomer could have an adverse effect on the ultimate heat sink function to the soil in case of the failure of all the heat removal systems including HTS, SCS and RCCS. Therefore the insulation effect shall be optimized considering ultimate heat sink function.

2.2 Structural Design

The inlet and outlet of the RCCS flow path shall be protected by external effects and not be blocked physically. Screens are installed at inlet and outlet of rectangular duct to prevent the access of obstacles to the RCCS flow path. However, the pressure drop through the screen could have an adverse effect on the natural convection. Thus, the design of screen shall be optimized considering both the form loss through the screen and natural convection effect. Besides RCCS shall be designed to prevent common cause failure (CCF) of natural circulation and it shall be protected against sabotage. In addition, the structural integrity of RCCS shall be maintained at high temperature condition.

2.3 Inspection and Repair

An adequate in-service inspection (ISI) program shall be established because we have little experience of RCCS operation. Disassembly of the RCCS should be considered in the ISI program. In addition, the available time for RCCS repair shall be calculated reliably assuming that all of heat removal systems including HTS, SCS and RCCS are not operable.

3 MELCOR MODEL DEVELOPMENT

600 MWth HTGR based on the design of gas turbine-modular helium reactor (GT-MHR) of General Atomics (GA) is the reference model for the development of MELCOR input model in this study.
3.1 Development of Reactor Core Model

The core model of HTGR is based on ‘PMR600’ input deck provided by NRC. MELCOR 2.1 was mainly updated on core package (COR) to be applied to HTGR. Fuel element in COR represents the fuel compact while cladding element does graphite block. Cladding is assumed to be a cylinder with radial temperature distribution. Reflector is considered to be canister-next-to blade (CB) element. The reactor core is composed of inner reflector, three rings of active core and outer reflector in radial direction while it is composed of upper reflector, active core and lower reflector in axial direction. Tanaka-Chisaka model is used as the heat transfer model considering conduction and radiation of blocks including the effects of the coolant channels and fuel compacts.

3.2 Development of RCCS Model

Following reactor core are core barrel, coolant channel and reactor pressure vessel (RPV) in radial direction. Reactor cavity which is divided into two parts by hot riser of RCCS is located at the outside of RPV[5]. One part is up-flow region where the air is directly heated by RPV and flows upward. The other is down-flow region where the heated air flows downward between hot riser and downcomer of RCCS. However, these two parts of reactor cavity are not divided in reality since many rectangular riser panels are actually separated from each other. Riser of RCCS and inner/outer cavity around the hot riser are modeled as control volume (CV) for natural circulation and convection of air. Inner/outer surface of riser panel and inner panel of downcomer of RCCS are considered as heat structure (HS). Symmetry condition is used for the outermost HS of downcomer to consider insulation effect. Stainless-steel-304 is adopted for material properties of HS. Figure 2 shows the nodalization of developed MELCOR model.

![Figure 2: Nodalization of developed MELCOR model](image-url)
4 ANALYSIS RESULTS

4.1 Normal Operation

The analysis results of MELCOR code at normal operation showed accurate prediction capability of the design values of GT-MHR as shown in Table 1. The core conditions including temperature, coolant flow rate and pressure drop are similar to the actual design values. In particular, the maximum fuel and graphite temperature shown in Figure 3 agreed well so that the material property and heat balance were analysed precisely in normal operation.

Table 1: Analysis results of reactor core and RPV parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GT-MHR Design [6]</th>
<th>MELCOR Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor power [MWth]</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Coolant flow rate [kg/s]</td>
<td>320</td>
<td>317</td>
</tr>
<tr>
<td>Helium inlet temperature [K]</td>
<td>764</td>
<td>765</td>
</tr>
<tr>
<td>Helium outlet temperature [K]</td>
<td>1123</td>
<td>1128</td>
</tr>
<tr>
<td>Helium inlet pressure [bar]</td>
<td>69.728</td>
<td>70.4</td>
</tr>
<tr>
<td>Core pressure drop [bar]</td>
<td>0.503</td>
<td>0.5</td>
</tr>
<tr>
<td>Maximum fuel temp. [K]</td>
<td>1491</td>
<td>1527</td>
</tr>
<tr>
<td>Maximum graphite temperature [K]</td>
<td>1415</td>
<td>1448</td>
</tr>
<tr>
<td>RPV inside wall temperature [K]</td>
<td>758</td>
<td>763</td>
</tr>
<tr>
<td>Average outside wall temperature [K]</td>
<td>719</td>
<td>717</td>
</tr>
</tbody>
</table>

Figure 3: Maximum fuel and graphite temperature in normal operation

The heat removal via RCCS was also predicted well as represented in Table 2. Heat removal rate and flow rate of RCCS shown in Figure 4 & 5 are calculated with high accuracy. Due to such analytic results representing accurate prediction capability of heat removal function of RCCS, it is likely to possibly calculate the accident condition using MELCOR code when the heat removal function of RCCS is more important.
Table 2: Analysis results of RCCS parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GT-MHR Design [6]</th>
<th>MELCOR Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removal heat [MW]</td>
<td>3.3</td>
<td>3.3</td>
</tr>
<tr>
<td>Riser air flow Rate [kg/s]</td>
<td>14.3</td>
<td>14.34</td>
</tr>
<tr>
<td>Riser air inlet temperature [K]</td>
<td>316</td>
<td>316</td>
</tr>
<tr>
<td>Riser air outlet temperature [K]</td>
<td>547</td>
<td>546</td>
</tr>
</tbody>
</table>

Figure 4: RCCS heat removal rate in normal operation

Figure 5: RCCS flow rate in normal operation

4.2 D-LOFC condition

D-LOFC condition is considered to be a limiting event for HTGR which could lead to the highest maximum fuel temperature. Actually three of limiting events for 350 MWth MHTGR with respect to offsite doses are SRDC-6 (Depressurized conduction cooldown (DCC) with moderate moisture ingress), SRDC-10 (DCC with moderate primary coolant leak, and SRDC-11 (DCC with small primary coolant leak) from the safety evaluation results[7].

In this study, double-ended break of cross vessel at t=100 seconds was assumed simply for the depressurization condition of 600 MWth. As soon as the accident occurs, both heat exchanger and compressor in power conversion system failed to operate and reactor shut down automatically.
Figure 6: Maximum fuel temperature in D-LOFC accident analysis

The maximum fuel temperature is predicted to be much higher than 1,600 °C above which is taken as a maximum allowable fuel temperature limit because the accident fission product releases increase this temperature[8]. The response time of core temperature is so rapid considering the graphite heat capacity. The analysed temperature of graphite was not reasonable as well considering its heat capacity. These results were completely different from what was expected by normal operation analysis results.

Therefore, it is necessary to perform further studies for the resolution of these problems. The sensitivities of core afterheat and thermal properties of graphite and fuel including heat capacity and thermal conductivity, and so on shall be assessed.

5 CONCLUSIONS

The reliable operation of RCCS assures passive safety characteristics of HTGR. Thus, it is necessary to review design safety of HTGR and resolve safety issues in terms of function of RCCS. Afterheat, thermal conductivity, water vapour effect and downcomer insulation effect, etc, structural integrity to assure flow path of natural circulation and considerations of inspection and repair of RCCS are major safety issues regarding to heat removal function of RCCS.

MELCOR 2.1 code was selected as a candidate for regulatory auditing tools to efficiently review the design safety and resolve safety issues explained above. The MELCOR input model for HTGR with RCCS was developed and analyses of normal operation and D-LOFC condition were carried out. The normal operation condition including RCCS heat removal capability was accurately calculated comparing design values. However, the analysis of D-LOFC accident condition showed significant discrepancies including thermal response time and fuel and graphite temperature.

Hereafter further studies are necessary to derive reasonable results of D-LOFC accident. The sensitivities of core afterheat and thermal material properties of graphite and fuel, and so on shall be assessed.
ACKNOWLEDGMENTS

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REFERENCES


