DEVELOPMENT OF MARS-GCR/V1 FOR THERMAL-HYDRAULIC SAFETY ANALYSIS OF GAS-COOLED REACTOR SYSTEMS

WON-JAE LEE*, JAE-JUN JEONG, SEUNG-WOOK LEE and JONGHWA CHANG
Korea Atomic Energy Research Institute
150 Deokjin-dong, Yuseong-gu, Daejeon 305-353, Korea
*Corresponding author. E-mail : wjlee@kaeri.re.kr

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In an effort to develop a thermal-hydraulic (TH) safety analysis code for Gas-cooled Reactors (GCRs), the MARS code, which was primarily developed for TH analysis of water reactor systems, has been extended here for application to GCRs. The modeling requirements of the system code were derived from a review of major processes and phenomena that are expected to occur during normal and accident conditions of GCRs. Models for code improvement were then identified through a review of existing MARS code capability. Among these, the following priority models necessary for the analysis of limiting high and low pressure conduction cooling events were evaluated and incorporated in MARS-GCR/V1: 1) Helium (He) and Carbon Dioxide (CO_2) as main system fluids, 2) gas convection heat transfer, 3) radiation heat transfer, and 4) contact heat transfer models. Each model has been assessed using various conceptual problems for code-to-code benchmarks and it was demonstrated that MARS-GCR/V1 is capable of capturing the relevant phenomena. This paper describes the models implemented in MARS-GCR/V1 and their verification and validation results.

KEYWORDS : Gas-Cooled Reactor, Thermal Hydraulic, Safety, MARS, Heat Transfer, Gas Property

1. INTRODUCTION

Recent research and development in advanced reactor systems and nuclear applications to hydrogen generation has highlighted GCRs as viable candidates for Generation-IV reactors. In particular, the following four GCR design concepts were proposed: a pebble bed modular reactor system (PBMR), a prismatic modular reactor system (PMR), a very high-temperature gas-cooled reactor system (VHTR), and a fast neutron spectrum gas-cooled reactor system (GFR) [1]. Further evaluation of candidate concepts categorized PBMR and PMR as potential near-term concepts and VHTR and GFR as advanced Gen-IV concepts with the potential for extended capabilities [2]. Technical gaps, R&D scope, and challenges required for the development of these advanced reactor systems were also set forth, in which it was recommended that considerable development and benchmarking of accident and transient system codes is required for accurate and reliable prediction of plant safety and performance. While a considerable amount of technology and experience has been accumulated for PBMR and PMR, stricter regulatory requirements and more advanced requirements for plant safety design and operation would necessitate further development of existing and new technologies, not only for PBMR and PMR but also for the more advanced VHTR and GFR.

Since 1997 the Korea Atomic Energy Research Institute (KAERI) has been developing a multi-dimensional system TH analysis code, MARS [3], for the realistic simulation of water reactor transients. The code has been improved for realistic and extended modeling of various water reactor types such as conventional and advanced PWR, CANDU, and research reactors. In addition, a coupled analysis capability with three-dimensional core kinetics [4] and containment thermal hydraulics was implemented and a visual graphic user interface was provided for user friendliness [5].

In this study, we extended the MARS modeling capability for general application to GCRs that use He or CO_2 as coolant. For this, the modeling requirements of a system code for GCR applications were derived for major processes and phenomena that are expected to occur during normal and accident conditions. Specific models for MARS improvement were then identified through a review of the existing MARS capability. Among them, the following priority models necessary for the limiting safety analysis were selected and implemented into MARS-GCR/V1: 1) He and CO_2, which are current coolant options, were incorporated as one of the main system fluids to accurately model coolant states, 2) gas heat transfer models that are applicable to the TH conditions expected to occur during GCR transients were evaluated and incorporated, and 3) radiation and contact heat transfer models that are major decay heat removal mechanisms were incorporated in the code. The code implementation was verified and validated using various code assessment problems.

2. IDENTIFICATION OF MODEL IMPROVEMENTS

Typical GCR systems consist of a single phase gaseous coolant, He or CO_2, a pebble or block type core, a reflector, coolant flow paths in and outside the reactor vessel, gas-to-gas heat exchangers, gas-to-water heat exchangers, compressors, turbines, a reactor cavity, and a Reactor Cavity Cooling System (RCCS) for passive afterheat removal. Thermal hydraulics involved in GCRs is basically single phase gas flow; however, there is a chance of water or air ingress and consequent chemical reaction with graphite structures during accidents. Multidimensional flow and thermal mixing occurs in the core, vessel plenums, riser and reactor cavity during steady and transient processes. Convection heat transfer falls into forced convection during normal operations and is more likely to be in mixed or free convection during accident conditions where the buoyancy effect plays an important role. Vessel internals such as fuel pebbles, fuel blocks, and reflector blocks contact each other and conduct heat in a multi-dimensional manner. Typical limiting event scenarios of GCRs are a high pressure conduction cooling event initiated by loss of primary flow and a low pressure conduction cooling event initiated by loss of coolant. During these accidents, core afterheat is transferred to the vessel wall by conduction and radiation inside the vessel internals. The afterheat is then transferred to the RCCS by radiation and partly by convection inside the reactor cavity. The conduction mechanism inside the vessel internals includes heat conduction in materials, gas conduction, and contact heat transfer.

From these observations, the modeling requirements of a system code for GCR applications were derived as follows:

- Multi-dimensional single and two-phase hydrodynamics models
- Thermodynamic and transport properties of He, CO_2, and water
- Convection heat transfer models covering forced, mixed, and free convection regimes
- Radiation heat transfer models
- Multi-dimensional heat conduction models
- Contact heat transfer models
- System component models for compressor, turbine and heat exchangers
- Air/water mixing models
- Graphite chemical reaction and multiple gas species models
- TH models for specific designs such as pebble, prismatic or plate cores and tubular, helical or plate heat exchangers, etc.

Based on the above requirements, the modeling capability of the MARS code was evaluated. The MARS code is a generic TH network code equipped with fundamental and integral sets of hydrodynamics, heat conduction, and point reactor kinetics equations. The hydrodynamics equation sets consist of one-dimensional and multi-dimensional governing equations for mass, energy, and momentum conservation, constitutive equations for mass, energy, and momentum transfer and special process models for choking, area changes, etc. It can model light and heavy water as the main system fluids along with non-condensable gases in thermal and mechanical equilibrium with a vapor phase. One-dimensional reactor system component models for pumps, valves, turbines, etc. are also provided in the code. Thus, the MARS code is basically capable of modeling the GCR system transients if the relevant models for state, constitutive, and components are incorporated.

Multi-dimensional hydrodynamics can be simulated using the MULTID component model of the MARS code. The MULTID component [6, 7, 8] is formulated using multi-dimensional porous media models in rectangular and cylindrical coordinates. Of advantage for GCR applications are the inclusion of diffusion terms in the momentum and energy equations, with which the local dynamic and turbulent viscosities and the local fluid conduction and thermal mixing can be simulated. Thus, local flow and temperature distributions in the core, vessel plenums, riser, and reactor cavity can be effectively modeled using the MULTID component.

Whereas He flow can be modeled using non-condensable gas models in thermal and mechanical equilibrium with the vapor phase using MARS, there is no non-condensable model for CO_2 flow. He properties are calculated using a simple ideal gas assumption at a vapor temperature, and as a result the accuracy of the calculated properties is not sufficient to realistically represent TH conditions over the ranges of GCR transients. Fig. 1 compares the He properties calculated by MARS with those of the NIST database [9]. As shown in the figure, the maximum deviations of density, thermal conductivity, and viscosity are about 6.9%, -8.4% and -11%, respectively. Such deviations and the lack of CO_2 property models necessitate the incorporation of more accurate property models in the code.

MARS heat transfer models applicable to gas flow consist of two regimes, a force turbulent convection based on the Dittus-Boelter model and a simple model for low Reynolds numbers below 10^6. The simple model takes the maximum of forced turbulent, forced laminar and free convection heat transfer coefficients, since they do not significantly affect the results in water reactor transients.

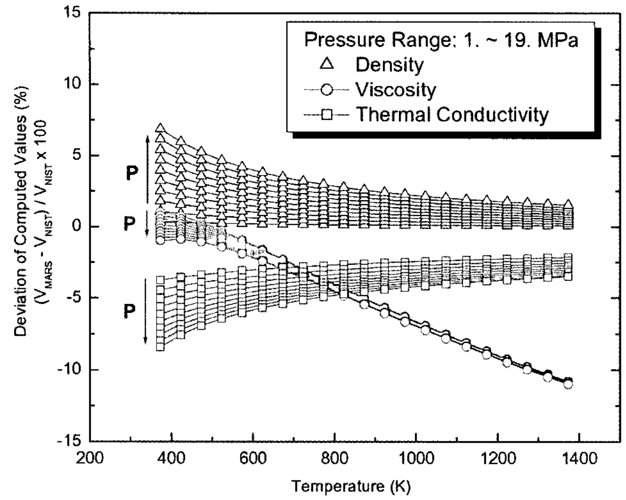


Fig. 1. Comparison of He Properties by Original MARS with NIST

However, in the GCR, the range of the Reynolds numbers is much lower, even during normal operation, and decreases down to several hundreds during accident conditions while the range of Grashof numbers is still large. Thus, the convection heat transfer is more likely to be in mixed or free convection during GCR transients, where the buoyancy effect plays a more important role. From this, it is clear that the original models are not accurate enough to cover the range of the Reynolds and Grashof numbers expected during GCR transients, that is, they are not suitable for mixed or free convection. Even for the forced convection turbulent heat transfer, it was reported that the Dittus-Boelter model overestimates it and that the effect of the flow geometry and wall temperature becomes more dominant [10]. Thus, it is imperative that the heat transfer models of the MARS code be improved for GCR applications.

The MARS code lacks the models for multi-dimensional heat conduction, radiation and contact heat transfer, air/water mixing, graphite chemical reaction with multiple gas species, and system components. Accordingly, these models ultimately need to be incorporated into the code. Among them, multi-dimensional heat conduction can be approximated using both a two-dimensional heat conduction model that solves both radial and axial conduction and a contact heat transfer model. System components such as compressors and turbines are also expected to be approximated using existing pump and turbine models. Air/water mixing can be approximated using non-condensable models embedded in the code. On the other hand, graphite chemical reaction and multiple gas species models appear to be beyond the system code scope, and thus a specialized code is being developed for this purpose.

There are TH models for specific designs such as the pebble, prismatic or plate cores and the tubular, helical or plate heat exchangers. These models should be implemented in the code as the reference design progresses. However, it should be noted that the existing database and models are limited such that they cannot cover the full spectrum of process and phenomena that may occur during GCR transients. We will put them as relevant studies will be ready.

Based on a review of existing MARS capability, priority models that are necessary for the analysis of limiting transient scenarios have been identified. Here, the limiting transient scenarios represent the high and the low pressure conduction cooling transients initiated by loss of flow and coolant respectively, where the core afterheat is removed mainly by conduction and radiation and partly by convection. The priority models identified for MARS improvement are the models for gas properties, gas convection heat transfer, radiation heat transfer, and contact heat transfer.

3. DEVELOPMENT OF MARS-GCR/V1

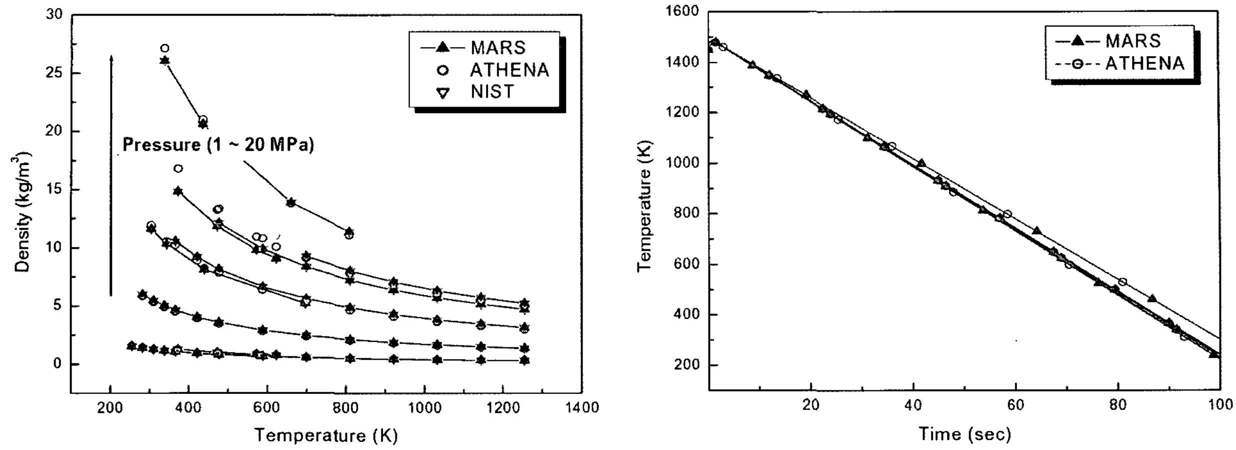
3.1 Incorporation of He and CO_2 Properties

He and CO_2 gases, the current coolant options of GCRs, are incorporated in the MARS code as main system fluids rather than mixed non-condensable gases. This yields enhanced accuracy and enables generic and flexible modeling of complicated fluid systems by fully utilizing the existing capability of the code. For this, thermodynamic property tables of He and CO_2 were generated outside the code using the program, GasProp [11], which was written using NIST routines. The gas property tables cover a range from the triple point to supercritical states with fine data intervals near the critical state. Various gas table-search routines were developed and incorporated in the code. State-of-the-art models for the dynamic viscosity and thermal conductivity [12, 13] were incorporated in functional forms.

The improved version of the code was verified and validated by comparing the results with those of the NIST database and ATHENA [14], as shown in Fig. 2. Fig. 2 a) compares the He properties calculated for a steady pipe flow problem, where the pressure varies from 1 to 20 MPa while the temperature varies from 255 to 1255K. Fig. 2 b) compares the CO_2 properties calculated for a simple pipe cooldown transient problem, where the pipe inlet temperature is decreased from 1450 to 220K in 100 seconds and the inlet flow is increased from 0 to 5 m/sec in 1 second at various system pressures, i.e. 200, 100, 75, and 5 bars. From the comparison, it was found that the code is capable of calculating the fluid properties as accurately as the NIST database over a wide range from the subcritical single and two-phase to supercritical states. The slight deviation from ATHENA is attributed to the use of a different property database.

3.2 Incorporation of Gas Heat Transfer Package

In an effort to improve gas heat transfer models, various



a) Steady Problem – He Density

b) Transient Cooldown Problem – CO_2 Temperature

Fig. 2. Verification and Validation of Gas Property Models

published heat transfer models were reviewed and evaluated. We selected the heat transfer regimes map [15] developed by the Massachusetts Institute of Technology (MIT), shown in Fig. 3. This model was developed based on the Methais and Eckert map [16] and classifies the regimes into the forced, mixed, and free convections. Each regime was sub-divided into turbulent, transition, and laminar heat transfer modes. As shown in the figure, the Reynolds number (Re) is selected as the y-abscissa and is used to determine whether the flow is laminar, turbulent or transitional. The x-abscissa takes the Rayleigh number (Ra) that represents the buoyancy effect, a multiplication of the Grashof and Prandtl numbers. The Aicher model [17] is selected as a demarcation criterion between forced and mixed convection and the Burmeister model [18] is selected as a demarcation criterion between mixed and free convection. The transition between laminar and turbulent convections is treated specifically in each flow regime. It is also shown in the figure that the TH conditions fall into mixed or forced convection during post-LOCA decay heat removal of a GFR with He or CO_2 as the coolant.

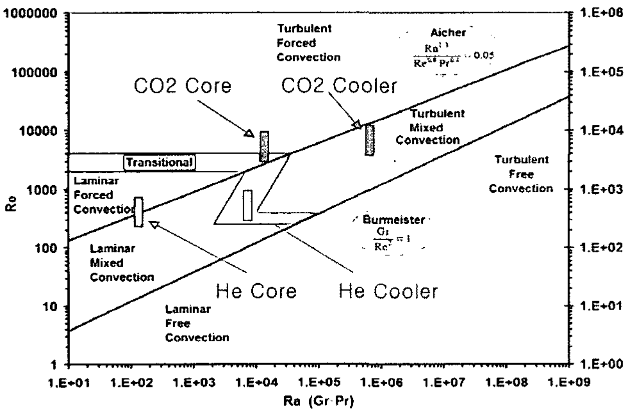


Fig. 3. Heat Transfer Regime Map

Through a qualitative and quantitative evaluation of various heat transfer models specific to each heat transfer regime and mode, we selected the models that are suitable for GCR applications, as summarized in Table 1.

For the forced turbulent convection model, the Gnielinski [19] and Olson [20] models were evaluated. Both models take into account the effects of the flow geometry and wall temperature. Their application range for Reynolds numbers is from 2,300 to $5\text{x}10^6$ and the Prandtl numbers range from 0.5 to 2,000. The major difference between the two models is the wall temperature multiplier. The Gnielinski model takes into account only the effect of the wall temperature whereas the Olson model considers the effects of both wall temperature and pressure. Fig. 4 compares the heat transfer coefficients calculated by both models for various heating and cooling conditions at different pressures. As shown in the figure, the deviation increases up to more than 20% at low pressure and highly cooled conditions. Considering real GCR transients, where the effects of wall temperature and pressure are considerable, the Olson model was selected as a default model. For forced laminar convection, a Nusselt number of 4.364 is chosen for uniform wall heat flux conditions while 3.657 is selected for uniform wall temperature conditions. The transition between turbulent and laminar convection is modeled such that it occurs between Reynolds numbers from 2,300 to 5,000. A weighted linear interpolation of the laminar and turbulent heat transfer is used in the transition region.

Mixed convection occurs when the effects of both buoyancy and pressure gradient are balanced. There are

Table 1. Heat Transfer Models Incorporated in the MARS-GCR/V1

Regime	Laminar	Transition	Turbulent
Forced	Nu = 4.364 (heating) Nu = 3.657 (cooling)	Interpolation between hlam and h_{tur} (2300 < Re < 5000)	Olson [20]
Transition Criterion	Aicher ($Ra^{1/3}/(Re^{0.8}Pr^{0.4})>0.05$) [17]		
Mixed	Churchill [22]	Minimum (h_{lam}, h_{tur})	Churchill [22]
Transition Criterion	Burmeister ($Gr>Re^2$) [18]		
Free	Churchill-Chu [23]		

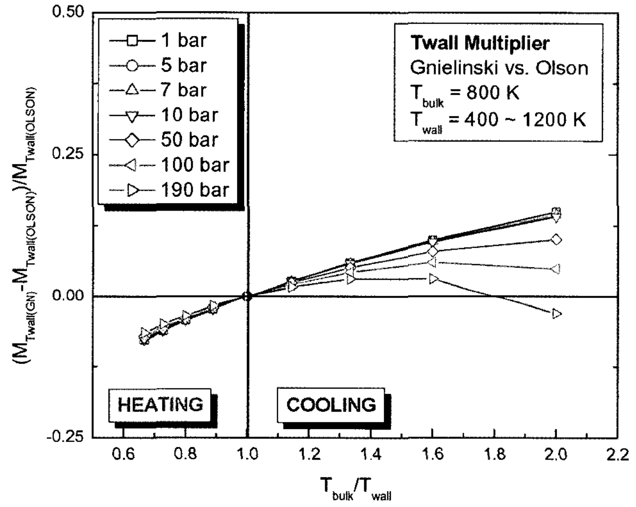


Fig. 4. Comparison of the Gnielinski and Olson Model

two distinct types of mixed convection in a vertical channel: 1) buoyancy aided (heated upflow or cooled downflow), and 2) buoyancy opposed (cooled upflow or heated downflow). Turbulent heat transfer decreases in buoyancy aided flow, while it increases in buoyancy opposed flow. For laminar mixed convection, the opposite occurs, that is, the heat transfer increases in buoyancy aided flow and decreases in buoyancy opposed flow [21]. In MARS-GCR/V1, we employed a simple Churchill model [22] as recommended by MIT. Since the transition criteria between laminar and turbulent mixed convection have not yet been clearly defined, we selected a minimum of laminar and turbulent for conservatism.

Free convection occurs when the buoyancy force becomes dominant. We incorporated the Churchill and Chu model [23], which was reported to be applicable to both laminar and turbulent free convection.

The above models were implemented in the code as user options. The overall heat transfer package was then verified and validated using a conceptual problem for a passive decay heat removal loop of a CO_2-cooled GFR [15]. Fig. 5 shows the schematic of the decay heat removal loop and relevant nodalization. Fig. 6 compares the decay heat removal capability calculated by MARS-GCR/V1 with that by the LOCA-COLA code, a steady-state CO_2-loop analysis code developed by MIT [15]. As shown in the figure, both results are in good agreement. With these results, we can conclude that the gas heat transfer models are well implemented in the code and that the MARS-GCR/V1 code is capable of simulating the various heat transfer regimes expected to occur in a GCR.

3.3 Incorporation of Radiation Heat Transfer Model

The radiation heat transfer model incorporated in MARS-GCR/V1 is based on RELAP5, and it models the radiosity (R_i) using the black body emission ($\varepsilon\sigma T^4$) and the reflection of the incident radiation ($(1-\varepsilon_i)\Sigma R_j F_{ij}$) as

$$R_i = \varepsilon_i \sigma T_i^4 + (1-\varepsilon_i)\sum_{j=1}^{n} R_j F_{ij} \tag{1}$$

where ε_i is emissivity, σ is the Stefan-Boltzmann constant, and T is temperature.

$$Q_i = R_i - \sum_{j=1}^{n} R_j F_{ij} \tag{2}$$

The surface heat flux (Q_i) is then calculated using where F_{ij} represents the view factor from surface i to surface j.

The improved code was assessed using the IAEA Benchmark Problem-I for HTR-10 RCCS heat removal [24]. This problem is a code-to-code benchmark problem and is designed to verify the heat transport capability of a water-cooled RCCS under a steady condition of a heat-up

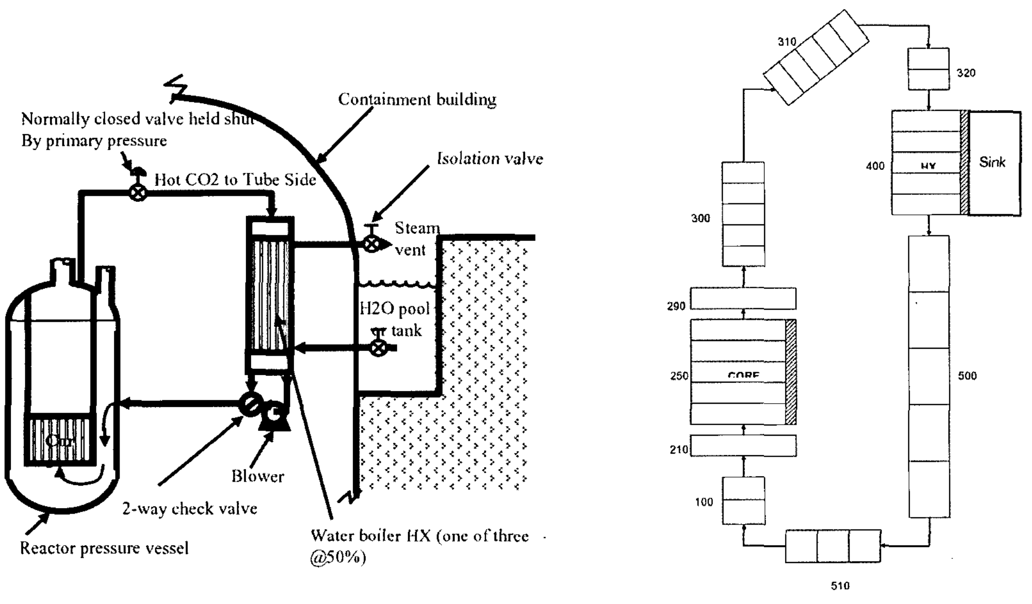


Fig. 5. Schematic and Nodalization of GFR Decay Heat Loop

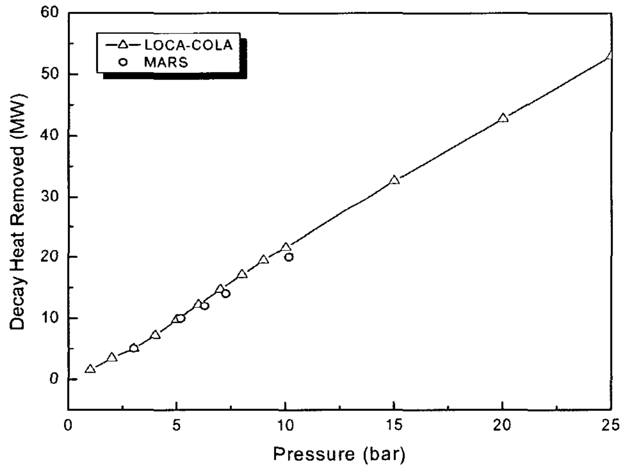


Fig. 6. Verification and Validation of Gas Heat Transfer Models

experiment. The surface temperature of the core vessel (CV) is given as the boundary condition. Under this steady condition, the temperature distributions of the reactor pressure vessel (RPV) and water cooler panel (WCP) were calculated and the RCCS performance parameters were evaluated. Fig. 7 shows the schematic of the HTR-10 RCCS system and its nodalization using MARS-GCR /V1. The results of MARS-GCR/V1 were compared with those of RELAP5 and THERMIX. For comparison with RELAP5, the same TH models were used for consistency and the reactor cavity was modeled one-dimensionally in order to eliminate the effects of natural convection inside the cavity. As shown in Fig. 8 a), it was demonstrated that the results of MARS-GCR are identical with those of RELAP5.

From this we can conclude that the radiation heat transfer model has been correctly implemented in the code. For comparison with THERMIX, the cavity was modeled two-dimensionally using the MULTID component in order to take into account the natural convection inside the reactor cavity. It was found that the results of MARS-GCR/V1 are in good agreement with those of THERMIX, as shown in Fig. 8 b). Thus, we can conclude that not only the radiation heat transfer but also the multi-dimensional hydrodynamic models in the code can capture the major phenomena that occur during the progress of RCCS heat removal.

3.4 Incorporation of Contact Heat Transfer Model

In order to approximate the multi-dimensional heat conduction by contact of heat structures such as fuel pebbles, blocks, and vessel internals, a simple contact heat transfer model was incorporated in the code. If the surface of a heat structure i contacts another heat structure j, the contact heat transfer can be modeled as

$$Q_{con} = A_{con} H_{con} (T_i - T_j) = A_i (A_{con}/A_i) H_{con} (T_i - T_j) = A_i H_{eff} (T_i - T_j) \quad (3)$$

where A_{con} represents the real contact area, H_{con} is $k/\delta x$, that is, conductivity divided by the distance between heat structures, and T is the surface temperature of a relevant heat structure.

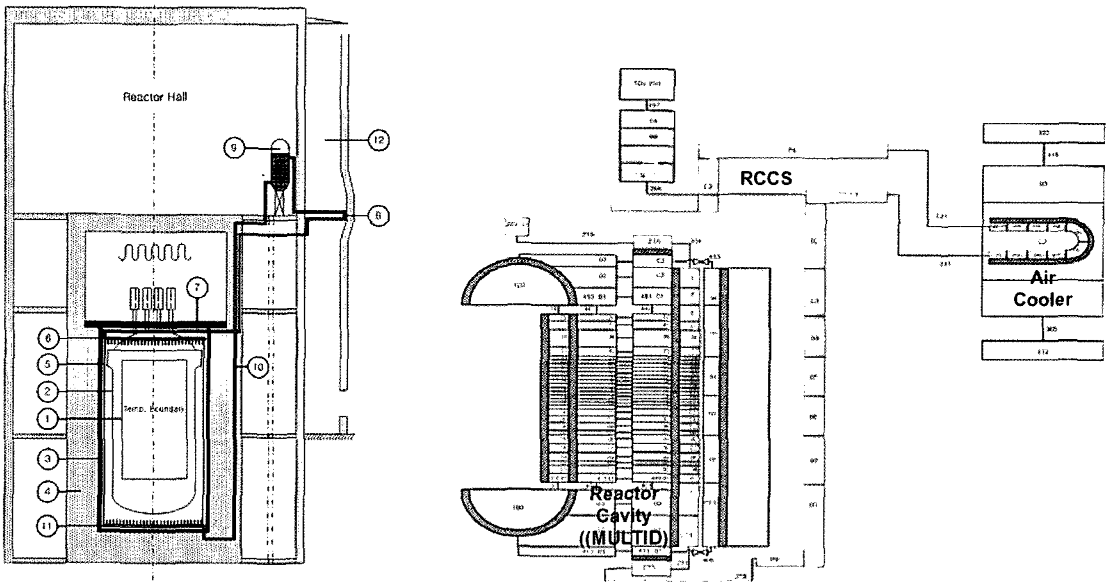
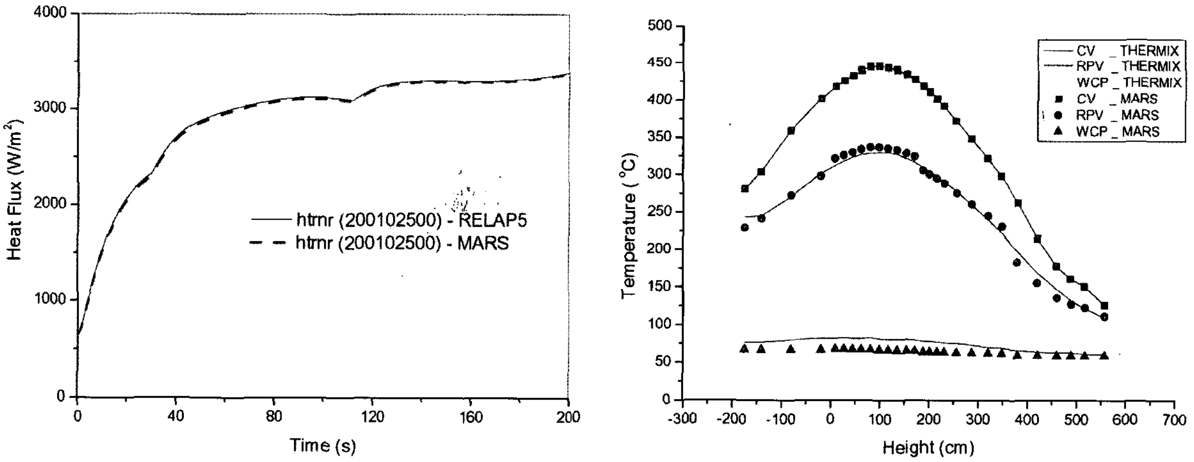


Fig. 7. Schematic and Nodalization of HTR-10 RCCS



a) Comparison of MARS and RELAP5

b) Comparison of MARS with THERMIX

Fig. 8. Verification and Validation of Radiation Models

Currently, users are requested to provide effective thermal conductivity, H_{eff}, as input. The implementation of the model was verified and validated on a debugger level using various steady and transient problems. A mechanistic contact heat transfer model will be developed in connection with a more sophisticated multi-dimensional heat conduction model in the future.

4. CONCLUSIONS AND FUTURE WORK

The capability of the MARS code has been extended for application to the safety analysis of GCRs. From the modeling requirements of a system code for GCR applications, priority models that are necessary for the limiting safety analysis were identified and implemented in the

MARS-GCR/V1 code. The improved models are those for the He and CO_2 properties, the gas convection heat transfer, the radiation heat transfer and the contact heat transfer. The model implementations were verified and validated using various conceptual and benchmark problems. From this, it was demonstrated that the MARS-GCR/V1 code provides an integral and viable code framework for the safety analysis of GCR system transients.

We plan to further improve and validate the code not only for the major TH phenomena expected to occur during GCR transients but also for the integrated code performance. Future development of TH models will focus on the refinement of gas heat transfer, pressure drop and contact heat transfer models, and new models for multi-dimensional heat conduction and system components such as compressors, heat exchangers, and gas turbines. We will also extend the code capability for a coupled analysis with three-dimensional core kinetics and hydrogen production system transients.

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