Development of MARS-GCR/V1 for Thermal-Hydraulic Safety Analysis of Gas-Cooled Reactor Systems

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1. Introduction

In an effort to establish a thermal-hydraulic (TH) safety analysis code for Gas-cooled Reactor (GCR) systems, the MARS code that was primarily developed for the thermal-hydraulic system analysis of water-cooled reactor transients has been extended for GCR applications. As the first step, the code was improved to model Helium (He) and Carbon Dioxide (CO2) as main system fluids, then, the gas heat transfer package and the radiation heat transfer model that are applicable to expected ranges of GCR transients were incorporated. This specific version of the MARS was named as MARS-GCR/V1. This paper describes the models incorporated in the code and their verification and validation results.

2. Development of MARS-GCR

The MARS code [1] has been developed under the Nuclear R&D program primarily for application to water reactor transients, and as such, there are TH models that should be developed and improved for the GCR applications. Since the MARS code is a generic TH network code equipped with fundamental and integral sets of fluid equations, it can be extended for applications to other fluid systems if the relevant state relationships and constitutive equations are incorporated. A review of the MARS code showed that it could model the He flow as a non-condensable gas mixed in vapor phase in thermal and mechanical equilibrium, but not the CO_2 flow. However, it was found that the TH models associated with the gas flows are not sufficient to accurately model TH conditions expected to occur during GCR transients. He properties are calculated using a simple ideal gas law, in which the maximum deviation of the density is about 2.5% and that of the thermal conductivity is about -5.6% at 7 MPa and 375 K [2]. In addition, the embedded heat transfer models are not applicable to the ranges of gas flow transients and the radiation heat transfer model should be added in order to model self-acting afterheat removal system.

2.1 Incorporation of He and CO_2 Properties

The He and CO2 gases that are the current coolant options of GCR are incorporated in the MARS code as main system fluids rather than mixed non-condensable gases. This enables not only the enhanced accuracy but also the generic and flexible modeling of the 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 a program, STGAS, that was written using NIST [3] routines. Then, various table-search routines for the gas tables were developed and implemented into the code. And, the state-of-the-art models for the dynamic viscosity and thermal conductivity [4,5] were incorporated in a functional form.

The improved version of the MARS code, the MARS-GCR, then, was verified and validated using various steady state and transient problems. It was found that the code is capable of calculating the fluid properties accurately over the wide ranges from the subcritical, saturated and supercritical states and that the code is integral enough to simulate various transients and flexible enough to model complicated fluid systems.

2.2 Incorporation of Gas Heat Transfer Models

The single phase heat transfer regime of the original MARS code consists of two regimes. One is the force turbulent convection that uses the Dittus-Boelter model. And, the other is a simple model for Reynolds numbers below 10^6, in which the maximum of the forced turbulent, forced laminar and free convection heat transfer is taken. Considering that the heat transfer regimes during the GCR transients are more likely to be in the mixed or free convection regimes where the buoyancy effect plays an important role, it is clear that the original models are not valid for the expected ranges of Reynolds and Grashof numbers during the GCR transients. Even for the forced turbulent convection heat transfer, it was reported that the Dittus-Boelter model overestimates the heat transfer and that the effect of flow geometry and wall temperature becomes more dominant. Thus, it is quite imperative that the heat transfer models of the code should be improved.

In an effort to improve the gas heat transfer models, various published heat transfer models were evaluated. We selected the heat transfer regimes map by MIT [6] that classified the regimes into the forced, mixed and free convections. Each regime was sub-divided into the turbulent, transition and laminar heat transfer modes.

Through the 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 [7].

Table 1. Heat Transfer Package incorporated in the MARS-GCR

Regime	Laminar	Transition	Turbulent
Forced	Nu = 4.364 (heating) Nu = 3.657 (cooling)	Interpolation between h_{lam} and h_{tur} (2300 < Re < 5000)	Olson
Transition Criterion	Aicher		
Mixed	Churchil	Minimum (h_{lam}, h_{tur})	Churill
Transition Criterion	Burmeister		
Natural	Churchill-Chu		

These models were incorporated in the code as user options. The improved code was, then, verified and validated using a conceptual problem for a decay heat removal loop of CO2-cooled fast reactor. Fig. 1 compares the decay heat removal capability calculated by the MARS-GCR with that by the LOCA-COLA, a steady-state CO2-loop analysis code developed by MIT [6]. 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 code is capable of simulating the various heat transfer regimes expected to occur in GCR.

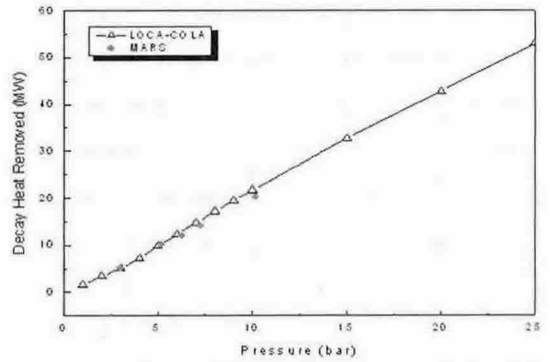

Fig. 1. Comparison of Decay Heat Removal Capability

2.3 Incorporation of Radiation Heat Transfer Model

High temperature GCR adopts a reactor cavity cooling system (RCCS) as the self-acting ultimate afterheat removal system, in which the radiation heat transfer is the major heat transfer mechanism. Thus, proper radiation heat transfer models should be incorporated in the code.

The radiation heat transfer model incorporated in the MARS-GCR 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 ($\rho_i \Sigma R_j F_{ij}$) as;

$$R_i = \varepsilon_i \sigma T_i^4 + \rho_i \sum_{j=1}^{n} R_j F_{ij}$$

Then, the surface heat flux (Q_i) is modeled as;

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

where, F_{ij} is the view factor.

The improved code was assessed using the IAEA Benchmark Problem for HTR-10 RCCS heat removal. It was found that the results of the MARS-GCR are almost identical with those of the RELAP5 and also in good agreement with those of THERMIX [8]. Thus, we can conclude that the radiation heat transfer model has been well implemented in the code

3. Conclusions and Future Works

The MARS-GCR/V1 code has been developed as a basic and viable code frame for the realistic system TH analysis of GCRs. The improved models include the gas property, gas heat transfer and radiation heat transfer models. We will further improve and validate the code for the major TH phenomena expected to occur during the GCR transients. Future development of TH models will focus on the gas heat transfer, pressure drop, effective thermal conductivity, multi-dimensional heat conduction models and the TH models for system components (compressor, intermediate heat exchanger and gas turbine) and for the interfacing systems of a high temperature engineering loop, etc.

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