

# Development of Safety Analysis Code for High Temperature Gas-cooled Reactor using AI

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## 1. Introduction

The high-temperature gas-cooled reactor (HTGR) is a Generation-IV reactor that uses helium as the coolant and features high thermal and passive safety. Depending on the design, HTGRs adopt either a prismatic or a pebble-bed core, and they are characterized by higher-temperature, lower-pressure operation than ordinary PWR (Pressurized Water Reactor) with passive safety systems. In addition, unlike light water reactors (LWRs) that use fuel pellets and cladding, HTGRs adopt TRISO fuel, so the correlations and analysis methods established for LWRs cannot be applied directly.

Regulatory audit codes such as MARS-KS are optimized for the thermal-hydraulic characteristics of light water reactors, and thus have difficulty reflecting the new design features of non-LWR systems, such as high-temperature operation, various coolants, porous cores, and passive safety systems [1,2]. MARS-GCR was previously developed for gas-cooled reactors [3], but due to the long absence of maintenance, the code is not available at the moment. In this study, therefore, a thermal-hydraulic analysis code for HTGR regulatory audit, AIR-MARS-gc (AI-Regenerated MARS for gas cooled), is newly developed using a generative artificial intelligence based development workflow, and preliminary verification is performed through comparison with GAMMA+ [4] reference solutions.

## 2. Overview of the AIR-MARS-gc Code

### 2.1 Development methodology

AIR-MARS-gc is written through an AI-based development workflow using a large language model, Anthropic Claude (Table 5). The reference materials were restricted to the publicly available MARS manuals [1,2] and the papers and reports directly provided by the user, and to prevent any potential security incident, no other document was allowed to be referenced. In addition, since the existing MARS code is based on Fortran and has limited extensibility, AIR-MARS-gc is developed in Intel Python.

### 2.2 Code structure and input system

AIR-MARS-gc follows the architecture of the existing MARS code. The system is assembled from control volumes and junctions and employs a staggered grid with a semi-implicit pressure equation. Furthermore, for the features not included in the existing MARS, such as prismatic cores, pebble-bed cores, and multi-dimensional analysis, the required input items were extracted from the GAMMA+ input manual and implemented as new extension cards. The overall structure and relation between modules are shown in Fig. 1.

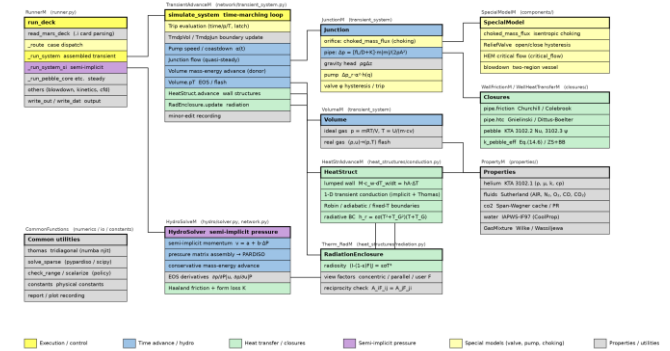


Fig. 1. Modular structure of AIR-MARS-gc

### 2.3 Key models and correlations

The key properties and correlations of the two codes are compared in Table 1. The pebble-bed convective heat transfer (KTA 3102.2) and the gray-diffuse enclosure radiosity model for radiative heat transfer are common to both codes.

The remaining models differ. AIR-MARS-gc implements the KTA 3102.1 helium properties, whereas GAMMA+ evaluates the fluid properties from its own temperature-dependent property functions. For the pebble-bed pressure drop, AIR-MARS-gc follows the German licensing standard KTA 3102.3, while GAMMA+ applies the Forchheimer-extended Darcy law with the KTA 3102.3 coefficients. The effective thermal conductivity of the pebble bed is obtained from a SANA-experiment-based correlation (Zehner-Schlünder with a radiation component) in AIR-MARS-gc and from a modified Zehner-Schlünder model in GAMMA+. For the pipe-wall heat transfer, AIR-

MARS-gc uses the Gnielinski forced-convection correlation, whereas GAMMA+ adopts the Churchill–Chu and McAdams natural-convection correlations for vertical and horizontal tubes, respectively.

Table 1. Material Properties and Correlations in AIR-MARS-gc and GAMMA+

| Physical phenomenon               | Model/correlation                |                                                             |
|-----------------------------------|----------------------------------|-------------------------------------------------------------|
|                                   | AIR-MARS-gc                      | GAMMA+                                                      |
| Helium properties                 | KTA 3102.1 (rho, mu, k, cp)      | Temperature dependent transport properties                  |
| Pebble-bed convection             | KTA 3102.2 Nu                    |                                                             |
| Pebble-bed pressure drop          | KTA 3102.3 psi                   | Forchheimer-extended Darcy law with KTA 3102.3 coefficients |
| Pebble-bed effective conductivity | Zehner-Schlunder + radiation     | Modified Zehner/Schlunder                                   |
| Pipe heat transfer                | Gnielinski (1976)                | Churchill-Chu (vertical tube)<br>McAdams (horizontal tube)  |
| Radiative heat transfer           | Gray-diffuse enclosure radiosity |                                                             |

### 3. Comparative Verification against GAMMA+ Example Problems

To examine the computational performance of AIR-MARS-gc, comparative verification was carried out against five GAMMA+ example problems representing different physical regimes. The geometry, operating conditions, and material properties were extracted directly from the original GAMMA+ inputs and problem descriptions, and no additional tuning was performed to match the results.

#### 3.1 Example 1: Piping flow

Example 1 is a problem in which a pipe (total length 30 m, diameter 0.2 m, air at 1 bar and 25 °C) connecting two locations with an elevation difference of 20 m (EL 0/20 m) reaches a hydrostatic balance between the two atmospheric boundaries.

The geometry data and nodalization of Example 1 are shown in Fig. 2.

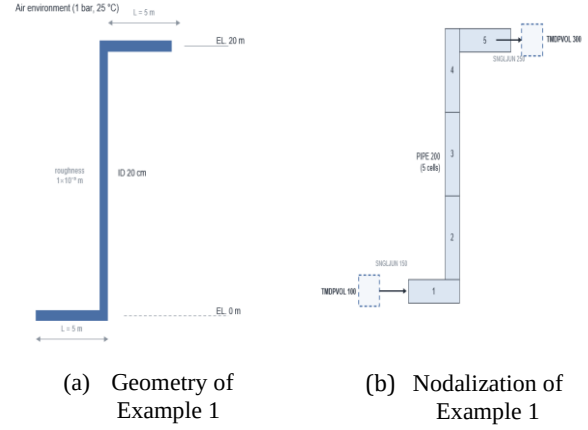


Fig. 2. Geometry and nodalization of Example 1

In both GAMMA+ and AIR-MARS-gc, the initial pressures of the two time-dependent volumes (TMDPVOL) differ by 232 Pa, so a flow is first induced by the pressure difference and the net flow rate then converges to zero.

However, the peak net flow rate during the transient differs: -3.1 g/s for GAMMA+ versus -5.2 g/s for AIR-MARS-gc as shown in Fig. 3. This discrepancy is judged to originate not from the correlations but from differences in the transient damping characteristics (code structure, such as the time step and junction inertia treatment).

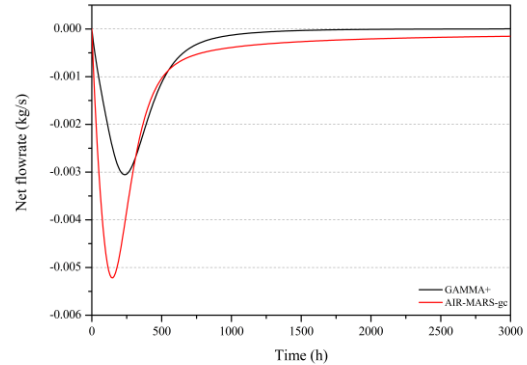


Fig. 3. Net flow rate transients of Example 1

#### 3.2 Example 2: Supercritical CO<sub>2</sub> flow in a fuel channel

Example 2 couples a cooling channel (2 m, 20 cells) with upward supercritical CO<sub>2</sub> flow (20 MPa, inlet 300 °C, 2.02 kg/s) and 61 fuel rods (UO<sub>2</sub>-He gap-Alloy 800H, total 500 kW). In AIR-MARS-gc, the problem was assembled from fluid boundaries (TMDPVOL and TMDPJUN), a pipe (1DPIPE), and cylindrical heat structures (1DHEAT) with convective coupling; the CO<sub>2</sub> properties use the Span-Wagner reference equation of state and the wall convection uses the Gnielinski correlation. The nodalization of Example 2 is shown in Fig. 4.

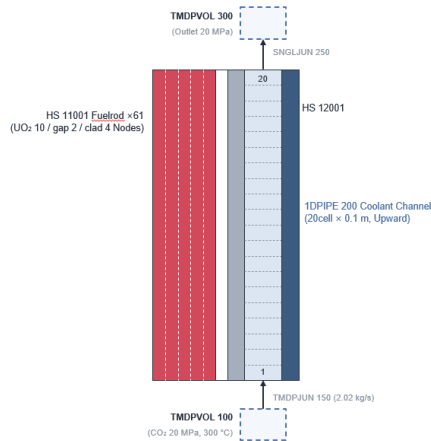


Fig. 4. Nodalization of Example 2

Both GAMMA+ and AIR-MARS-gc show the same trend in which the coolant outlet, cladding surface, and fuel centerline temperatures increase along the flow direction (upward) as shown in Fig. 5. As summarized in Table 2, however, the coolant bulk, cladding surface, and fuel centerline temperatures show deviations of -0.7%, -1.9%, and -1.6%, respectively, which are judged to arise from differences in the convective correlations and the discretization methods.

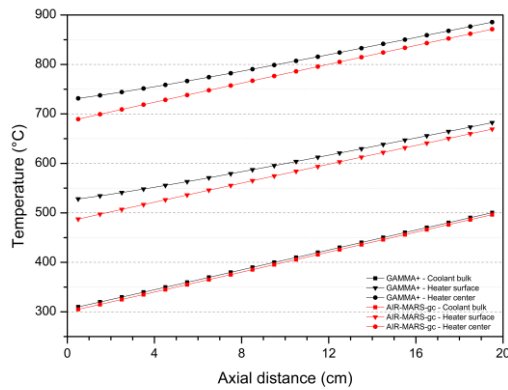


Fig. 5. Axial temperature distributions of Example 2

Table 2. Average temperatures at the coolant outlet, cladding surface, and fuel centerline (Example 2)

| Component      | Average Temperature (°C) |        |           |
|----------------|--------------------------|--------|-----------|
|                | AIR-MARS-gc              | GAMMA+ | Error (%) |
| Coolant Bulk   | 500                      | 496    | - 0.7 %   |
| Heater Surface | 682                      | 669    | - 1.9 %   |
| Heater Center  | 886                      | 871    | - 1.6 %   |

### 3.3 Example 3: Nitrogen natural convection in an annular cavity

Example 3 is a buoyancy-driven natural circulation problem in a nitrogen-filled vertical annular enclosure ( $R_i/R_o = 0.13/0.45$  m, height 1 m) whose inner and outer walls are maintained at 300 °C and 30 °C, respectively. The problem was analyzed with the multi-dimensional fluid component [5], and as shown in Fig. 6, the circulation structure of upward flow along the

inner wall and downward flow along the outer wall, together with the hot thermal stratification in the upper region, was reproduced identically to GAMMA+.

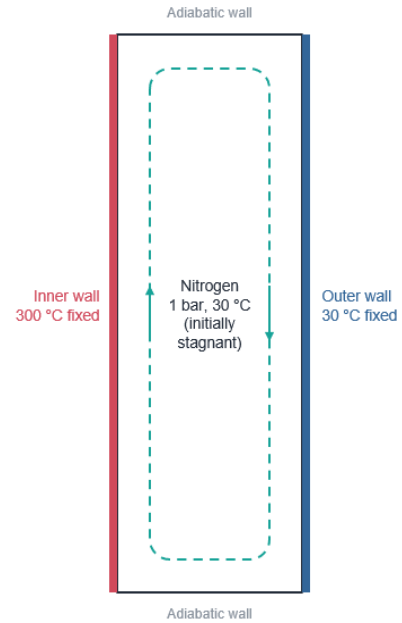


Fig. 6. Initial and boundary conditions of Example 3

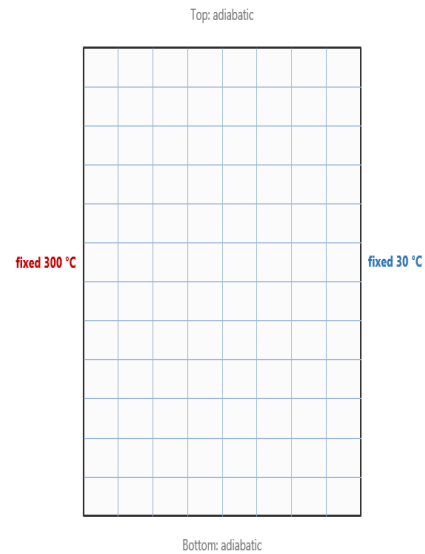


Fig. 7. Nodalization of Example 3

The upward mass flow rate in the inner-wall ring was 13.4 g/s compared with 11.6 g/s in GAMMA+ (+16%), and the downward flow rate in the outer-wall ring was -14.5 g/s versus -11.8 g/s. Also, as shown in Fig. 8, result of flow rate distribution at mid-height of AIR-MARS-gc is different with GAMMA+. In GAMMA+, the datas of flow rates at mid-height are almost zero excluding central wall and outset wall. But in AIR-MARS-gc, the values of flow rate at mid-height are non-zero for whole pipe. Whereas GAMMA+ solves the full two-dimensional momentum equations on the

same grid, the present code uses a ring-column reduction with closure models, so the flow-rate residual is attributed to the difference in multi-dimensional momentum resolution.

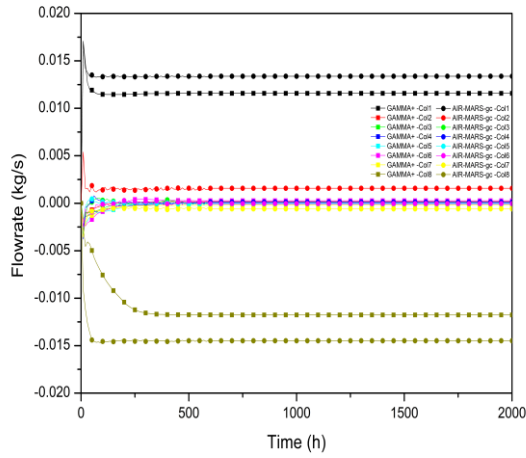


Fig. 8. Flow rate at mid-height in the annulus of Example 3

### 3.4 Example 4: Fuel sphere (pebble) heat-up transient

Example 4 is a transient problem in which a fuel sphere consisting of a 2.5 cm-radius fuel meat and a 3.0 cm Alloy 800H cladding is heated at 2 kW until the heat source is turned off at 50 s, and is then cooled to a 30 °C environment by surface radiation (emissivity 0.8) and different convective coefficients on the upper and lower hemispheres (5/10 W/m<sup>2</sup>K). The computed maximum-temperature history overlaps GAMMA+ over the entire transient: the temperature peak is 1308 °C versus 1314 °C in GAMMA+ (-0.5%), and the heat-up/cool-down time constants and the surface heat removal curve also agree. The evolutions of the maximum and average temperatures are shown in Fig. 9.

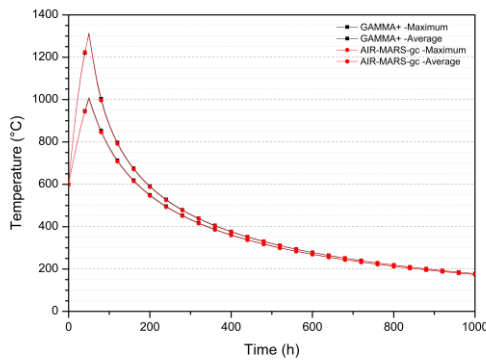


Fig. 9. Maximum and average temperature histories of the fuel sphere of Example 4

### 3.5 Example 5: Prismatic core cooling by conduction

As shown as in Fig. 10, example 5 analyzes the two-dimensional axisymmetric conduction of a prismatic core with multiple radial regions (central heat-

generating graphite column-graphite-ceramic insulator-He gap-steel vessel,  $r = 0.0788/0.2084/0.373/0.375/0.40$  m, height 3.6 m, heating power 2 kW), in which the He gap is treated as radiation-equivalent conduction (emissivity 0.4) and the vessel outer wall rejects heat by radiation to the 30 °C surroundings (emissivity 0.4).

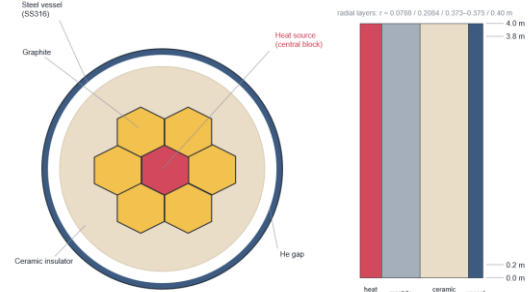


Fig. 10. Geometric data of Example 5

The radial temperature distribution is shown in Fig. 11. The maximum core temperature is 602 °C compared with 608 °C in GAMMA+ (-1.1%), and the vessel temperature agrees at 94 °C; the axially uniform (vertical) temperature profile expected under adiabatic top/bottom boundaries with uniform heating is also reproduced. The radiation-equivalent heat transfer coefficient of the He gap back-calculated from the converged GAMMA+ temperature field (3.64 W/m<sup>2</sup>K) was confirmed to agree with the concentric-cylinder radiation theory (3.65 W/m<sup>2</sup>K). The core temperature residual is judged to originate from the reconstruction error of the temperature-dependent thermal conductivity of the ceramic insulator.

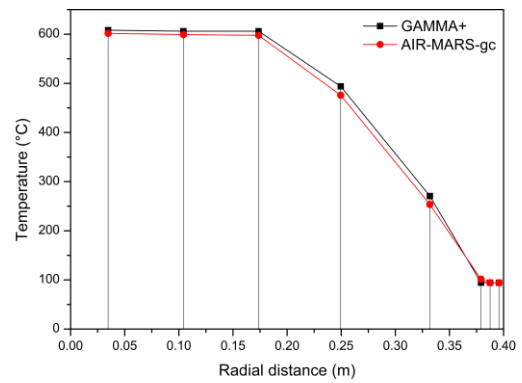


Fig. 11. Radial temperature distribution of the prismatic core of Example 5

### 3.6 Summary of the example problem results

The results of the example problems are summarized in Table 3.

Table 3. Summary of result of example problems

|     | Criteria                                  | GAMMA+      | AIR-MARS-gc | Error       |
|-----|-------------------------------------------|-------------|-------------|-------------|
| Ex1 | Convergence flowrate                      | $\approx 0$ | $\approx 0$ | -           |
| Ex2 | Temperature of outlet and center position | 496/871     | 500/886     | -0.7%/-1.6% |
| Ex3 | Flowrate in cavity                        | +11.6       | +13.4       | +16%        |
| Ex4 | Maximum Temperature                       | 1314        | 1308        | -0.5%       |
| Ex5 | Maximum Temperature in Core               | 608         | 602         | -1.1%       |

#### 4. Conclusions

In this study, a thermal-hydraulic analysis code for HTGR regulatory audit, AIR-MARS-gc, was developed by applying a generative AI-based development workflow, and preliminary verification was performed with five GAMMA+ example problems representing pipe flow, real-gas convection, multi-dimensional natural convection, radiation-coupled transient conduction, and multi-region conduction-radiation.

The temperature indices agreed with the reference solutions within 2%, and energy conservation was confirmed. The residuals in the natural-circulation flow rate (+16%) and in the peak transient flow rate of the piping problem were attributed to the multi-dimensional momentum resolution and to the transient damping characteristics, respectively. The remaining differences between the two codes are attributed to the differences in the material-property models, closure correlations, and modeling approaches. Future work will extend the verification scope to the pebble-bed core benchmark (PBMR-400) and to transient analyses coupled with point kinetics.

#### ACKNOWLEDGMENTS

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