Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 24-25, 2024

CAPP/GAMMA+ Coupled Analysis of Air and Water Ingress Accidents in VHTR-350

Seungsu Yuk*, Nam-il Tak, Hong Sik Lim, Ji Su Jun, Tae Young Han
Korea Atomic Energy Research Institute, 111, Daedeok-daero, 989beon-gil, Daejeon, 34057, Korea
**Corresponding author: syuk@kaeri.re.kr*

***Keywords: VHTR, multi-physics, accident analysis, water ingress, air ingress**

1. Introduction

Very High Temperature Reactor (VHTR) is one of the Generation IV reactors and is gaining attention as a solution for reducing greenhouse gas emissions in the industrial sector. Korea Atomic Energy Research Institute (KAERI) has been conducting research on the design technology of VHTR and is currently focusing on developing design technology for producing high temperature heat above 900°C to improve hydrogen production efficiency.

When designing such very high temperature systems (VHTS), the margin between the maximum fuel temperature and the fuel temperature limit decreases. To overcome this challenge, it is necessary to develop highly accurate design technology. KAERI has been working on improving the accuracy of safety analysis by coupling the safety analysis code GAMMA+ [1] with the core analysis code CAPP [2] to consider more accurate core power behavior. This approach has been developed and applied to secondary loop temperature/ flow fluctuations [3] and depressurized conduction cooldown accident [4].

This study deals with scenarios where external substances ingress into the VHTR during accidents. Air ingress and water ingress accidents involve external substances entering the system, increasing core reactivity or decreasing the loop flow, raising temperatures, and causing chemical reactions with the core structure. This study examines how to apply the coupled calculation method to these two accidents and compares the results of the coupled calculation with those obtained using the conventional point kinetics method.

2. Methods and Models

2.1. CAPP/GAMMA+ for Transient Analysis

KAERI developed the GAMMA+ [1] code to analyze the behavior of VHTRs during accidents such as air ingress accident. GAMMA+ calculates the reactivity and power of the core in transient states using the point kinetics model. However, assuming the core as a point has limitations in accuracy. To overcome this, a method for applying the CAPP/GAMMA+ system to accident analysis was developed [5, 6]. The CAPP code is a core analysis code for VHTRs that can obtain a three-dimensional power distribution and neutron flux in the core. Since CAPP can analyze core behavior in more detail than the point kinetics model, using CAPP/GAMMA+ can provide more accurate safety analysis results.

Fig. 1 shows a schematic of the CAPP/GAMMA+ coupled analysis system. During transient calculations, the CAPP and GAMMA+ codes exchange temperature and power distributions within the core through an intermediate server program called INTCA. In the cases of air ingress and water ingress accidents, GAMMA+ calculates isotope amounts such as hydrogen and oxygen ingress into the core during the accident and sends the isotope distribution data. CAPP receives the isotope distribution data, calculates the region-wise nuclear cross sections, and reflects them in the neutron flux calculations.

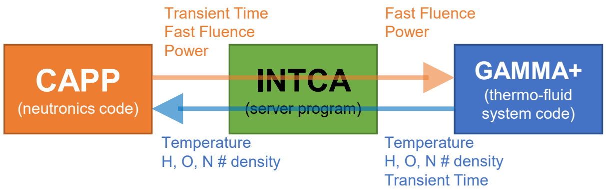

Fig. 1. CAPP/GAMMA+ coupled code system for transient analysis.

2.2. Water Ingress Accident

The following two sections describe the water ingress accident and air ingress accident in a VHTR and the analysis results. We considered VHTR-350 [7] for analyzing the accidents in a VHTR. VHTR-350 has a thermal power of 350 MWth, core inlet and outlet coolant temperatures of 490°C and 950°C, respectively. A printed circuit heat exchanger (PCHE) is used for heat transfer in the secondary system. Fig. 2 shows the core configuration of the VHTR-350.

The water ingress accident scenario assumes that the both side of a tube in the PCHE are broken and 125 kg/s of water enters in the reactor cooling system over 22 seconds. The water ingress increases reactivity, causing the reactor power to rise, which in turn triggers a reactor shutdown signal. In this analysis, the reactor shutdown signal was not considered to observe the increase in reactivity and power due to the water ingress.

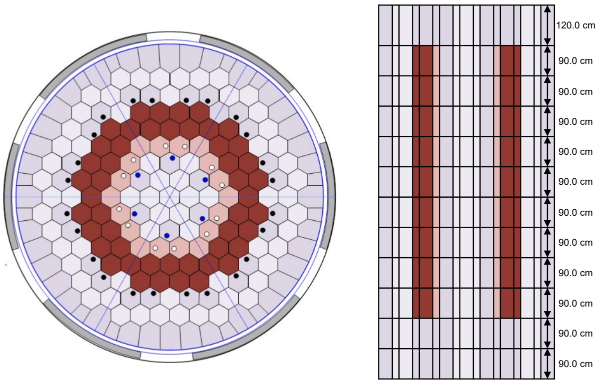

Fig. 2. VHTR-350 core configuration (left: radial, right: axial)

Fig. 3 shows the changes in power during the water ingress accident. As the temperature rises due to the increased power, a negative reactivity feedback effect naturally occurs, lowering the reactor's reactivity. The power, which had been steadily increasing, then decreases and converges to a power level where the net reactivity is zero. In this coupled calculation, a power increase of approximately 20% was observed. Compared to the point kinetics model, the behavior is almost the same, but the peak power level shows some differences. This is because the point kinetics model calculates reactivity in a simplified manner by multiplying the average isotope amounts and reactivity coefficient in the core, whereas the coupled calculation uses the distributed amounts of hydrogen and oxygen in the core, with contributions to reactivity by location due to differences in temperature and isotope amounts. This difference in reactivity calculation results in slightly different converged critical states.

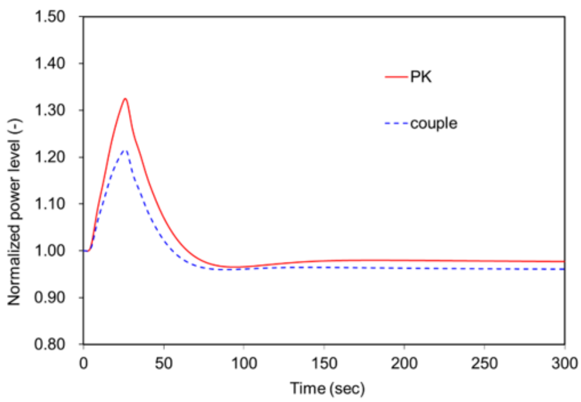

Fig. 3. Reactor power level for water ingress accident.

However, as shown in Fig.4, there is almost no difference in the calculation of graphite corrosion. Primary loop flow rate and pressure are also almost the same for both methods. Because of the difference level of the power, the difference of the maximum fuel temperature is about 10℃.

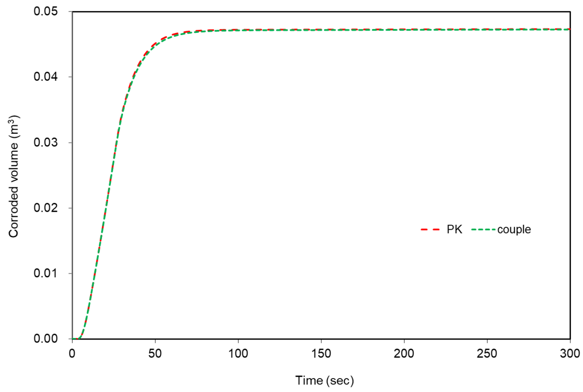

Fig. 4. Graphite corrosion volume for water ingress accident

2.3. Air Ingress Accident

The air ingress accident assumes that both ends of the reactor vessel are broken (chimney break), allowing external air to enter into the system due to the chimney effect. Because the forced circulation is lost, low pressure and low flow rate signals are detected, a reactor shutdown signal is triggered, stopping the helium circulator, but assuming that the control rod shutdown signal fails, preventing the shutdown rods from insertion.

Fig. 5 compares the power level and heat removal in the CAPP/GAMMA+ coupled calculation with the point kinetics model results. When the reactor shutdown signal is triggered, stopping the helium circulator and secondary loop flow, which reduces the flow within the reactor, lowering the reactor's reactivity and making it subcritical. After a few days, as the amount of Xe-135 in the reactor core decreases, the reactor gains positive reactivity, becoming re-critical, and after several power fluctuations, it reaches a new critical state, but at a very low power level. The heat generated at this time is transferred to the heat sink by the inherent characteristics of VHTR (thermal conduction cooling and natural circulation), preventing the reactor temperature from exceeding the fuel temperature limit. Compared to the point kinetics model, the significant difference is the re-criticality time.

Fig. 6 shows the maximum fuel and reactor vessel temperature during the air ingress accidents. Because the coupled calculation predicts the re-criticality after 35 hours, the maximum temperature increases after the re-criticality time.

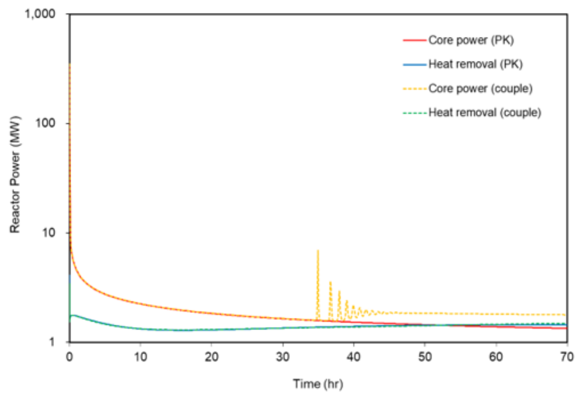

Fig. 5. Reactor power level for air ingress accident.

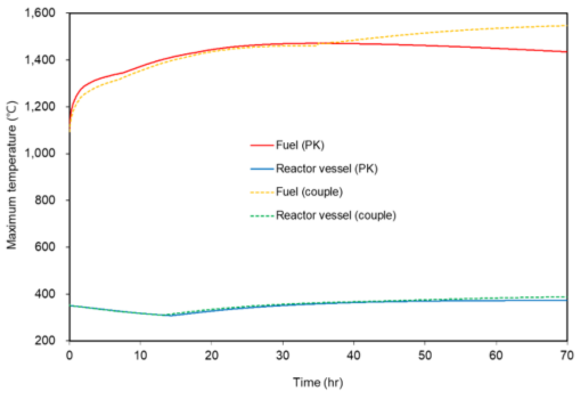

Fig. 6. Maximum temperature for air ingress accident.

4. Conclusions

In this study, we analyzed accidents involving the ingress of external substances into VHTR-350 using CAPP/GAMMA+ coupled code system for accurate safety analysis. For both water ingress and air ingress accidents, we simulated the direct distribution of substances into the core to more accurately calculate the changes in reactivity. Although the point kinetics model appears to overestimate the reactivity changes due to the ingress of external substances, it was confirmed that the maximum temperature limit was not reached during the calculation process, and the trends were similar in both calculations. However, there is a difference in the re-criticality time, with CAPP/GAMMA+ predicting an earlier re-criticality. Further study is needed on this matter.

ACKNOWLEDGEMENTS

This study was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2020M2D4A2067322).

REFERENCES

[1] H. S. Lim, H. C. No, GAMMA Multidimensional Multi-Component Mixture Analysis to Predict Air Ingress Phenomena in an HTGR, Nuclear Science and Engineering, Vol. 152, pp. 87-97, 2006.
[2] H. C. Lee et al., Development of the HELIOS/CAPP code system for the analysis of pebble type VHTR cores, Annals of Nuclear Energy, Vol. 71, pp. 130-144, 2014.
[3] S. Yuk et al., CAPP/GAMMA+ Coupled Transient Analysis for Very High Temperature Gas-cooled System, Transactions of the Korean Nuclear Society Autumn Meeting, Changwon, Korea, October, 20–21, 2022.
[4] S. Yuk et al., Development of Neutronics/Thermo-Fluid Coupled Code System for VHTR Transient Analysis, Proceedings of ICAPP2023, Gyeongju, Korea, April 23-27, 2023.
[5] N. Tak et al., CAPP/GAMMA+ code system for coupled neutronics and thermo-fluid simulation of a prismatic VHTR core, Annals of Nuclear Energy, Vol.92, pp. 228-242, 2016.
[6] S. Yuk et al., CAPP/GAMMA+ Coupled Code System for Transient Analysis of a Block-Type HTGR Core, Proceedings of M&C2019, Portland, Oregon USA, August 25-29, 2019.
[7] S. Yuk, C. K. Jo, A Preliminary Study on 950 ℃ VHTR Core Design, Transactions of the Korean Nuclear Society Autumn Meeting, Changwon, Korea, October, 22–23, 2020.