MARS-GCR/CAPP Coupled Multi-Physics Calculation for the OECD/NEA PBMR-400 Benchmark Problem

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1. Introduction

The OECD/NEA PBMR-400 neutronics/thermal-hydraulics coupled benchmark problem was proposed to test the existing analysis methods for high temperature gas-cooled reactors (HTGRs) and to develop more accurate and efficient tools to analyze the neutronics and thermal-hydraulics (TH) behavior for the design and safety evaluations of the PBMR [1].

Three cases are defined for the steady state phase (Phase I) of the benchmark. The first case of the steady state phase (SS-1) is a neutronics stand-alone case with fixed cross-sections while the second case of the steady state phase (SS-2) is a TH stand-alone case with fixed heat source. The third case of the steady state phase (SS-3) is a TH/neutronics coupled case, which is the initial state of the TH/neutronics coupled cases defined in the transient state phase (Phase II). Six cases are defined for phase II of the benchmark. They are depressurized loss of forced cooling (DLOFC) without SCRAM (TR-1), DLOFC with SCRAM (TR-2), pressurized loss of forced cooling (PLOFC) with SCRAM(TR-3), load follow (TR-4), reactivity insertion by control rod withdrawal (CRW) and control rod ejection (CRE) (TR-5), and cold helium inlet (TR-6).

The final results for the SS-1 and SS-2 have been reported and the preliminary results for SS-3, TR-5a, TR-5b and TR-6 have also been reported in our previous work [2,3,4]. In this paper, we present our final results for SS-3, TR-3, TR-5a, TR-5b, and TR-6 of the benchmark problem and they are compared with those of other participants.

2. Methods and Results

MARS-GCR [5] code and CAPP code were coupled through a dynamic link library (DLL). MARS-GCR plays the role of main program and CAPP is called as a subroutine in the coupled code system. Each material zone defined in the benchmark problem was used as a mesh in MARS-GCR calculation while each material zone was divided into 5x5 sub-meshes in the CAPP finite difference analysis.

2.1 Coupled Steady State Results

Figure 1 compares the effective multiplication factors and the maximum power densities reported by the participants. The results of MARS-GCR/CAPP code are similar to those of PARCS/THERMIX, TINTE, and DORT/THERMIX.

Figure 2 shows the radial moderator temperature distributions of the participants. There are relatively large differences and we can find that MARS-GCR/CAPP gives the steepest temperature gradient at the inner region of the core. On the contrary, however, there were relatively small discrepancies in axial temperature distributions.

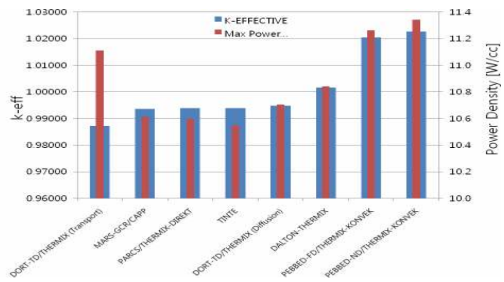

Fig. 1. Maximum power density and k-eff in SS-3

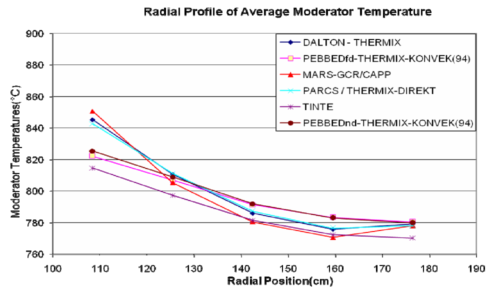

Fig. 2. Radial moderator temperature distribution in SS-3

2.2 Coupled Transient State Results

The inlet helium mass flow reduces from the nominal value to zero over 13 seconds and then all the control rods are inserted over 3 seconds in TR-3. Figure 3 shows the moderator temperatures during the transient. The moderator temperatures increase due to the decay heat and then eventually they decrease slowly due to the increase of heat loss through the reactor vessel surfaces. The result of MARS-GCR/CAPP code agreed with that of TINTE code while DALTON-THERMIX code predicted rather faster cooling of the system.

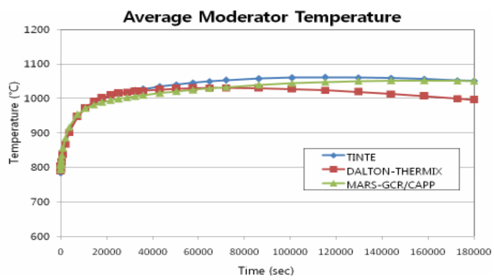

Fig. 3. Moderator temperatures in TR-3

All the control rods are withdrawn at the speed of 1cm/sec until 200sec in TR-5a. A rapid power increase at the beginning of withdrawal, a rapid power decrease at the end of withdrawal, and a slow power increase between the two periods were observed. These phenomena can be explained by the following prompt jump approximated point kinetics equation with one delayed neutron precursor [6] :

$$\dot{p}(t) = \frac{\lambda\rho + \dot{\rho}}{\beta - \rho}\, p(t) \cdot \qquad (1)$$

$\dot{\rho}$ jumps up to a finite value from zero at the beginning of the withdrawal and it jumps down to zero from the finite value at the end of withdrawal and these jumps are the cause of the rapid increase and the rapid decrease of the reactor power. The fluctuations during the slow power increase imply that the cusping effect reduction method given in the benchmark specification is not adequate for the prevention of the cusping effect.

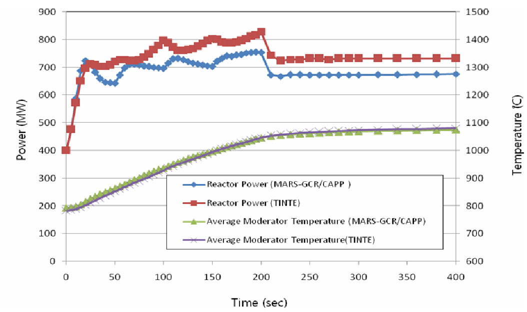

Fig. 4 Powers and moderator temperatures in TR-5a

All the control rods are ejected in 0.1 seconds from the core in TR-5b. The reactor power increases rapidly and decreases again due to the temperature feedback. However, the peak value of MARS-GCR/CAPP code calculation is almost nine times larger than that of TINTE code calculation in figure 5. It is ascribed to the fact that the MARS-GCR code has no explicit kernel model. MARS-GCR assumes that the fueled zone of a pebble is a homogeneous mixture of graphite and fuel materials. The explicit kernel model implemented in TINTE code treats the fuel kernel and the coating layers explicitly to obtain the fuel temperature. With the explicit kernel model, the fuel temperature in the TINTE code calculation increases much earlier, which prevents a huge peak in the reactor power.

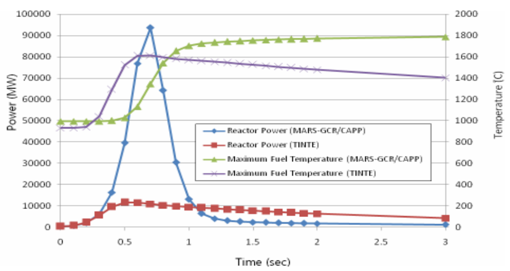

Fig. 5. Powers and fuel temperatures in TR-5b

The inlet helium temperature decreases by 50°C over 10 seconds and it increases to the original value over 10 seconds from 300 seconds. Figure 6 shows the reactor powers and the fuel temperatures in TR-6. The cold inlet helium cools down the moderator and fuel temperatures, which causes an increase in the reactor power untill 300 sec. The hot inlet helium heats up the moderator and fuel, which causes a decrease in the reactor power again. The results of the MARS-GCR/CAPP code agree well with those of the DALTON/THERMIX code. It seems that something is wrong in the TINTE calculation because there is no good reason why the reactor power increases again after a long time. The reactor power should eventually decrease and return to the initial power when the Xe consumption during the high power period is recovered.

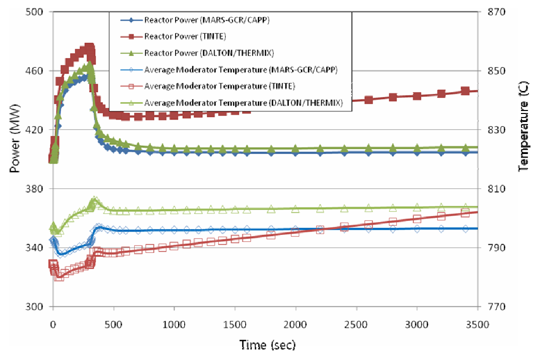

Fig. 6 Powers and moderator temperatures in TR-6

3. Conclusions

In this paper, we presented our final results for the OECD/NEA PBMR-400 neutronics/TH coupled benchmark problem. All the results except for TR-5b were reasonable and agreed with those of other participants. The huge peak of the reactor power in TR-5b is ascribed to the fact that the MARS-GCR code has no explicit kernel model and an explicit kernel model is crucial for an accurate analysis of a fast transient.

REFERENCES

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