A Preliminary Study on 950 °C VHTR Core Design

Seungsu Yuk* and Chang Keun Jo
Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Daejeon, 34057, Korea
**Corresponding author: syuk@kaeri.re.kr*

1. Introduction

Very High Temperature gas-cooled Reactor (VHTR) is one of the promising hydrogen production methods and is expected to supply a massive amount of high-temperature heat economically. To produce hydrogen efficiently, the coolant outlet temperature should be sufficiently high, e.g. 950 ℃. However, the high temperature condition reduces the safety margin of reactor core design and it makes the VHTR core design a challenge.

In this paper, we presents a preliminary study on a 950℃ VHTR core design. Based on the previous study for decreasing power peaking factor [1], a two-dimensional core is designed. A three-dimensional core analysis is also provided and it shows that this VHTR core satisfies the design limit of maximum fuel temperature.

2. Methods and Results

2.1 Basic Reactor Core Specification

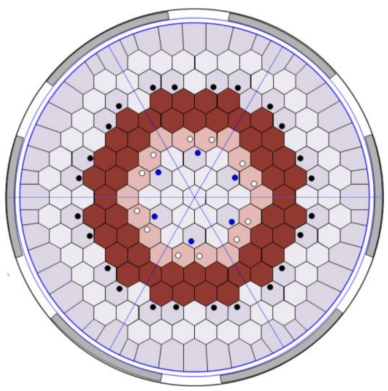
Korea Atomic Energy Research Institute (KAERI) has developed VHTR design technologies in recent years. KAERI has focused on a block-type VHTR. Compared to the pebble-type VHTR, the limit of thermal power is large and it is easy to trace nuclear materials.

This paper describes a 950℃ VHTR core design based on the MHTGR-350 [2] and PMR200 [3]. Table I shows the major design parameters of a 950℃ VHTR core. Total thermal power is 350 MWth and coolant inlet/outlet temperatures are 490/950℃.

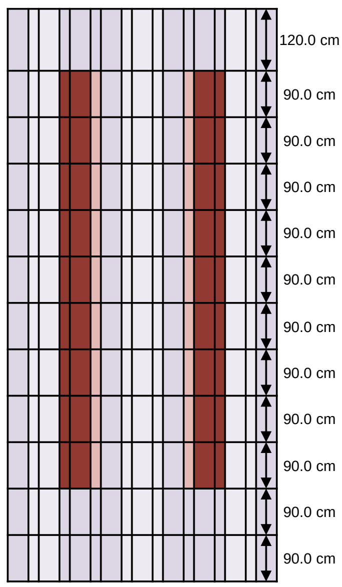
Table I: A 950 ℃ VHTR Core Design Parameters

Parameter	Values
Thermal power (MWth)	350
Coolant inlet temperature (℃)	490
Coolant outlet temperature (℃)	950
Coolant pressure (MPa)	7
Active core height (cm)	810
Number of fuel columns	66
Number of axial fuel block layers	9
Top/bottom reflector height (cm)	120 / 180
Fuel block height (cm)	90
Block pitch (cm)	36.1
Nuclear fuel material	UO_2
U-235 enrichment (w/o)	≤15.5
Burnable absorber material	B_4C
TRISO kernel diameter (μm)	500
Core power density (W/cm^3)	5.83

Fig. 1 shows the core configuration. The colored hexagonal blocks are nuclear fuel blocks and the gray hexagonal blocks are reflector blocks. The other outermost gray blocks are permanent reflector blocks. The annular core consists of 66 fuel columns and a fuel column consist of nine fuel blocks. There are graphite reflectors inside and outside the annular active core. The circles in the reflector blocks are control rod (CR) holes (24 operating CRs at outer reflector, 6 start-up CRs at inner reflector). Twelve circles in the fuel blocks are reserved shutdown control system (RSC) holes. The blocks with these holes are arranged so that the core is 1/6 symmetric.



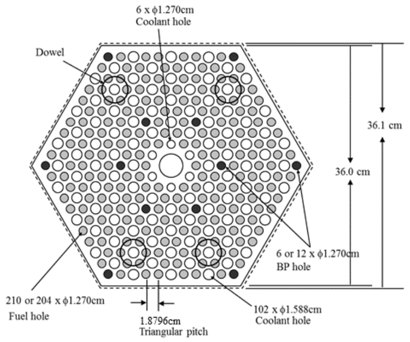
(a) Radial cut view



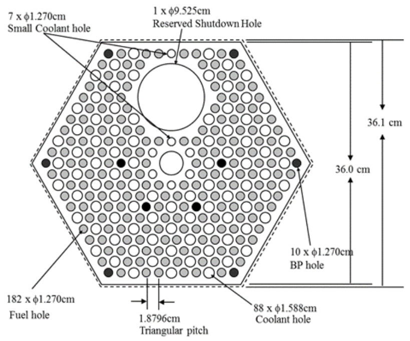
(b) Axial cut view

Fig. 1. A 950℃ VHTR core model

Fig. 2 shows the radial configuration of fuel blocks. These blocks are similar to the MHTGR-350, PMR200 fuel blocks. Compared to MHTGR-350 fuel blocks, more burnable absorber compacts are added in the middle region to control the excess reactivity at the beginning of cycle.



(a) Standard fuel block



(b) RSC fuel block

Fig. 2. Radial configuration of fuel blocks

2.2 Two-Dimensional Reactor Core Model

In the VHTR core design, the maximum fuel temperature should be less than 1250 ℃ in the normal operation to prevent the damage of TRISO fuel particles. The radial pin power peaking factor (RPPF) should be limited to satisfy the above requirement. In the previous study [1], the radial pin power peaking factor should be less than 1.4 when the coolant outlet temperature is 950 ℃. On the other hand, the axial power peaking factor is less important than RPPF because there is no safety issues about vaporization of coolant like the conventional pressurized water reactors.

In the previous study, several core models are provided to decrease RPPF: 2-ring model with reduced block size, and 3-ring model with enrichment zoning. This study selected a 3-ring model with enrichment zoning. To improve the RPPF, more aggressive enrichment zoning is applied to the two-dimensional core model. Fig. 3 is the two-dimensional core model and the fuel-loading pattern. All fuel compacts has the same packing fraction, 30%. On the other hands, 5~15.5 wt% enrichment zoning is applied. The U-235 enrichment of fuel is higher as it is closer to the middle fuel blocks and lower as it is closer to the reflector blocks. Different weight fractions of B_4C and radii of burnable absorber regions are also used for power flattening.

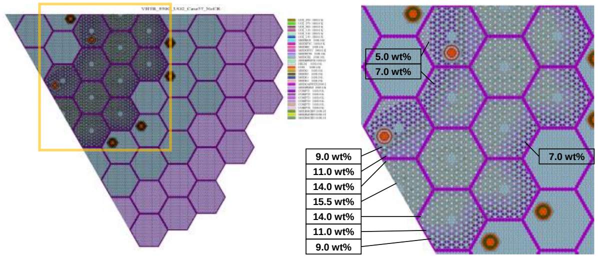


Fig. 3. DeCART2D [4] core model and fuel loading pattern

Table II shows the numerical results of DeCART2D [4] calculation for this 2-D 950 ℃ VHTR core model. RPPF is 1.3050, which satisfies the requirement of the VHTR core design. Fig. 4 shows the relative pin power distribution of 2-D core model. It shows that the power distribution is flat enough.

Table II: Summary of DeCART2D Calculation

Parameter	Value
UO_2 enrichment (w/o)	5 ~ 15.5
Packing fraction (%)	30
Temperature (℃)	726.85
Results	Value
Multiplication factor	1.04214
Radial power peaking factor (Block)	1.0322
Radial power peaking factor (Pin)	1.3050

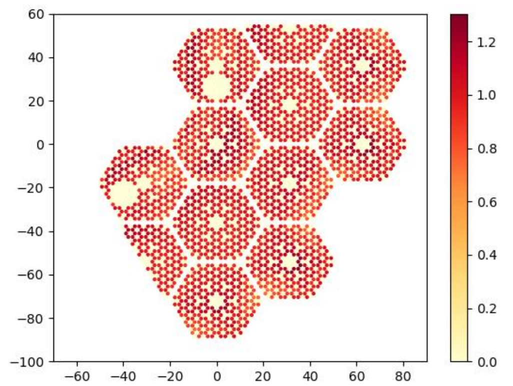


Fig. 4. Pin power distribution of 2-D core model

2.3 Three-Dimensional Reactor Core Calculation

By the DeCART2D/CAPP code system [5, 6], three-dimensional block-type VHTR core can be analyzed. DeCART2D calculation for 2-D core model produces the block-wise homogenized group constants for CAPP.

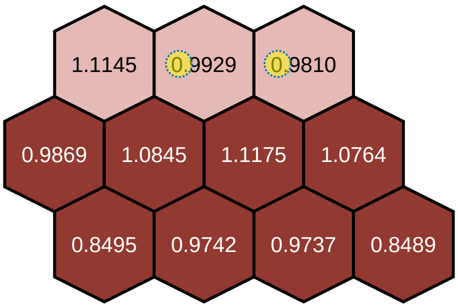
When the branch calculations of DeCART2D with temperature variation are performed, CAPP can provides both the 3-D power and temperature distribution.

Table III shows the numerical results of 3-D CAPP calculation for the 950℃ VHTR core. The steady-state calculation with the critical control rod position (half of the operating CRs are inserted into the middle of core) is performed. The maximum fuel temperature is 1226.01 ℃. It does not exceed the design limit, 1250℃.

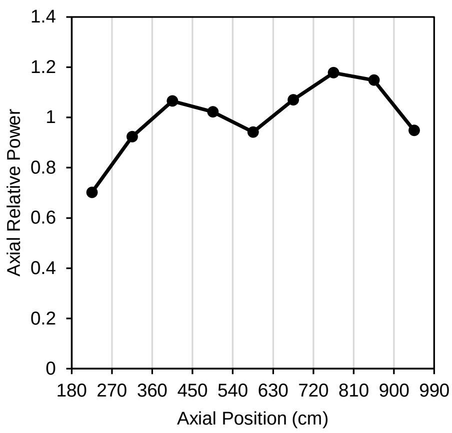
Fig. 5 shows the power distribution of the 950℃ VHTR core. The radial block power peaking factor is larger than that of the DeCART2D calculation due to temperature feedback and control rod position. Because some of control rods are inserted to the middle of core, the graph of the axial power looks like M-shape. The coolant flows downward, so the upper part is cooler and the power is higher.

Table III: Summary of CAPP Calculation

Results	Values
Multiplication factor	1.00002
Axial offset (%)	7.14
Radial block-wise power peaking factor	1.1175
3-D pin power peaking factor	3.249
Average fuel temperature (℃)	839.22
Maximum fuel temperature (℃)	1226.01



(a) Radial power distribution



(b) Axial power distribution

Fig. 5. Block-wise power distribution of 3-D core model

3. Conclusions

This paper presents a 3-D 950℃ VHTR core model, which satisfies the requirement of VHTR core design. Based on the MHTGR-350 reactor core, the enrichment zoning is used to decrease the radial pin power peaking factor. DeCART2D calculation shows that the 2-D core model achieves the requirement of RPPF. Using the 2-D calculation, 3-D core model is constructed and analyzed by CAPP. It shows that the 3-D core model satisfies the design limit of maximum fuel temperature. Therefore, it is expected to perform the VHTR core design based on this model. However, because the maximum fuel temperature is close to the limit, it seems necessary to find a more optimized core model. On the other hand, the depletion calculation is another obvious future work.

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REFERENCES

[1] T. Y. Han and H. C. Lee, "A Study on the Core Design for Decreasing the Power Peaking Factor in a VHTR Core," Transactions of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, October, 29–30, 2015.
[2] J. Ortensi et al., Benchmark of the MHTGR-350 MW Core Design. Volumes I and II, NEA/NSC/R(2017)4, Nuclear Energy Agency, 2017.
[3] H. C. Lee et al., "Decay Heat Analysis of VHTR Cores by Monte Carlo Core Depletion Calculation," Annals of Nuclear Energy, Vol. 37, pp. 1356–1368, 2010.
[4] J. Y. Cho et al., DeCART2D User's Manual, KAERI/TR-5116/2013, KAERI, 2013.
[5] H. C. Lee, C. K. Jo, and J. M. Noh, "Development of CAPP Code Based on the Finite Element Method for Analysis of VHTR Cores," Proceedings of HTR2008, Washington, DC, USA, September 28–October 1, 2008.
[6] S. Yuk et al., "Improvement of the DeCART2D/CAPP Code System for Prismatic VHTR Cores," Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May, 17–18, 2018.