COMPARISON OF FUEL LOADING PATTERN IN HTR-PM

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ABSTRACT: In order to maintain the inherent safety feature of the modular high temperature gas-cooled reactor (MHTGR) and to further increase the economic features by increasing the power of each module, this paper compares three different fuel loading patterns of pebble bed core of same outer dimension, namely the 1-zone core, 2-zone core whose inner zone is filled with high burnup fuel balls, and 2-zone annular core whose inner zone is filled with graphite balls. It can be shown from calculation result that the inner graphite zone is very effective to decrease the maximum fuel temperature after accident, or to say to increase the total power if maintaining the same reactor dimension and same temperature limit.

KEYWORDS: Modular High-Temperature Gas-cooled reactor(MHTGR), fuel loading pattern, maximum fuel temperature, decay heat.

0. INHERENT SAFETY OF MODULAR HTGR AND INCREASE OF THE REACTOR POWER

As the world economy is increasing continuously, but the energy supply from natural resources such as oil, coal and etc are limited, and the green house gas release problem because very serious, the nuclear power becomes inevitable. And the safety and economy are two key factors for the development of the nuclear power.

From the viewpoint of the safety, comparing to other type of nuclear reactors, modular high-temperature gas-cooled reactor (MHTGR) has obvious advantages because of its inherent safety features, such that the residual (decay) heat can be removed from the core passively, and the maximum fuel temperature will never exceed famous 1600°C under any designed accident conditions, and without any active safety system. Therefore the fission product will never released to environment under any case, as the SiC layer of TRISO fuel kernel in MHGTR will contain all fission products. Most famous MHTGR designs are the 200MWth HTR-MODUL [1], a pebble bed core designed in Germany, and 350MWth prismatic MHTGR designed in USA.

But the inherent safety features is achieved in the cost of constrain on the core design. In order to achieve the inherent safety, only choice is to reduce the decay heat itself or remove them quickly out from the core, that’s to say to constrain the power density(to reduce the decay heat production) and to limit the core shape and size (to conduct the decay heat out of the core faster).

Taking HTR-MODUL, a pebble bed core with multiple pass of the fuel balls, as an example. In order to achieve the inherent safety, the active zone of core is designed as a slender cylinder of height 9.43 meters and diameter of 3 meters, and the power density is limit to 3 MW/m3, therefore the thermal power output of this reactor is limited to 200MW.

Now the market is very sensible to the economic property of the reactor. This 200MWth HTR-MODUL design is very success from the point view of safety. But the reactor power is somewhat small, although it provides more flexibilities for market and economic possibility because a power plant can contain multiple modules via batch and standard construction. The economic property of the reactor is very sensitive to the total power, because the economy/cost is evaluated in the unit of output power, and the cost of some systems are not directly proportional to the power, or only related to the number, not the size of the system.

As well known, the annular core configuration, as adopt by Chinese HTR-PM (pebble bed core) design, South African PBMR (pebble bed core) design, and US MHTGR (prismatic core) design, can increase the total power of each MHTGR module while maintaining the inherent safety, aimed to improve the economic features. Inside the annular active zone, the inner core zone is made of movable graphite balls or fixed graphite column. In this case, the decay heat in the outer annular active zone can be conducted to both the outer graphite reflector, then to ultimate heat sink through the residual heat removal system, and to the center cooler graphite zone, so the maximum temperature in the outer fuel zone can be reduced.

Of course, the annular core also arises some new problems. Taking pebble bed core as an example, it is difficult to maintain the boundary between the central movable graphite ball zone and outer fuel zone, and it is expensive to replace the central fixed graphite column after several tens years of reactor operation. As a result, a special 2-zones core configuration is proposed, whose center part is filled with fuel balls of higher burnup, instead of the pure graphite balls.

This paper will compare the properties of these three core configurations, or fule loading patterns, namely the one zone pebble bed core (pattern 1), the 2-zones core whose inner zone is made of higher burnup balls (pattern 2), and the 2-zones annular core whose inner zone is made of pure graphite balls (pattern 3), based on the detailed nuclear design for these three core.

1. THREE MODELS COMPARED

For these three fuel loading patterns, detailed nuclear models are setup. In order to make the comparison of the properties of these three patterns straightforward and meaningful, three models have same assumption and some common parameters as following.

First, three patterns are all pebble bed core, they all are pebble bed core, which are very similar to the core configuration of HTR-MODUL. The fuel ball will pass the core ten times, and final 10% highest burnup balls will discharged from the core, the fresh fuel balls will put to the core, and mixed with other middle burnup fuel balls to pass the core.

Second, the outer dimension of the active zone is same, the equivalent height of the active zone is 9.43 meters, outer diameter of the active zone is 4 meters.

Thirdly, the temperature of the inlet helium and outlet helium from the core maintain the same, namely the 250°C and 750°C.

The basic parameters of these models can be shown in Table 1.

These models are analyzed by VSOP package[2], which is developed by Juelich, Germany. VSOP package treat following special character of pebble bed high temperature reactor very well: 1) Double

heterogeneous of the fuel element, 2) Neutron stream effect, 3) Top void cavity above the active zone, 4)Buckling feedback in spectrum calculation, 5) The movement and shuffling of the pebble bed. This package is adopted in the nuclear design of 10MW High temperature gas cooled test reactor (HTR-10), and is proven successful in the predication of initial loading of HTR-10[3].

Table 1 Common nuclear parameter for three patterns

Parameters	Values
Height of the core (cm)	943
Outer diameter of the core(cm)	400
Core volume(m^3)	118.5
Height of top void /cm	50
Thickness of side graphite reflector (cm)	75
Density of reflector graphite(g/cm^3)	1.76
Thickness of outer boric carbon brick (cm)	25
Density of carbon brick(g/cm^3)	1.59
Percent of B_4C in Carbon brick (%)	5
Average burnup for discharged fuel(MWd/tU)	80000
Helium inlet temperature(°C)	250
Helium outlet temperature (°C)	750
Number of pass for fuel ball through the core	10
Filling factor of the fuel ball	0.61
Diameters of fuel ball (cm)	6.0
Diameter of fuel zone in fuel ball (cm)	5.0
Uranium load in fresh fuel ball (g)	7.0

And the difference of three fuel loading pattern can be described as following. The fuel pattern 1, which adopt the single fuel zone with multiple pass, just as the case in HTR-MODUL. The fuel loading pattern 2, the fuel zone is divided into two zones, outer annular zone is filled with multiple pass pebble, but with low burnup fuel balls and fresh fuel balls, and inner fuel zone of diameter 2 meters is filled with other higher burnup balls. And the burnup level of fuel balls out from the outer zone will be checked, the balls whose burnup is lower than 75% of design burnup will return to outer zone again, and the balls with higher burnup will put into inner zone for next turn of pass in the core. For the fuel loading pattern 3, the inner zone of diameter 2 meters is filled with pure graphite balls, and the outer zone is filled with fuel balls which is the mixing of all batchs of different burnup fuel

balls (except the ball whose burnup reached design level) and fresh balls. The boundary between the inner zone and outer annular zone is maintained by the natural movement of the pebble bed, and is treated as straight for this theory analysis.

2. THE COMPARISON OF THREE FUEL LOADING PATTERNS

In order to compare the property of three different fuel loading patterns in different viewpoint, two results are presented.

In the first case, same power level, namely 380MW, is assumed for all three patterns. The result of final equilibrium core is shown in Table.2. It can be shown that the maximum fuel temperature under loss of coolant and loss of pressure accident for three model is 1845°C, 1745°C, 1515°C respectively.

Table 2 Comparison of three patterns under reactor power of 380MW

Fuel loading pattern	Pattern 1	Pattern 2	Pattern 3
Core configuration	1-zone	2-zones with different burnup	2-zones with fuel and graphite
Reactor power (MW)	380	380	380
Enrichment of fresh fuel balls(%)	7.29	7.44	8.765
Maximum power density(MW/m^3)	6.891	6.166	9.754
Maximum operating fuel temperature (°C)	954.4	868.7	1031.5
Maximum accident fuel temperature (°C)	1845.10	1745.20	1515.63

And the power density distribution along the radium in the middle axial plane can be shown in Fig.1.

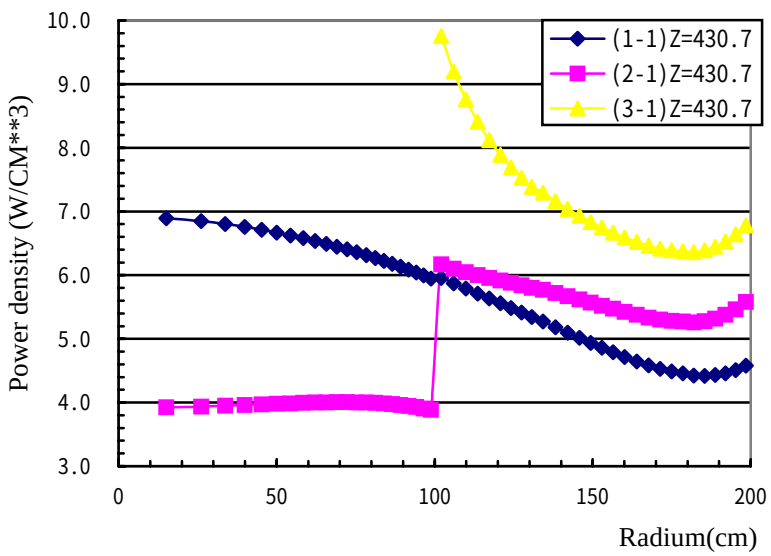

Fig.1 Power density distribution along radium in the middle axial plane for three patterns in 380MW

If the maximum fuel temperature under the accident of loss of coolant and loss of pressure is limited to same 1515°C as shown in pattern 3 in Table 2, the maximum power level can achieved for each fuel loading pattern is listed in Table 3, as seen 253MW, 289MW, 380MW respectively.

For both cases, it can be seen from the calculation result that the annular core of fuel loading pattern 3 is very effective to reduce the maximum accident fuel temperature for same power level and same core dimension, or in another word, it is very effective to increase the power level for same maximum accident fuel temperature. And the power level reached by 1-zone pattern is lowest, and the pattern 2 is ranked as middle. But for the enrichment requirement and maximum operating fuel temperature, the rank is different for these three patterns, as shown in Table 2 and Table 3.

Table 3 Result of three patterns if constrain the maximum accident fuel temperature to 1515 ℃

Fuel loading patters	Pattern 1	Pattern 2	Pattern 3
Core configuration	1-zone	2-zones with different burnup	2-zones with fuel and graphite
Number of fuel balls in core	639144	639144	479358
Number of graphite balls in core	0	0	159786
Maximum reactor power(MW)	252.8	289	380
Enrichment of fresh fuel balls(%)	7.21	7.38	8.765
Maximum power density (MW/m^3)	4.559	4.674	9.754
Maximum operating fuel temperature (°C)	957.2	869.7	1031.5
Maximum accident fuel temperature (°C)	1515.34	1515.81	1515.63

3. DISCUSSION

The purpose to compare three different fuel loading pattern is to verify how to increase the power level of each MHTGR module and finally to increase the economy features of MHTGR while maintaining the inherent safety features.

From the viewpoint of increasing the total reactor power of one MHTGR module, the annular core, namely the fuel loading pattern 3 in this paper, is most effective. It is well known in HTR researchers and can be easily explained as following.

If reactor shutdown after constantly operating at power P for T2 seconds, the decay heat of the reactor in the time of t1 seconds after shutdown can be approximated as:

Pd(t1,T2) = 4.1E11*P*(t1**(-0.2)-(t1+T2)**(-0.2)) MeV/s

That’s to say the decay heat will decrease very fast along time. The maximum fuel temperature under

accident condition can be reduced if the decay heat is conducted from the core in the early stage will be more effective.

For fuel loading pattern 1, the maximum power density is located in the center of the core, therefore, the maximum decay heat will also locate in center of the core, but this decay heat can be conducted only from there through outer zone of the core, therefore, the maximum fuel temperature will produced in the center of the core. For the loading pattern 2, the inner zone of the core is filled with high burnup ball, the power density will be much lower than outer zone because the fission nucleus is less than that in outer zone, therefore the decay heat in inner zone will be much lower than the outer zone, and maximum fuel temperature after accident will be lower than that for fuel loading pattern 1 for same reactor dimension and reactor power level. For fuel loading pattern 3, the power and decay heat in inner graphite zone will be zero, and the initial temperature in inner graphite zone will be much lower than the fuel zone after shutdown of reactor, therefore the decay heat in outer fuel zone can be conduct to outer graphite reflector and inner graphite zone, especially in the early stage when the decay heat is relatively large and the temperature in inner graphite zone is relative low. Therefore the maximum accident fuel temperature will be much lower than fuel loading pattern 1 and fuel loading pattern 2.

And this annular core can be further improved [4], to increase the outer diameter of the active zone, for example 22 meters, and to maintain the thickness of the annular active zone, for example 2 meters, therefore to increase the power level of each reactor to much larger number, for example 3000MWth, while maintaining the inherent safety features of MHTGR principle. In this case, inside the annular active zone, the (inner) graphite reflector and residual heat removal system can be equipped.

Of course, in order to optimize the overall economic feature and operation performance of the MHTGR, many other factors must also be taken account of, although this paper concerns only the fuel temperature and power level. For example, the fuel cost (related to the enrichment and number of fuel balls), the engineering feasibility (for example how to maintain the boundary of inner movable graphite ball zone or how to replace the inner fixed graphite column, for the case of annular core), the detailed economic analysis on the final design, the control rod worth, the physical and thermo-hydraulic stability of larger reactor. The discussion of these factors is out of the scope of this paper, but they are very important for the practical design of a nuclear power plant.

4. CONCLUSIONS

Modular high temperature gas-cooled reactor is very success in its inherent safety, but the power is limited to certain level. If the power of each reactor can further increase, while keeping the inherent safety feature, the economic features can be further improved. Starting from the basic 1-zone pebble bed core configuration, annular core with inner zone filled with graphite, and a compromised annular core whose inner zone is filled with higher burnup fuel balls, are proposed and analyzed. This paper compares the reasonable reactor power, or maximum accident fuel temperature, and other physical design result for these three core configurations, or fuel loading patterns, while keeping the outer dimension of the core same, and keeping the inherent safety requirement same. It can be shown that the annular core whose inner zone is filled with graphite balls is very effective to reduce the maximum accident fuel temperature, and to increase the reactor power for same dimension of the core. It is also shown that the 2-zone core, whose inner zone is filled with fuel balls of higher burnup, is also

somewhat effective to reduce the maximum accident fuel temperature, while the number of fuel balls, the discharging fuel ball burnup, and many configurations keep same, so it is feasible for engineering design. This analysis can provide some information for future MHTGR design.

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