Ordered Bed Modular Reactor design proposal

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Abstract

The Ordered Bed Modular Reactor (OBMR) is a design as an advanced modular HTGR in which the annular reactor core is filled with an ordered bed of fuel spheres. This arrangement allows fuel elements to be poured into the core cavity which is shaped so that an ordered bed is formed and to be discharged from the core through the opening holes in the reactor top. These operations can be performed in a shutdown shorter time.

The OBMR has the most of advantages from both the pebble bed reactor and block type reactor. Its core has great structural flexibility and stability, which allow increasing reactor output power and outlet gas temperature as well as decreasing core pressure drop. This paper introduces ordered packing bed characteristics, unloading and loading technique of the fuel spheres and predicted design features of the OBMR.

KEYWORDS: HTGR, VHTR, Ordered bed, Power distribution, Temperature distribution, Pressure drop

1. Introduction

The Very High Temperature Reactor (VHTR) as a Generation IV reactor concept has been recognized a most promising technology for high efficiency electricity generation and high temperature process heat applications including hydrogen production. The VHTR concept is required to produce an outlet gas temperature at around 1000 °C, in order to improve the economic performances, e.g. thermodynamic cycle and hydrogen processes efficiency [1].

A reference reactor concept of the VHTR has a 600 MWth helium cooled core based on either the prismatic block fuel of the Gas Turbine–Modular Helium Reactor (GT-MHR) or the pebble fuel of the Pebble Bed Modular Reactor (PBMR) [2,3].

The two very different fuel elements, the pebble type element and the block type element, gave rise to very different modular reactor designs, which are quite distinct from each other in the reactor performance.

The modular HTGR designs predicted the maximum thermal power level of the pebble bed reactor (PBR) is less than that of the block type reactor (BTR) in the bulk limit of the modular annular reactor core. Because the pebble fuel spheres move merely from top to bottom in the core,

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which cannot provide a relative uniform power distribution in axial direction. In addition, since the modular core form is long and slender and coolant vertical flow through the long core filled by stochastic pebble balls, there is a very high pressure drop across the core. Thus maximizing the thermal power output and the net generating electricity efficiency cannot be achieved in the PBR [4-6]. The core design of the commercial demonstration reactors predicted the maximum thermal power level of 400MW for the PBMR and 600MW for the GT-MHR.

Although the continuous refueling of the fuel spheres is in favor of neutron economy in the PBR, it has relatively less effect on the generating electricity cost than that of the factors of the power size and generating electricity efficiency.

But then, the PBR has many advantages compared with BTR. The pebble fuel elements have a single enrichment and a single coated particle design, and give a simple core design. The manufacture of pebble fuel lends itself ideally to mass production with low costs. The each discharged fuel sphere could be assayed for burn-up and identified to reuse or to discharge to the spent fuel storage. Thus the low fuel element costs and optimization of fuel utilization are achieved.

The spherical elements have good shape stability, but prismatic fuel blocks are exposed to different neutron fluences and temperatures that will result in distortions in different blocks of varying degrees. The fuel handling system for a BTR must be able to shuffle fuel axially and radially, and all the fuel unloading and loading operations must be carried out under shielded conditions using remote handling equipments. The pebble fuel elements can be transported in shielded ducts with similar fuel spherical diameter using simpler core refueling mechanisms.

This paper offers a design proposal presenting a novel reactor core design in order to overcome the shortcomings of existing core designs and possess these main advantages of both PBR and BTR. The design proposal features that the annular reactor core cavity is filled with an ordered bed of fuel pebbles, named Ordered Bed Modular Reactor (OBMR), which could be a more promising technology for the VHTR.

2. Ordered Bed Modular Reactor Concept

2.1 Ordered Bed Core Description

The ordered beds are packed in a rhombohedral geometry in which the unit cell layer is formed by four spheres lying at the corners of a square, and the individual spheres in subsequent layers fill the cusps formed by them (Fig.1) [7,8]. The closest center-to-center spacing of spheres in each layer is selected as 1.167 sphere diameters in this design, i.e. the spacing is 70 mm since graphite spheres diameter is 60 mm (Fig.2). This horizontal sphere spacing allows the bed to compensate the core cavity horizontal dimension difference and the sphere diametric difference as great as 5% without becoming disordered. Channels are formed between the spheres in the ordered packing and continuous through the entire bed.

The core cavity of the ordered bed has properly oriented a graphite bottom and sidewalls. The bottom must be oriented on flat graphite support surface with suitably spaced countersunk holes. The graphite sidewalls must be in parallel with the unit cell layer or its diagonals. The annular core of the modular HTGR must be designed to become an octagonal cross section to adapt for filling with ordered packing of fuel spheres (Fig.3). The annular core could also be designed to become a quasi-circular cross section composed by the polygon. The octagonal core cavity will permit the formation of an absolutely ordered packed bed when balls are poured random into the core (Fig.4). The ordered bed was found to possess great structural flexibility and stability because it moves in springlike fashion. This kind of flexibility and stability permits the bed to compensate for thermal and pneumatics fluctuations and bear pressure from vertical or horizontal pressure variations.

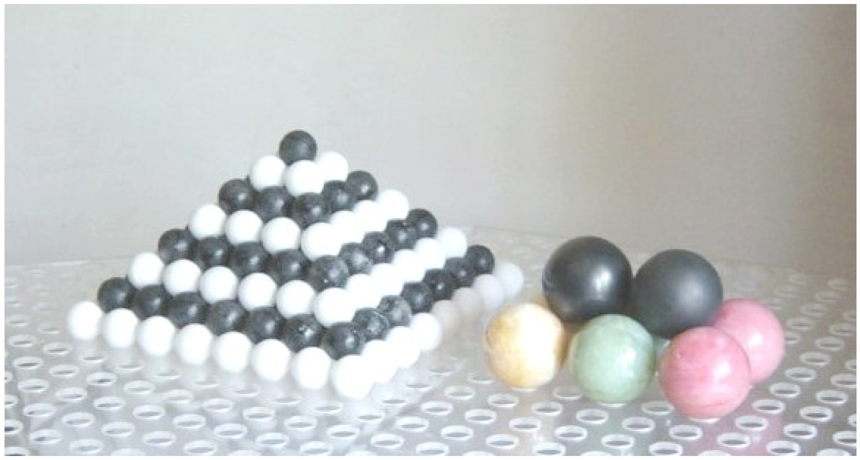

Fig.1: Plastic ball pyramid (left) and graphite balls of 60mm diameter (right)

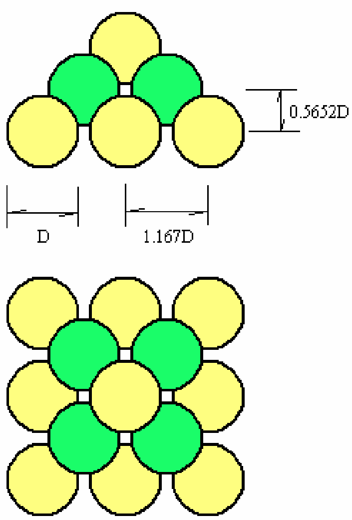

Fig.2: Ordered rhombohedral square packing

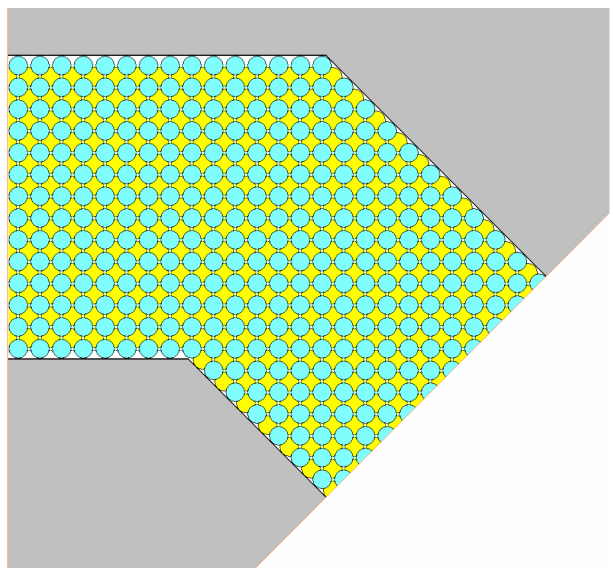

Fig.3: One eighth of octagonal annular core

2.2 Ordered Bed Parameters for Modular HTGR

The center-to-center bed height of adjacent layers for the sphere spacing as 1.167 sphere diameters is 0.5652 sphere diameters, i.e. 33.912 mm (Fig.2). This packing bed corresponds to a sphere packing density of 0.6806 within an infinite bed.

The ordered bed reactor is of annular core whose thermal power is maximized within the inherent and passive reactor safety requirement and that still complies with the stated safety features. The geometry of the core structures for keeping such that passive cooling to the environment and maximum fuel temperatures within the safe limits as proven with predecessor reactors will shape long and slender with similar dimensions as existing modular reactors. As shown in Fig.3, the reactor core of a reference design is an octagonal annulus composed of inner and outer graphite reflectors. The octagonal core is 2950 mm in width between the inner flats and 4610 mm between the outer flats, and 8063 mm in height.

The vertical and horizontal cross-section of OBMR is shown in Fig.5. Because the core inventory is replaced as a whole, this concept is called the ordered bed reactor with batch-wise fuel loads.

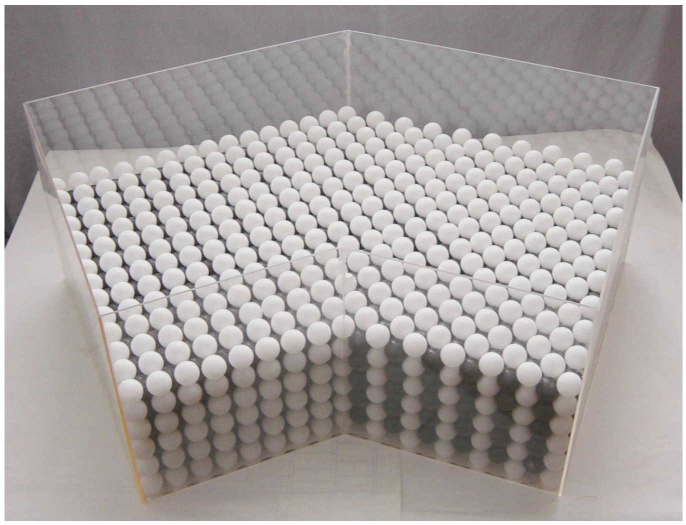

Fig.4: One eighth simulator of octagonal core

2.3 Power and Temperature Optimal Distribution

The ordered packing bed shows that reactor core can be divided into many regions radially and axially, which can be filled with fuel balls of different burn-up level. The fuel balls contain not only coated fuel particles, but also some burnable poison particles, which are used to control the excess reactivity present at beginning of cycle. When the fuel balls are discharged, they will be determined on burn-up level and burnable poison history by assay for each ball, then some of them will be returned and positioned accurately in the zoned core according to requirements of power and temperature optimal distribution. Therefore, the ordered packing of the fuel spheres can improve power density distribution that lowers maximum fuel temperature after a loss of coolant event. It can also decrease peak fuel temperature in normal operation that limits fission products release. These predict that the OBMR concept would have better power and temperature maps and exceed existing PBR and BTR modular reactor designs in the maximizing thermal power level and the increasing outlet gas temperature.

2.4. Coolant Flow Scheme and Pressure Drop

The ordered beds possess great structural flexibility because the bed movement is similar to the action of a scissor jack, in which a decrease in the horizontal spacing increases the vertical distance, and vice versa. The reactor core therefore tends to remain structurally stable with whichever vertical and horizontal pressure variations, which is distinct from the PBR. Marked reduction of pressure drop can be achieved in the annular core by means of changing the existing single vertical flow to the two-direction vertical flow or the radial

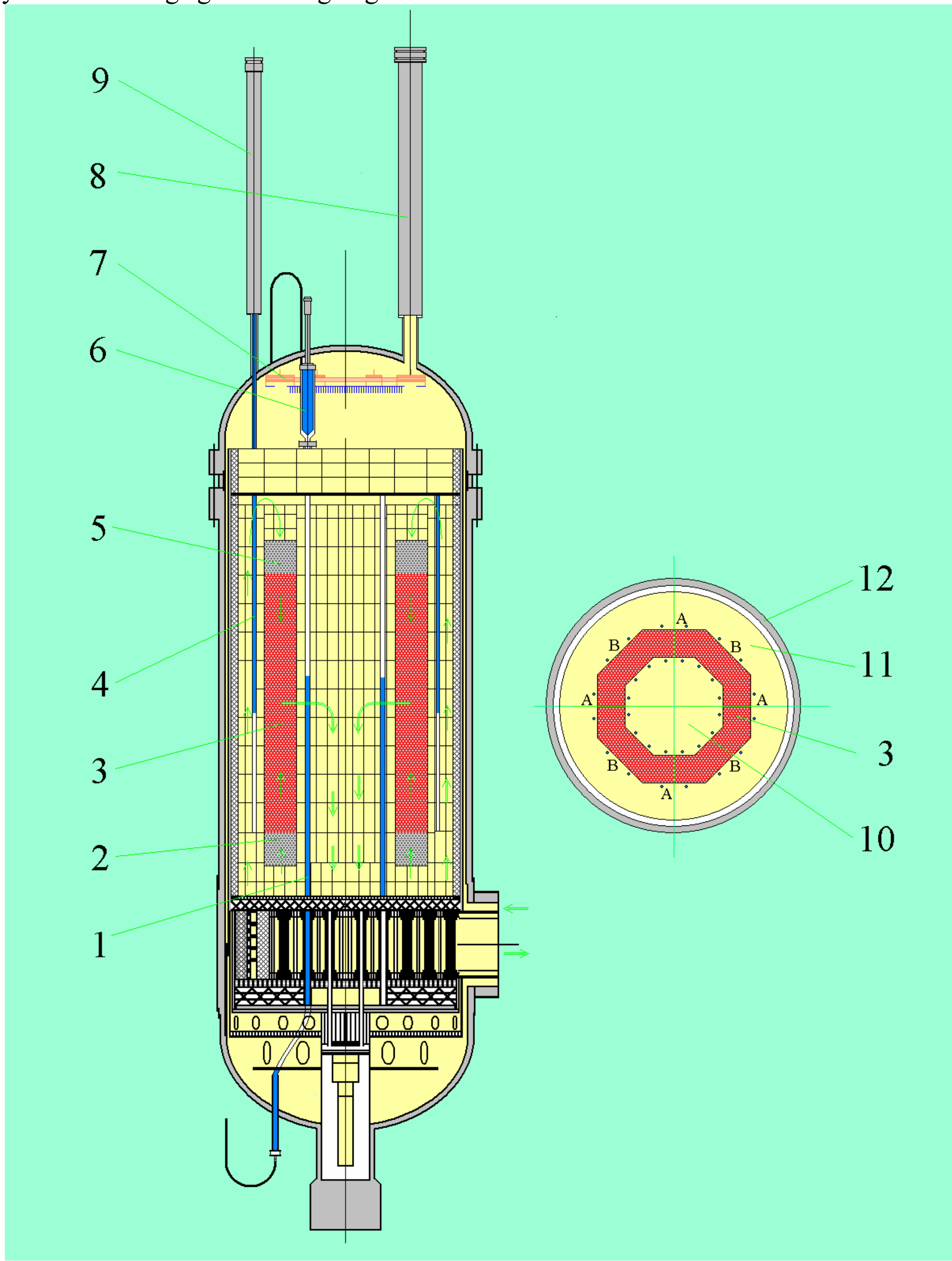

Fig.5: Vertical and horizontal cross-section of OBMR

1-Small absorber ball control system; 2-Lower graphite ball reflector; 3-Reactor annular core; 4-Control rod; 5-Upper graphite ball reflector; 6-Small absorber ball storage container; 7-Refueling distributor shelf; 8-Refueling penetration; 9-Control rod driver; 10-Inner graphite reflector; 11-Outer graphite reflector; 12-Pressure vessel;

flow. Fig.5 shows a two-direction vertical flow from up and down to center in the core. The reduction of pressure drop will allow to increase thermal power output and lead turbine power system can generate electric power at higher cycle thermal efficiency [9,10].

In addition, the ordered bed reactor makes it possible to substitute graphite balls for the upper and lower graphite block reflectors adjacent to the core in order to avoid the replacing of these graphite blocks.

3. Unloading and Loading of the OBMR

Although the ordered bed reactor possesses many attractive properties, it requires the fuel spheres with different burn-up level to be distributed to axial and radial given locations of the core, and these refueling operations should be completed during a shutdown shorter time. This is a key issue of the OBMR concept.

As early as 1970s, a number of experimental studies on random and ordered packing of spheres were carried out at the zero power reactor physics laboratory of Institute of Nuclear Energy Technology (INET) of Tsinghua University in China. These experiments include: the sphere flow in random packed bed, the formation of an ordered bed and the removal of balls from the top of a container, using glass balls with 25 mm diameter and plastic balls with 40 mm diameter. Based on the previous experimental experience and the existing simulator testing, the loading and unloading scheme of the ordered bed is designed [11] and described briefly as follows:

3.1. Unloading of the Ordered Bed Core

Unloading of the reactor with ordered bed is carried out in reactor shutdown and at low temperature and pressure. The unloading movable devices through the holes on the pressure vessel cover lower into the ordered packed bed and position above bed surface. The gas flow will push balls into the hole on head of the device and move them one by one up to out of the vessel when the head rotates and lowers as shown in Fig.6 left. There are eight holes on the pressure vessel cover, the positions of them correspond to the center of one eighth of the octagonal core.

After the eight devices run simultaneously and arrive at bottom of the core, the fuel balls are all discharged. The estimate is that one ball can move out per one second when the head of device rotates. If there are 700000 balls in the annular core, it will expend time about one day for discharging of them continuously.

The discharged balls will be assayed and routed to their destinations, graphite sphere tanks, spent fuel storages or temporary fuel storages with different burn-up level, by means of valve systems. Cooling systems for cooling of afterheat from fuel balls are equipped in the storages, thus unloading procedure can start quickly after the reactor shutdown.

3.2. Loading of the Ordered Bed Core

The octagonal core cavity will permit the formation of an absolutely ordered packed bed when balls are poured random into the cavity from reactor top. Some special facilities, such as fueling ducts, television cameras, light sources, refueling shelf and loading distributors A and B, will be used.

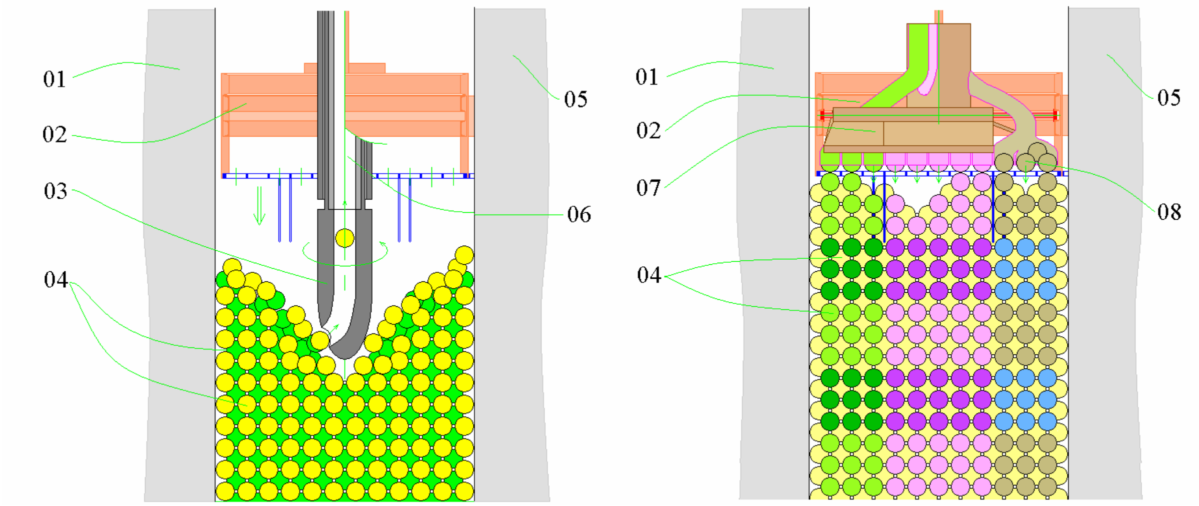

Fig.6: Unloading and loading of ordered bed

01- Outer graphite reflector; 02- Refueling distributor shelf; 03- Unloading movable device; 04- Balls in ordered bed; 05- Inner graphite reflector; 06-Ball duct; 07- Loading distributor A; 08- Dropping ball;

The various fuel spheres from the reactor top will be delivered to the loading distributors A or B, and then flow down to exits of the distributors as shown in Fig.6 right. The fuel spheres are distributed to the three radial regions of the annular core, and drop into below the plate of the refueling shelf and form ordered packing bed. After this row of the holes are full, the loading distributor will move horizontally to the next row of holes and deliver fuel spheres again.

Four loading distributors A and B move respectively in the subsections A and B of the octagonal core (Fig.5 right) from one end to another. Thus all holes on the four subsections A and B will be filled completely. Then the refueling shelf will be taken up and the lift is selected as 6 multiples of the bed height, i.e. $33.912 \times 6 = 203.5$ mm, in this design as shown in Fig.6 right. The repeating of above approach will complete the loading of the whole core. The fuel spheres with different burn-up level will be distributed to axial and radial given locations of the core.

The fuel spheres are transported between the storages and the core by means of the fuel ducts and the valve systems controlled by control system during the unloading and the loading. Some special facilities are used in the systems, such as graphite sphere separators, broken sphere separators, burn-up sensors and indexers, sphere number recorders and valves.

This refueling operation using such loading and unloading facilities and systems will run synchronously in eight channels. The fuel spheres are charged and distributed mainly by gravity that has high reliability. These lead to the refueling procedure can be completed quickly. Furthermore, it is possible that the system becomes a fully automatic operation managed by a control system.

4. Predicted Performance Data of the OBMR

Based on design parameters from existing modular HTGR, the main reactor design data of the

OBMRs, such as the core size, the inventory of fuel spheres, the thermal power, the helium flow rate and the core pressure drop, are predicted and listed in Table 1 in order to offering a farther design base.

Table 1: Predicted performance data of OBMR

Performance	Case No1	Case No2	Case No3	Case No4	Case No5	Case No6
Thermal reactor power, MWt	600	600	600	824	894	894
Equivalent core inner diameter, m	3.01	3.01	3.01	3.01	3.01	3.01
Equivalent core outer diameter, m	4.79	4.79	4.79	4.79	4.91	4.91
Core height, m	8.063	8.063	8.063	11.05	11.05	11.05
Number of fuel balls	515284	515284	515284	706556	768996	768996
Number of graphite balls (Upper & lower)	78264	78264	78264	78264	85176	85176
Average fuel ball power, kW/ball	1.16	1.16	1.16	1.17	1.17	1.17
Average core specific power, MW/m3	6.83	6.83	6.83	6.84	6.84	6.84
Helium flow scheme	Single	Two	Two	Two	Two	Radial
Inlet helium temperature, □	250	250	490	490	490	490
Outlet helium temperature, □	750	750	850	850	850	850
System pressure, MPa	7	7	7	7	7	7
Helium flow, kg/s	229	229	320	439	477	477
Core pressure drop, kPa *	251	31	75	186	187	≤30 **

* Including upper and lower graphite ball reflectors;

** Including inner and outer side graphite block slits;

The octagonal annular core of above reference design has equivalent core inner diameter of 3.01 m and equivalent core outer diameter of 4.79 m. This core packed bed is composed of 237 fuel ball layers and 8.063 m in height. Upper and lower graphite ball reflectors respectively are composed of 18 graphite ball layers and 0.61 m in height (Fig.5). Other reference designs have core height of 11.05 m, like existing PBR design, and equivalent core outer diameter of 4.91 m.

Based on the thermal power of 600 MWth, the pressure drops across the core were calculated using the previous experimental results [12] in order to show the difference between various coolant flow schemes. After the reactor design and engineering analysis in detail are completed, the maximum achievable reactor power level would exceed 600 MWth.

5. The Advantages of the OBMR

The OBMR is an innovative modular HTGR providing a promising alternative for the utilization of nuclear energy to produce electricity and hydrogen. The OBMR has the most of advantages from both the PBR and the BTR as follows:

1. The more uniform power density and temperature distribution can be achieved radially and axially, thus higher power output and outlet gas temperature are allowed in the modular annular core;
2. The ordered bed core has great structural flexibility and stability, which allow turning coolant single vertical flow to the two-direction vertical flow or radial flow schemes. Thus it has lower pressure drop across the core and higher net generating electricity efficiency;
3. The ordered bed has higher fuel ball packing density in favor of neutron economy and compensates partially for loss caused by incontinuous refueling;
4. The upper and lower reflectors can consist of graphite balls. Even inner and outer side reflectors adjacent to the core could also consist of graphite balls as a replaceable reflector conveniently;
5. The fuel unloading and loading operations of the OBMR can be completed in a shorter downtime than that of BTRs though they are all batch-wise fuel loads;
6. The OBMR dose not need that to be unloaded from the reactor bottom thus avoiding the complicated bottom configuration of the PBR and reducing pressure vessel size;
7. The OBMR has no use for load and unload systems of fuel balls at high temperature and pressure, and they are substituted by low temperature and pressure equipments and instruments which run only in reactor downtime;
8. The OBMR allows the effective utilization of weapons grade plutonium and various fuel cycles, and achievement of high burn-up since it has the negative temperature coefficient caused by burnable poisons;
9. The experiments of sphere flow in a simulative core are necessary for each design and core size in the PBRs. These experimental data need still to coupling with neutronic-thermalhydraulic calculation. But it is unnecessary for the OBMR;
10. The neutron flux profiles of the reactor are measurable radially and axially through the channels in entire core during the reactor start-up. Thus the experimental value of the power distribution can be obtained before the reactor power steps up.

6. Conclusion

The OBMR features an innovative ordered packed bed reactor of fuel pebbles. It has main advantages of the existing PBR and BTR modular reactor designs. The ordered packing of the fuel spheres can improve power density distribution, decrease peak fuel temperature and reduce core pressure drop, and results in the increasing thermal power output and the outlet gas temperature and the improving thermodynamic cycle efficiency.

Before it is put into engineering practice, the verification of the concept needs just to perform experiments on the ordered packing using unfueled spheres with full size in a simulative core and the development of relative facilities and instruments.

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