A brief review of the development of high temperature gas cooled reactor

Huan Li
Wu Yuzhang Honors College of Sichuan University, Sichuan, China
2017141471055@scu.edu.cn

Abstract. With the continuous development of nuclear energy, the high temperature gas cooled reactor (HTGR) is considered as one of the advanced reactor types of the fourth generation nuclear power system because of its new inherent safety concept, modular concept, high economic competitiveness and increasing construction flexibility. In this paper, the development history of high temperature HTGR is briefly summarized and the latest research is summarized.

Key words: HTGR; development overview; inherent safety; pebble bed; Spherical fuel element.

1. Introduction
In the 20th century, the discovery of nuclear energy has provided people with the possibility of endless energy. In the development of electric power, its creation and hidden value is immeasurable. In addition to using nuclear energy to generate electricity, nuclear energy is also widely used in heating, hydrogen production, seawater desalination and other fields [1]. But it is a pity that although nuclear power can solve the problem of human energy in theory, its safety and high cost have been hindering the rapid development of nuclear power. Since the peaceful use of nuclear power, the development of nuclear power has been put in the first place. After the Fukushima nuclear power plant accident in Japan, the Three Mile Island nuclear accident in the United States and the Chernobyl nuclear accident in the former Soviet Union [2], people urgently need new and safer nuclear reactors. After continuous exploration and transformation, researchers have proposed new nuclear reactors, such as ABWR, AP1000, EPR, VVER, etc., and their safety has been greatly improved [3]. However, with the improvement of safety, the construction cost of nuclear reactor has also increased unprecedentedly, so reducing the construction cost has become the latest problem. In this context, HTGR has been paid more and more attention, which is characterized by using gas (carbon dioxide, helium, etc.) as coolant.

2. Development History of HTGR
The real research of HTGR began in 1960s. First of all, Britain began to build the experimental "dragon" with a thermal power of 20MW by virtue of its own strong graphite gas cooled reactor technology in 1960, and reached full power operation in April 1966. The peach bottom gas cooled experimental reactor with an electric power of 40MW was built. During this period, Germany developed spherical fuel element and pebble bed HTGR with its own technical characteristics. Based on the high temperature reactor physical criticality test facility, Japan began to build a 30 MW high temperature gas cooled
Engineering Experimental Reactor (HTTR) in 1991. The Institute of nuclear energy and new energy technology of Tsinghua university built a 10MW HTGR (HTR-10) in 2000[4]. And the demonstration project of the modular high-temperature gas-cooled reactors (MHTGCR) is built in Rongcheng Shidao Bay, Weihai City, Shandong Province [5].

3. The cycle of High Temperature Gas Cooled Reactor
HTGR has many circulation modes. Among them, gas turbine cycle is considered as one of the most promising circulation modes because of its high safety, outstanding thermal efficiency and the ability to break through the temperature limit brought by steam cycle. Gas turbine cycle is also divided into direct cycle and indirect cycle.

3.1. gas turbine direct cycle
The working fluid in the primary circuit of HTGR is heated and directly drives the turbine. And after cooling, compression and heating, it will return to the core to be heated, which is called direct circulation. Direct circulation saves heat exchanger and other heat exchange equipment, optimizes the system, and has a great advantage in economic cost.

3.2. gas turbine indirect cycle
If a heat exchanger is added between the primary coolant and the working fluid of the turbine, this kind of circulation is called indirect circulation. The cost of indirect cycle is slightly higher than that of direct cycle economy, but the engineering difficulty is smaller and the layout is more flexible.

4. Research Progress of High Temperature Gas Cooled Reactor

4.1. Flow and heat transfer in pebble bed
A distinctive feature of HTGR core is the use of spherical fuel element. Therefore, the flow and heat transfer of pebble bed are important factors affecting the safety of high temperature gas cooled reactor. According to the core shape, it can be divided into pebble bed HTGR and prismatic HTGR. Ferng [6] compared the effects of different arrangements (BCC and FCC) on HTGR using computational fluid dynamics (CFD). The simulation results show that: the face centered cubic stacking mode has stronger heat transfer capacity, so the temperature of the pebble bed is lower under the same conditions, which means that the core of HTGR is safer. De [7] analyzed the effects of heat conduction and radiation on heat transfer, and discussed them respectively by combining physical measurement with CFD numerical simulation. Chen [8] measured the local heat transfer characteristics of a spherical fuel element by using a face centered cubic packing method.

4.2. Spherical fuel element
Tang [9] introduced the parameters and manufacturing process of the fuel ball used in high temperature gas cooled reactor, and tested its performance. With the help of the experimental platform, Sun [10] measured the characteristics (motion, collision, wear, etc.) of the graphite ball in the riser, and measured the number of collisions between the graphite ball and the pipe wall. MurataMori [11] developed a method for calculating the continuous energy distribution of pebble bed fuel based on Monte Carlo model. The Monte Carlo model is used to simulate the filling process of the pebble bed, and the vector method is used to reduce the penetration error. Zhou [12] discussed the failure conditions and development of current coating materials.

5. Characteristics of High Temperature Gas Cooled Reactor
People try to improve the safety of nuclear reactors, hoping that no large nuclear leakage will occur in any accident, and the safety of the public and the surrounding environment will not be endangered. HTGR is a new type of reactor developed under this background. HTGR attaches great importance to safety.
The negative reactivity coefficient of core temperature is large, which can automatically shut down the reactor under any circumstances; when the helium coolant is lost, the residual heat can be reliably conducted, radiated and naturally convective discharged, so that the fuel element temperature does not exceed the limit of 1600 °C. This is not to say that there is no emergency cooling device in the core, but that the HTGR can ensure safety under the worst conditions. Therefore, it will not cause serious accidents in any operation and accident. This inherent safety feature also ensures the safety of spherical fuel element and ensures that there will be no core melting or even radioactive material leakage.

6. Conclusion
In this paper, the development history of HTGR is summarized. HTGR can ensure its inherent safety because of its unique structure. The circulation mode, flow and heat transfer of pebble bed and fuel ball element of HTGR are summarized. Finally, the characteristics of HTGR are summarized.

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