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Thermal–hydraulic feasibility analysis on uprating the HTR–PM

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Abstract

In order to meet energy demand in China, the high temperature gas-cooled reactor–pebble-bed module (HTR–PM) is being developed. It adopts a two-zone core, in which graphite balls are loaded in the central zone and the outer part is fuel ball zone, and couple with a steam cycle. Outer diameter of the reactor core is 4.0 m and height of the core is 9.43 m. The helium inlet and outlet temperature are 250 and 750 °C, respectively. The reactor thermal power is 380 MW. Preliminary studies show that the HTR–PM is feasible technologically and economically. In order to increase the reactor thermal power of the HTR–PM, some efforts have been made. These include increasing the height of reactor core, optimizing the thickness of fuel zone and better selection of the scheme of central graphite zone, etc. Basic design concepts and thermal–hydraulic parameters of the HTR–PM are given. Measures to increase the thermal power are introduced. Thermal–hydraulic analysis results are presented. The results show that, from the viewpoint of thermal–hydraulics, it is possible to increase the reactor power.

1. Introduction

The nuclear energy use will play an important role in China's energy supply in the future, as it is seen as an effective measure to meet the requirements of energy demand, environmental protection, and energy security. For the utilization of nuclear energy in China to a large amount, the modular high temperature gas-cooled reactor (HTR) is an important type of advanced reactor to meet the energy demand and yet offer inherent safety features. The modular HTR possesses the following major characteristics: inherent safety features; capability to provide high temperature heat; suitability for various power conversion cycles. For these reasons, the modular HTR will play an important role in future energy supply of China, and will be used in many areas, including electric power generation, coal gasification and liquefaction to produce synthetic fuels, high temperature process heat for industrial sectors, and production of hydrogen (Wang and Lu, 2002).

For exploring and developing modular HTR technology, a 10 MW(t) high temperature gas-cooled reactor-test module (HTR-10) had been designed and built by the Institute of Nuclear and New Energy Technology (INET). It reached the first criticality in the end of 2000 and carried out full power operation in the beginning of 2003. It showed that China had grasped key technologies of modular HTR. Since the most important advantage of the modular HTR is its inherent safety features, after full power test operation of the HTR-10, some important safety demonstration experiments had been carried out with this reactor. These experiments verified the safety features of modular HTR and promoted better understanding of these features.

The high temperature gas-cooled reactor–pebble-bed module (HTR–PM) is a follow-up project being put into practice after successful design, construction, and operation of the HTR-10. As an industrial application project, its objective is to demonstrate the technological maturity and economic competitiveness of modular HTR used as a commercial power plant. It started as soon as the criticality of HTR-10 (Zhang and Yu, 2002) and was accelerated after full operation of the HTR-10 under support by electricity utilities. At the moment, the preliminary feasibility study of HTR–PM is under way.

2. Brief description of the HTR–PM

During the development of HTR–PM, safety, maturity, and economy are the primary concerns (Zhang and Yu, 2002).

- The unique safety characteristics of modular HTR are the most attractive aspects for the government, public, and util-

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ities when they consider this reactor technology. Therefore, HTR–PM will keep the unique safety characteristics, one of which is that the maximum fuel temperature should be lower than 1600 °C under any conditions.
- Technological maturity is the basis to make this project successful. Therefore, HTR–PM makes the most of proven technologies, including the technologies used in construction of the HTR-10 and THTR-300, and technologies verified during the development of HTR-Module. Although HTR–PM could couple with various power conversion cycles, a mature steam cycle is coupled to the first HTR–PM in order to reduce the technological risk.
- Economic competitiveness is a precondition for broad application of HTR–PM. The reactor thermal power should be as high as possible while meeting safety requirements.

Fig. 1 shows the vertical section of HTR–PM. It adopts a two-zone core, in which graphite balls are loaded in the central zone and the outer part is fuel ball zone. Outer diameter of the reactor core is 4.0 m and height of the core is 9.43 m.

Helium is pumped into the reactor pressure vessel by a helium circulator. After entering the RPV, helium flows downwards through the annular space between the core vessel and the RPV and changes its flow direction at the lower part of the RPV. A small part of helium flows into the fuel discharging tube and merges into the core helium flow after cooling the fuel elements in the discharging tube. Most of helium goes around the support structures at the reactor bottom and enters into the cold helium channels in the graphite blocks of the side reflector. At the top of side reflector, helium is collected in the cold helium plenum located in the upper part of the top reflector. Then, a small part of helium flows into the control rod channels to serve as coolant of the control rods, and at bottom of the bottom reflector it passes through the side holes and flows into the small plenum located in the bottom reflector. Starting from the top of the core, mainstream helium goes downwards and continuously passes in succession through the reactor core and the channels in the bottom reflector, and finally it flows into the hot helium plenum in the reactor bottom. The helium flows with different temperatures are sufficiently mixed in the hot helium plenum and the mixture with an average temperature of 750 °C flows out of the RPV.

Main design parameters of the HTR–PM core are given in Table 1. The helium inlet and outlet temperature are 250 and 750 °C, respectively. The reactor thermal power is 380 MW and the electricity power generation rate is around 160 MW. In order to properly increase the reactor thermal power of the HTR–PM, some efforts should be made.

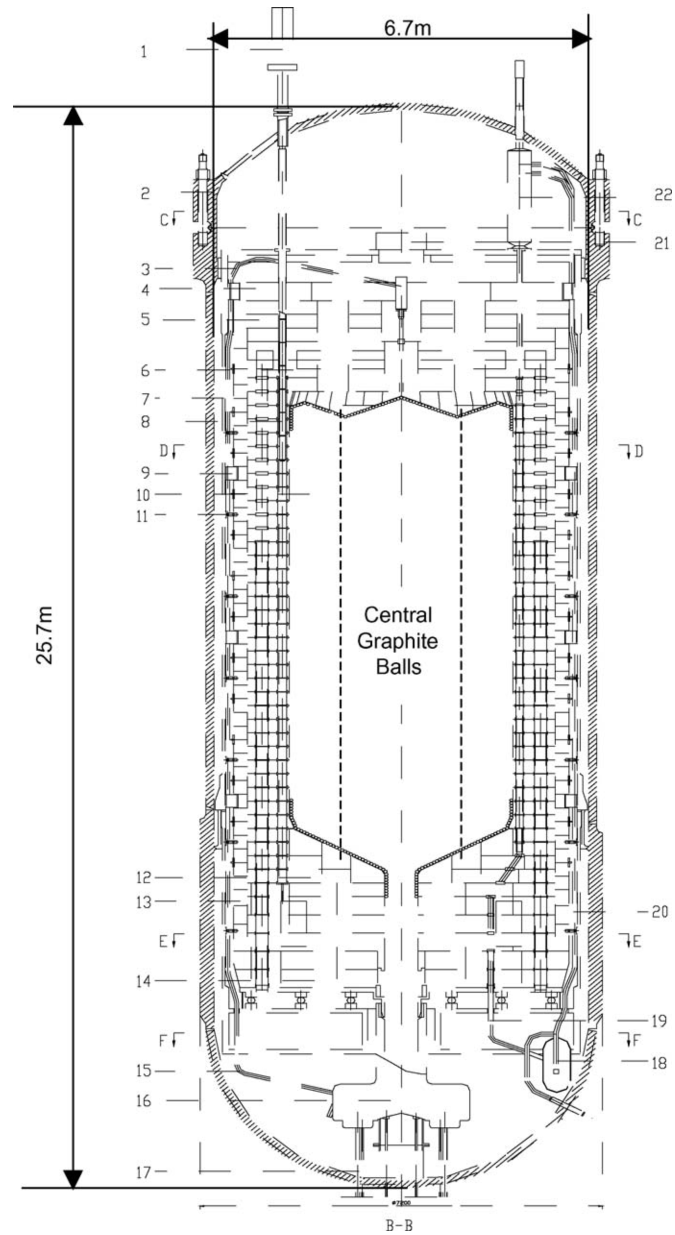

Fig. 1. Vertical section of HTR–PM: (1) control rod drive mechanism; (2) reactor pressure vessel; (3) fuel charging tube; (4) kentledge; (5) top thermal insulator; (6) top reflector; (7) core vessel; (8) control rod guiding channel; (9) stop wing plate; (10) reactor core; (11) supporting spring; (12) bottom reflector; (13) side reflector; (14) bottom thermal insulator; (15) fuel ball lifting tube; (16) single-nozzle; (17) ball discharging tube; (18) absorbing ball storage tank; (19) absorbing ball loading tube; (20) absorbing ball gas-loading tube; (21) shielding plug; (22) top absorbing ball storage tank.

3. Basic approaches on uprating the HTR–PM

Increase of the reactor thermal power is mainly restricted by the maximum fuel temperature limit. According to the state-of-the-art of fuel, the maximum fuel temperature should be lower than 1600 °C. Otherwise, the release rate of fission products will increase sharply when the fuel temperature surpasses 1600 °C. In order to increase reactor power and restrain the maximum fuel temperature at the same time, a two-zone core design in which graphite balls are loaded in the central zone has been adopted in the HTR–PM. That is, the central part of core is a non-fuel graphite zone, which does not generate heat; the outer part of core is fuel zone in which fuel elements are filled to form a pebble bed. Compared to a single-zone core, in a two-zone core, the maximum fuel temperature could be decreased under accidental conditions due to the heat capacity of central graphite zone. Concerning the non-fuel graphite zone, there are actually two candidate schemes that can be selected by designers. For