Annals of Nuclear Energy 77 (2015) 281–284

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

A nuclear-natural gas coupled-cycle for power generation

Jiafu Tian [*]

Institute of Nuclear Energy Technology, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 16 June 2014
Received in revised form 18 November 2014
Accepted 21 November 2014

Keywords:
Pebble bed
Ordered bed
Modular HTGR
Small modular reactor
Power conversion
Natural gas combined cycle

ABSTRACT

The ordered bed modular HTGR reactor is an improvement on the pebble bed reactors that can hold intrinsic advantages of spherical fuel element and eliminate some problems in the pebble bed reactor design. The reactor can be coupled with a conventional natural gas combined cycle to form a nuclear natural gas coupled cycle system. This system can be used for base-load power production using pure nuclear fuel as a small modular reactor. The combined two-component system, using both nuclear and gas fuel with a high cycle efficiency, can form a large power station sized more than 1000 MWe. Furthermore, the system can be used for base-load and peak power using nuclear heat and supplemental natural gas. It has the potential to offer low-cost base-load electricity and lower-cost peak power relative to the existing base-load nuclear plants and natural gas-fired peak-electricity production units.

1. Introduction

As China experiences an economic boom, the air surrounding the urban areas has been seriously polluted by high concentrations of sulfur dioxide, nitrogen oxides and particle matter. Most of the pollution comes from emissions of coal burning. During the past decade, China's coal consumption increased from a total of 1.52 billion tons in year 2000 to 3.48 billion tons in year 2011, approximately the same amount of total coal consumption for the rest of the world (U.S.EIA, 2013). The power plants are the main customers consuming about 50% of the coal. Changing direct coal combustion in power plants should be an imperative task in mitigating environmental pollution and reducing greenhouse gas emission. However, there are many obstacles in achieving this in China. Natural gas as a substitute for coal as the alternative energy source has been chosen by many countries, but natural gas for power generation is limited and expensive. Nuclear energy is a clean energy and can substitute coal on a large scale, but after the Fukushima nuclear accident in Japan, even a remote possibility of nuclear accident gets people on edge. As a result, China's nuclear projects also move forward slowly and cautiously. The High Temperature Gas-cooled Reactor (HTGR) has high level of reactor safety and a starting construction of a modular reactor, however some problems were discovered in pebble bed designs, which unable to sustain effectively on a large scale electric power industry. Wind power alternative is advancing rapidly in China, but the power grid often refuses to link up wind power generation.

Considering the pros and cons of these clean energy alternatives, this paper suggests an approach to take advantage of clean energy alternatives while reducing the disadvantages. A combination of an advanced HTGR reactor with a conventional gas fuel system will be able to meet the wide demand of power grid, substituting clean energy for coal.

2. The pebble bed HTGR reactor needs improvement

Currently the design of pebble bed HTGR reactor (PBR) is primarily based on experiences from operation and experiment of German reactor AVR and THTR. Some problems related to safety issues of reactor operation were recently discovered and recognized (Beck et al., 2010). These problems resulted from pebble random packing and movement in reactor core. In the 1960s, before the construction of the first experiment reactor AVR, experts paid attention primarily to the reactor critical safety issue caused by the bulk stability of random packing and moving of pebbles. Later, packing and moving pebbles experiments using simulative balls were performed. Based on these experiments, the AVR reactor was successfully made. Another result of these experiments confirmed that pebble random packing and moving could offer an on-line refueling scheme by means of pebble dropping from top and discharging at the bottom (Oehme and Schoning, 1970).

However, these experiments were all carried out under normal circumstances. The present studies showed the graphite friction coefficients in helium gas at high temperature were significantly

---

[*] Tel.: +86 10 62785132.
E-mail address: jftian@tsinghua.edu.cn

http://dx.doi.org/10.1016/j.anucene.2014.11.031
0306-4549/

higher than at normal condition. The AVR reactor operation at high temperature showed the following problems:

- The rolling and moving of pebbles, or "pebble flow", showed the velocity of flow on the edge of the core was much slower than at the center, probably because some pebbles appeared "crystalized" near the reflector wall, leading to over burn-up and high temperature locally.
- The rolling and moving of pebbles produced a large amount of graphite dust due to abrasion between fuel spheres. Present pebble modular reactor design requested the pebbles to be recycled many times through the core before disposal for flattening the axial power profile, which produced more graphite dust.
- There was no ability to measure core temperatures or power distribution in pebble random packing core, resulting the reactor to operate conservatively at lower temperature.

3. Ordered bed modular HTGR reactor

The problems in PBR design were nonexistent in the prismatic modular HTGR reactor (PMR). Some recognized problems (i.e. large fuel block radiation distortion) in the PMR were nonexistent in the PBR. An improvement to both design was the ordered bed modular HTGR reactor (OBMR), which was based on experiment experienced with both PMR and PBR, eliminating the afore mentioned problems, and was superior in the designed performances (Tian, 2006).

The OBMR design featured reactor core cavity that was filled with an ordered bed of fuel pebbles. The ordered beds were packed in a rhombohedral geometry in which the unit cell was formed by four spheres lying at the corners of a square, and the individual spheres layered subsequently to fill the cusps formed by them, as shown in Fig. 1.

As in other modular HTGR, this ordered bed was also designed to ensure passive decay heat removal without radioactive material releases in the case of an accident. In addition to the unique high level of reactor safety, the ordered bed was found to possess great structural flexibility and stability because the spheres in the ordered bed moved in a spring-like fashion. The flexibility and stability permitted the bed to compensate for thermal and pneumatics fluctuations and withstand pressure from different direction.

The preferred OBMR design was an octagonal core, which was 2930 mm in width and 8063 mm in height, and the volume of 57.4 cubic meters containing the balls of 338,542, as shown in Fig. 2. This was a reactor with batch fuel load where the core inventory was loaded and replaced as a whole. The top and bottom ends of the core had flat surfaces which were differed from the cone-packing of fuel spheres in PBR, simplifying reactor physics and thermal hydraulic designs. The inlet and outlet helium temperature of the reactor core were 250 °C and 850 °C at normal operation. These predicted data are listed in Table 1 for the purpose of offering a further design base.

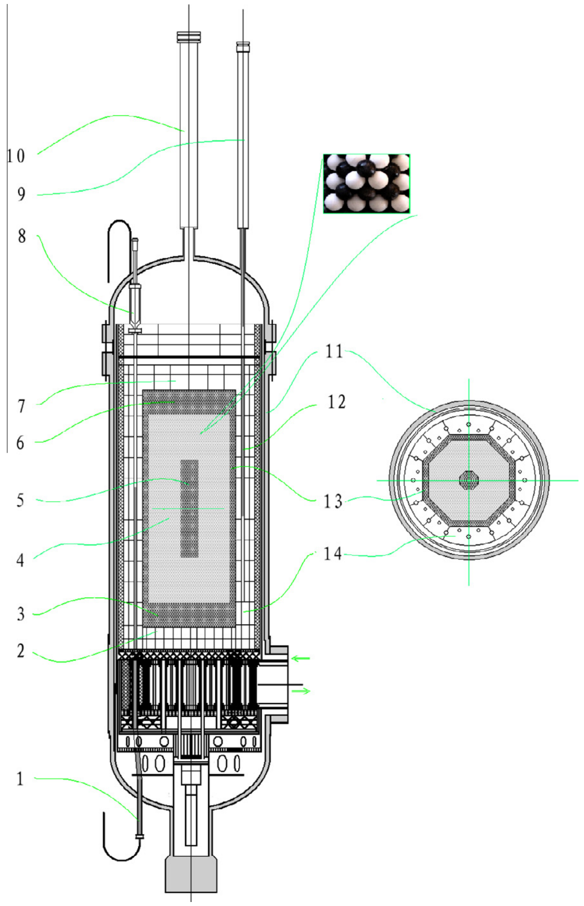

Fig. 2. Vertical and horizontal cross-section of OBMR. (1) Small absorber ball discharger; (2) lower graphite reflector; (3) lower graphite ball reflector; (4) reactor core; (5) central graphite balls; (6) upper graphite ball reflector; (7) upper graphite reflector; (8) small absorber ball storage container; (9) control rod driver; (10) refueling penetration; (11) pressure vessel; (12) control rod; (13) outer graphite ball reflector; (14) outer graphite reflector.

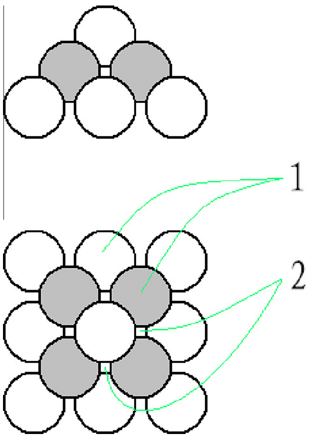

Fig. 1. Ordered square packing. (1) Fuel sphere; (2) channel.

This ordered packing method showed that reactor core can be divided into many regions radial and axially, which were filled with different fuel balls. It had better power and temperature maps, and could exceed existing PBR and PMR modular reactor designs in terms of maximum thermal power level. The thermal power output of this design could achieve 400 MWth. As shown in Fig. 2, if graphite pebbles were added in central region of an enlarged core, the reactor would be able to enhance thermal power output to 600 MWth or more, in which the average fuel ball power is 1.18–1.20 kW/ball, as listed in Table 1.

As shown in Fig. 1, the channels are formed between the spheres and continuous through the entire ordered bed. The channels allow entering of neutron detectors or activate wires for the measure of the neutron flux profiles radial and axially during reactor power started up or zero power operation. Before raising the power level, these detectors are extracted from the core, which channels as coolant paths through the entire core, resulting a lower pressure drop across the core as listed in Table 1. This is in contrast with the other random packing pebble bed design which could not be equipped with these types of instruments and get experiment data of the