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Pneumatic transportation pattern of fuel pebbles in a pebble-bed reactor

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ABSTRACT

Pebble-bed high temperature gas-cooled reactors have many advantages such as inherent safety and high efficiency, so it has been considered as a preferred candidate for the Generation IV Nuclear Power Plants. Every day thousands of spherical fuel pebbles are transported pneumatically in the pipes outside the core of a pebble-bed reactor. During the transportation, each pebble will be lifted perpendicularly in a pipe of which the length is tens of meters. The lifting process affects the operation efficiency of the reactor directly, thus it is of great significance to the stability and reliability of the reactor. A pattern widely used nowadays is to lift a single fuel pebble each time, namely at any time there is at most one pebble lifted in a pipe. The efficiency of the pattern is low and it cannot meet the operational requirements, especially during loading and emptying the core. This paper introduces a new transportation pattern named two fuel pebbles lifted together. On this basis we obtain the force conditions of the pebbles. Then the dynamic characteristics of the pebbles are analyzed. The research shows that by controlling the time interval between transporting the two pebbles into the lifting pipe, the collisions between the pebbles can be avoided. In addition the transportation reliability and efficiency can be ensured. The experiment validates that the transportation pattern can meet the operational requirements of the reactor. The research is significant to improving the efficiency and reliability of the transportation of the fuel pebbles and provides an important basis for the design of the reactor.

1. Introduction

With the constant increase of the population and growth of the economy, the demand for energy all over the world is also increasing very fast. The increase is predicted to be 37% by 2040 (IEA, 2015). At the same time, the storage of fossil energy on the earth is decreasing and the greenhouse effect is intensifying. Many countries have paid a lot of attention to the development and utilization of non-fossil energy and given policy support to it (Lior, 2008; Sheldon et al., 2015). Among different kinds of non-fossil energy, nuclear energy has many advantages, such as lower cost and less pollution, so it is considered to be an economic and effective solution to the energy crisis (Visschers et al., 2011; Zhou and Zhang, 2010). In 1942, the first nuclear power plant (NPP) was constructed in the US. Since then, nuclear energy has been developing rapidly. Many countries have carried out a lot of medium and long term NPPs construction projects, such as HTR-PM (High Temperature Reactor-Pebblebed Modules), NGNP (Next Generation Nuclear Plant) and GT-MHR (Gas Turbine Modular Helium Reactor Plant) (Fertel, 2011; Goto et al., 2012; Ramana, 2009; Zhang et al., 2009). Up to the end of 2014, there were 438 nuclear NPPs in operation all over the world, with the installed capacity of 376.2 GWe, and a further 70 NPPs were being built (International Atomic Energy Agency, 2015). The installed capacity will be more than 620 GWe by 2040 (IEA: Directorate of Global Energy Economics, 2015).

Among so many kinds of NPPs, pebble-bed high temperature gas-cooled reactor (PBHTGR) is a very competitive reactor. It has inherent safety, high efficiency, short construction period and many other advantages (Koster et al., 2004; Zhang and Sun, 2007). Since the 1960s, Germany, China and South Africa have carried out the research and development of PBHTGR (BAUMER and KALINOWSKI, 1991; Harder et al., 1971; Koster et al., 2003; Matzner and Wallace, 2005; Wang et al., 1991; Wu and Yu, 2007; Xu and Zuo, 2002). China started the construction of HTR-PM in 2012, and will be connected to the grid in 2017 (Zhou et al., 2015). By then HTR-PM will be the first commercial PBHTGR demonstration plant. It is a key step in the development of Generation IV Nuclear Energy System.

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Pebble-bed reactors adopt spherical coated particle fuel pebbles. The fuel pebbles are transported in the pipes outside the core by gravity and compressed helium (Zeng et al., 2011). The diameter of the fuel pebble is very close to the internal diameter of the pipe in order to increase the transportation efficiency. This transportation is named pneumatic transportation of near-diameter spheres in pipe (PTNSP) (Zeng et al., 2012). Every day, over 6000 fuel pebbles are discharged from the core of the pebble bed reactor. Then their depletion will be measured one by one. If a fuel pebble has reached full depletion, it will be transported to the spent fuel pebbles storage system. If not, it will be returned to the core. Every day, 400 fresh fuel pebbles are added into the core (Zhang et al., 2006).

The structure of the fuel handling system (FHS) in a pebble-bed reactor is shown in Fig. 1 (Liu et al., 2003). During normal operation, 6000 fuel pebbles are discharged from the core every day. SG01 transports the fuel pebbles one by one to BP01. Then BP01 measures the depletion of the fuel pebble. If it has not reached its full depletion, AE01 will connect to lifting pipe 1. Then FN01 is started and the fuel pebble is lifted pneumatically and returned to the core. If the fuel pebble has reached its full depletion, AE01 will connect to lifting pipe 2. Then FN01 is started and the fuel pebble is transported to the section between AB04 and AB05. When the number of the fuel pebbles between AB04 and AB05 has reached the design value, AB04 closes and AB05 opens, and then FN02 is started. SG04 transports the fuel pebbles into lifting pipe 3 one by one. Then the fuel pebble is lifted pneumatically to FS02. When some fresh fuel pebbles need to be added into the core, SG05 will transport the fuel pebbles in FS01 to lifting pipe 1. The fuel pebbles are then transported into the core. Additionally, a large number of fresh fuel pebbles need to be transported into the core through lifting pipe 1 when the empty core needs to be loaded. When the core needs to be emptied for emergency, all the fuel pebbles will be transported pneumatically to FS02 though lifting pipes 2 and 3 in a short time.

It can be concluded that fuel pebble pneumatic lifting is an important link in pebble-bed reactor operation. A lifting pattern commonly used is lifting singly, which means at most one fuel pebble can be lifted in the pipe at any time. However, the lifting pipe is very long. The length can be more than 30 m. So lifting singly is the bottleneck of the fuel pebbles transportation. It will limit the efficiency of the fuel pebbles transportation as well as the reactor operation. Additionally, it also has influence on the safety and reliability of the reactor. For example, in the event of an accident, the core should be emptied as soon as possible, but lifting singly can hardly meet the requirements for efficiency. Thus, lifting more fuel pebbles in per unit of time is of great significance.

Since the 1960s, many scholars have carried out a lot of research on the pneumatic transportation of fuel pebbles. They put forward different methods to improve the efficiency of the fuel pebbles lifting. Faber et al. (1972) and Rysy (1973) analyzed the relationship between the velocities of the helium flow and the fuel pebble. They found some influencing factors of the lifting efficiency, such as the diameter of the fuel pebble, etc. On this basis, they carried out an experiment. They measured the drag force on the fuel pebble in helium flow. Liu et al. (1996) designed the FHS of HTR-10. They analyzed how the lifting efficiency was influenced by the dimension of the pipe, the density of the helium flow, and some other factors. Li et al. (2009) introduced the application of pneumatic transportation to PBHTGR. They compared different methods for the research of pneumatic transportation, such as theoretical analysis, numerical simulation and experiment. They also obtained the lifting velocity of the fuel pebble based on the two-phase flow theory. Zeng et al. (2012) established the dynamic equations for the fuel pebble pneumatic lifting. They also analyzed the influencing factors of the lifting efficiency when the fuel pebble

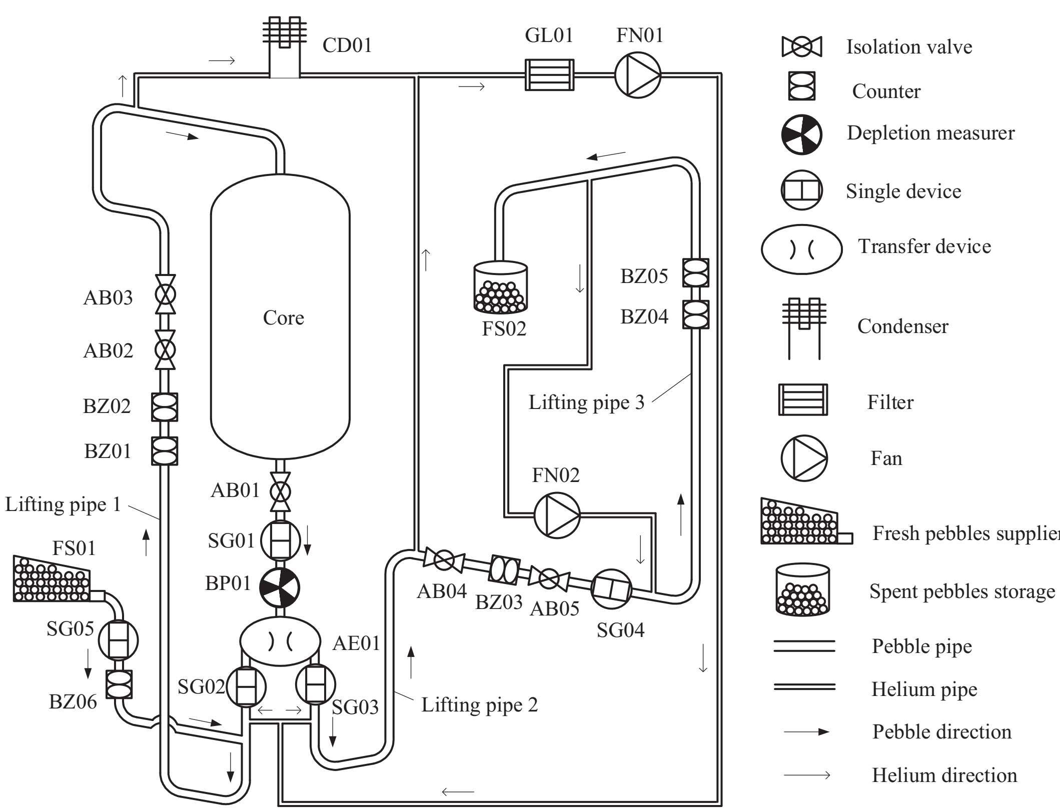

Fig. 1. Structure of FHS in pebble-bed reactor.

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