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Dynamic analysis and application of fuel elements pneumatic transportation in a pebble bed reactor

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ABSTRACT

Almost 10,000 spherical fuel elements are transported pneumatically one by one in the pipeline outside the core of a pebble bed reactor every day. Any failure in the transportation will lead to the shutdown of the reactor, even safety accidents. In order to ensure a stable and reliable transportation, it's of great importance to analyze the motion and force condition of the fuel element. In this paper, we focus on the dynamic analysis of the pneumatic transportation of the fuel element and derive kinetic equations. Then we introduce the design of the transportation pipeline. On this basis we calculate some important data such as the velocity of the fuel element, the force between the fuel element and the pipeline and the efficiency of the pneumatic transportation. Then we analyze these results and provide some suggestions for the design of the pipeline. The experiment was carried out on an experimental platform. The velocities of the fuel elements were measured. The experimental results were consistent with and validated the theoretical analysis. The research may offer the basis for the design of the transportation pipeline and the optimization of the fuel elements transportation in a pebble bed reactor.

1. Introduction

With the decrease of fossil fuel, nuclear power is playing a more and more significant role in the generation of electricity [1–3]. Among so many types of nuclear power plants, the modular pebble bed high temperature gas-cooled reactor has many advantages such as inherent safety features, high efficiency and economic competitiveness [4–8]. So it has been considered to be a candidate for the Generation IV nuclear power systems [9–11]. A pebble bed reactor uses spherical fuel elements and adopts continuous fueling and de-fueling [12,13]. Fuel elements are discharged from the bottom of the core one by one; after some processes, the burn-up of the fuel element is examined; if the fuel element has reached the target burn-up, it will be transported to the spent fuel elements storage system; if not, it will be transported to the top of the core and then returned to the core; some new fuel elements are loaded into the core at the same time. This process relies on many subsystems, including the core, the NFESS (new fuel elements storage system), the SFESS (spent fuel elements storage system), the FETPS (fuel elements transportation piping system) and the HPS (helium pneumatic system), as shown in Fig. 1 [14,15]. Fission occurs in the core. The NFESS stores a number of new fuel elements which will be fed into the core. The SFESS stores the spent fuel elements discharged from the core. The FETPS contains over a thousand meters of pipeline which is formed into a complex pattern. Fuel elements are transported in this pipeline by the force of compressed helium. The HPS offers the compressed helium. The number of the fuel elements transported in the FETPS every day is almost 10,000. If any fuel element cannot be transported successfully, the shutdown of the reactor and even safety accidents will occur. Thus the stable and reliable pneumatic transportation of the fuel element is of great significance to the operation of the reactor [16].

The fuel elements transportation process should meet the following requirements [17–21]:

The process ought to be stable and reliable. Fuel elements can be transported successfully in each section of the pipeline. Lack of airflow force and other causes of failed transportation must be avoided.

The velocity of the fuel element must be suitable. For example, the velocity should be below the maximum allowable value when the fuel element enters the core. In this way a big impact against the core can be avoided.

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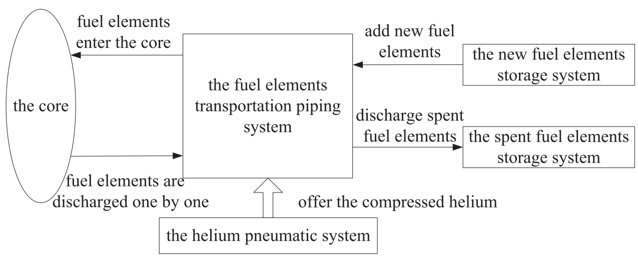

Fig. 1. Operation process of the fuel cycling in a pebble bed reactor.

The structure of the pipeline must be stable. Distortion or other failures caused by the impact of the fuel element against the pipeline should not occur.

The control logic of the reactor should be designed accurately based on the dynamic characteristic of the fuel element. For example, orders should be given by the control system according to the location and the velocity of the fuel element.

In order to meet the requirements above, the dynamic characteristics of the fuel element in the transportation process need to be studied. However, this process is very different from the traditional pneumatic transportation. The most distinguishing feature is that the diameter of the fuel element (D) is very close to the internal diameter of the pipeline (D_p). The transportation pattern is seldom studied. Besides, the structure and the pattern of the pipeline are usually very complex because of the space limitations and the functional requirements. These lead to the difficulty of the research on the pneumatic transportation.

Several researchers have investigated the dynamic characteristics of the fuel element in the pneumatic transportation. Rysy W et al. [22,23] proposed a hypothesis that the space behind the fuel element might be a zone of equal pressure. They analyzed the relationship between C_d and k. C_d is the drag coefficient and k is the ratio of D to D_p. Then they obtained the velocity of the fuel element. Liu Jiguo et al. [24] used an empirical expression to calculate the minimum allowable pneumatic flow which could ensure the successful transportation of the fuel element. Zeng Kai et al. [25] proposed a hypothesis that C_d might have no concern with the Reynolds number in their investigated situation. Then they established the mission profile of the fuel elements cycle-lifting system. Shen Peng et al. [26] established a dynamic model to describe the fuel element pneumatic conveying process. They used CFD technology to obtain some key data and studied the motion characteristics of the fuel element. Liu Hongbing et al. [27] designed a deceleration system to reduce the velocity of the fuel element. They analyzed the dynamic characteristic of the deceleration process. However, little attention has been paid to the derivation of the kinetic equations. Some equations in the previous studies are even incorrect. Besides, the dynamic analysis is incomplete. Lastly, several key parameters such as the impact force between the fuel element and the pipeline have not been calculated.

The aim of this paper is to provide the dynamic analysis of the fuel element transportation. First, we derive its kinetic equations. On this basis the transportation process in the main cycling pipeline is taken as an example. We calculate some important parameters such as the velocity of the fuel element, transportation efficiency and the impact force on the pipeline. We also carry out some experiments. The measured data have been compared with the analysis. The accuracy of the analysis is then confirmed. This research may offer a guide to the design of the fuel elements pneumatic transportation system and the control logic of the transportation process in a pebble bed reactor.

2. Dynamic analysis of the fuel element

2.1. Structure of the main cycling pipeline

A design of the main cycling pipeline in a pebble bed reactor is shown in Fig. 2. The pipeline consists of 13 sections (namely *AB*, *BC* … *NP*). Each section is a straight pipeline or an arc pipeline. The fuel element enters the pneumatic transportation pipeline at point *A*. *AG* is the extending pipeline in which the fuel element is transported to Point *G*. *GL* is the buffer pipeline. *LM* is the lifting pipeline in which the fuel element is lifted to the top of the core. *MP* is the entry pipeline and the fuel element enters the core at point *P*.

2.2. Kinetic analysis

Fig. 3 shows the motion and force condition of the fuel element in an arc pipeline. O is the center of the arc and O_{yz} is the center of the fuel element. Ox is a ray parallel to the horizontal plane. A polar coordinate $\{P\}$ is built. O is the pole of $\{P\}$ and Ox is its polar axis. Then the coordinate of O_{yz} in $\{P\}$ can be expressed with (r, θ). r is the radius of O_{yz} and θ is its polar angle. The velocity of O_{yz} in $\{P\}$ can be expressed with $\dot{r}$ and $\dot{\theta}$:

$$\dot{r} = \frac{\mathrm{d}r}{\mathrm{d}t}, \qquad (1)$$

$$\dot{\theta} = \frac{\mathrm{d}\theta}{\mathrm{d}t}, \qquad (2)$$

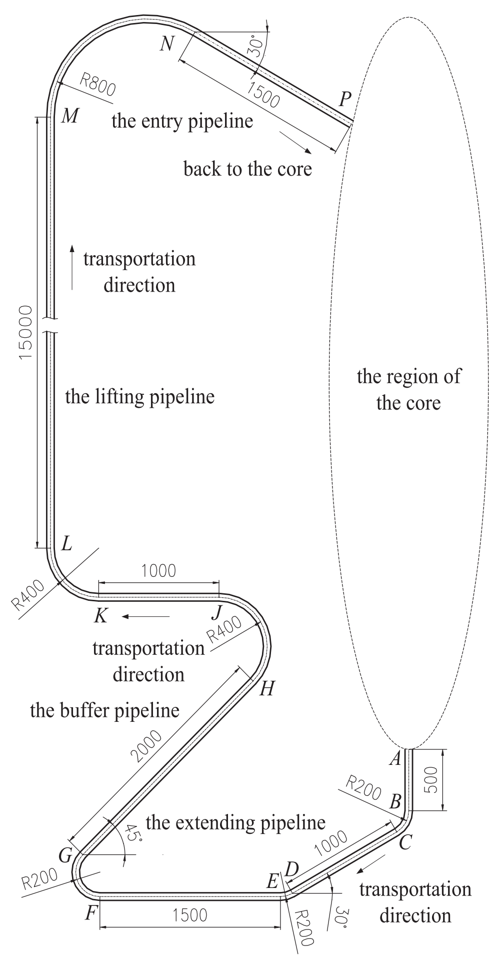

Fig. 2. Design of the main cycling pipeline in a pebble bed reactor (unit of length: mm).