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Research on flow field characteristics and force analysis of fuel elements pneumatic transportation in a pebble bed reactor

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A B S T R A C T

Thousands of spherical fuel elements are transported pneumatically in pipelines in a pebble bed reactor every day. The motion of the fuel element has a strong influence on the efficiency and reliability of the reactor. The motion is determined by the force condition of the fuel element which is determined by the characteristics of the flow field in turn. Thus, it is of great significance to analyze the characteristics of the flow field and the force conditions of the fuel element. In this paper, we carry out simulations of the flow field with a structured mesh based on CFD (computational fluid dynamics). We analyze the effect of the motion and position of the fuel element on the flow field. Then we accomplish the force analysis of the fuel element in the flow, and acquire the fitting formulae of the force and torque on the fuel element. The experiment was performed on the experimental platform. The experimental results are in agreement with the theoretical analysis and verify its accuracy. This research may provide an important rationale for the dynamic and kinematic analysis of the fuel element pneumatic transportation as well as the basis for the stable operation of the reactor.

1. Introduction

With the decrease of fossil energy and the intensification of the greenhouse effect, nuclear energy is regarded as an important solution to the energy crisis in the future [Wu and Zhang, 2000; Ramana et al., 2013; Fertel, 2011; Al-Mansour et al., 2014]. Up to September 2014, 437 nuclear power plants were running all over the world while the installed capacity of the nuclear power plants under construction was 374.5 GWe [Park, 2014]. The International Energy Agency released the World Energy Outlook by the end of 2014 [World Energy Outlook, 2014]. It says that the installed capacity all over the world will increase to 620 GW by 2040 from 392 GW in 2013. Among so many kinds of nuclear power plants, pebble bed high temperature gas cooled reactor (PBHTGCR) has attracted more and more attention because of its advantages such as safety and high efficiency [Kasten, 1991; Ponomarevstepnoy et al., 1991; Abram and Ion, 2008]. Since 1960s, Germany, China and South Africa have carried out the research and development of PBHTGCR in turn [Koster et al., 2004; Zhang, 2014]. China is constructing HTR-PM (high-temperature-reactor pebble-bed module) demonstration plant, of which the electric power is 200 MW [Zhou and Zhang, 2010; Wu and Yu, 2007]. It will be the first commercial PBHTGCR in the world. Moreover, China declared in 2013 that the construction of a PBHTGCR with electric power of 600 MW had been started [Wang, 2014].

Spherical fuel elements are transported pneumatically and singly in the pipelines with complex patterns in a pebble bed reactor [Zhang and Sun, 2006; Yang et al., 2014; Xiao and Liu, 2000]. At any time there is at most one fuel element in the pipeline. This transportation method is very different from traditional methods. The most salient feature is that D (the diameter of the fuel element) is very close to D_p (the internal diameter of the pipeline). So it is called pneumatic transportation of near-diameter spheres in pipeline (PTNSP) [Zeng et al., 2011a, 2012]. The gas used for transportation is helium. The number of the fuel elements transported in the pipelines every day is between 6000 and 9000 while the length of the pipelines is thousands of meters [Zhang and Sun, 2006]. Fig. 1 shows the force condition of the fuel element during the transportation. Z-axis coincides with the pipeline axis and Y-axis is perpendicular to the pipeline axis. The force on the fuel element by the helium flow includes F_d, F_y and M, as shown in Fig. 1. F_d is in the Z – direction and F_y is in the Y – direction. M is a torque perpendicular to Z-axis and Y-axis. This force and torque determine the motion of the fuel element. The motion affects the transportation efficiency

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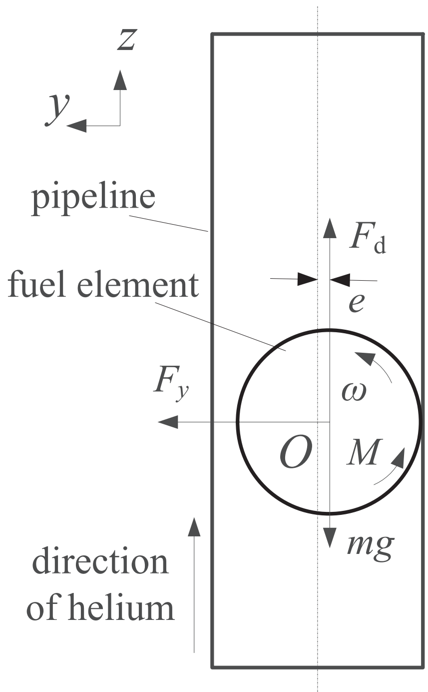

Fig. 1. Force condition of the fuel element.

and the collisions between the fuel element and the pipeline. This has great influence on the stability and reliability of the reactor. Thus, it is of great significance to analyze the characteristics of the flow field and the force condition of the fuel element [Liu and Xiao, 2001; Xiao et al., 1997].

Since the 1960s, several scholars have adopted different methods of research. Rysy [1973] thought that the force on the fuel element was determined by the density and velocity of the flow. They derived a formula for calculating the floating velocity. Liu et al. [2001] introduced the design of the pipelines and the type selection of the equipment for the fuel elements pneumatic transportation of HTR-10. They obtained the relationship between C_d (the drag coefficient of the fuel element) and k (the ratio of the D to D_p) using an empirical formula. On this basis they set up a physical model of the transportation process and obtained the velocity of the fuel element. Zeng et al. [2011b] acquired C_d with Bernoulli's principle and continuity equation. They derived the equations of the motion of the fuel element and described its motion characteristics. Shen et al. [2012a] analyzed the characteristics of the flow field based on CFD. Then they obtained the C_d, C_y (the lateral coefficient of the fuel element) and C_m (the torque coefficient of the fuel element). On this basis they established the motion equation of the fuel element. Liu et al. [2015] carried out a dynamic analysis of the fuel element. They obtained transportation efficiency, the frequency of the collision between the fuel element and the pipeline, and many other important parameters. However, most of the previous researches adopted empirical formulae to calculate C_d, C_y and C_m. They did not consider the effect of e (the distance from the center of the fuel element to the axis of the pipeline, as shown in Fig. 1) and ω (the angular velocity of the fuel element, as shown in Fig. 1) on the calculation, which led to a big deviation between the theoretical analysis and the experimental results. Shen et al. [2012b] used unstructured mesh for simulations. This reduced the speed of the calculation. Then the calculation speed became the bottleneck of the research. What is more important, all the previous research adopted a formula for flow past body (FFB), as shown in Eq. (1):

$$
\begin{aligned}
F_d &= \tfrac{1}{2} C_d A \rho (v_g - v)^2 \\
F_y &= \tfrac{1}{2} C_y A \rho (v_g - v)^2 \\
M &= \tfrac{D}{4} C_m A \rho (v_g - v)^2
\end{aligned}
\qquad (1)
$$

where A is the windward area of the fuel element; ρ is the density of the helium; and v_g and v are the velocity of the flow and fuel element in the direction of the pipeline axis. However, Eq. (1) is suited to a sphere in an infinite flow field, but not to PTNSP. So the accuracy of the calculation results cannot be ensured.

In this paper, the model of the pneumatic transportation process is established. We make simulations of the flow field with structured mesh based on CFD. Then we accomplish the force analysis of the fuel element and analyze the effect of e and ω on its force condition. The results are compared with those obtained with FFB. The applicability of FFB is analyzed. On this basis we carry out an experiment on the experimental platform. The experimental results are in agreement with the theoretical analysis and verify its accuracy. This research may provide an important rationale for the dynamic and kinematic analysis of the fuel element pneumatic transportation as well as the basis for the stable operation of the reactor.

2. Model and analysis of the pneumatic transportation

2.1. Modeling and meshing of the flow field

According to fluid mechanics principle, the force on the fuel element is a function of many parameters, as shown in Eq. (2):

$$
\begin{aligned}
F_d &= f(D_p, D, e, \rho, \mu, \Delta v, \omega, T, P, \varepsilon_p, \varepsilon) \\
F_y &= f(D_p, D, e, \rho, \mu, \Delta v, \omega, T, P, \varepsilon_p, \varepsilon) \\
M &= f(D_p, D, e, \rho, \mu, \Delta v, \omega, T, P, \varepsilon_p, \varepsilon)
\end{aligned}
\qquad (2)
$$

where μ is the dynamic viscosity of the helium, T and P are the temperature and pressure of the flow field, ε_p and ε are the surface roughness of the pipeline and the fuel element respectively, and Δv is the velocity difference of the helium at the inlet and the fuel element. In this paper, D_p, D, ρ, μ, T, P, ε_p and ε are all fixed values, as shown in Table 1 [Shen et al., 2013, 2012b; Li et al., 2009; He et al., 2003].

ANSYS ICEM CFD is used to mesh the flow field. ICEM is one of the most widely used softwares for mesh generation. Compared to others, ICEM's function for generating meshes is stronger. It can generate hexahedron meshes with high quality. For flow field with complex structure, ICEM can generate hexahedron meshes and

Table 1
Data used in the simulation.

Parameters	Symbol	Unit	Value
internal diameter of the pipeline	D_p	mm	65
diameter of the fuel element	D	mm	60
density of the helium	ρ	kg/m^3	7.0
viscosity coefficient of the helium	μ	kg/ms^{-1}	2.77×10^{-5}
temperature of the helium	T	°C	200
pressure of the helium	P	MPa	7.0
roughness height of the pipeline	ε_p	mm	3.2×10^{-3}
roughness height of the fuel element	ε	mm	6.3×10^{-3}
mass of the fuel element	m	kg	0.2
velocity difference of the helium and the fuel element	Δv	m/s	1, 2, 3, 4, 5
velocity of the helium flow	v	m/s	7.0
angular velocity of the fuel element	ω	rad/s	10π, 20π, 30π, 40π, 50π