

# Modeling and Application of Pneumatic Conveying for Spherical Fuel Element in Pebble-Bed Modular High-Temperature Gas-Cooled Reactor

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**Abstract** — *The fuel handling system is an important system for on-load refueling in pebble-bed modular high-temperature gas-cooled reactor. A dynamic model of pneumatic conveying for spherical fuel element in fuel handling system was established to describe the pneumatically conveying process. The motion characteristics of fuel elements in pipeline and the effect of fuel elements on gas velocity were studied using the model. The results show that the theoretical analyses are consistent with the experimental. The research has been used in developing full scope simulator for pebble-bed modular high-temperature gas-cooled reactor; also provides references for the design and optimization of the fuel handling system.*

## I. INTRODUCTION

The high temperature gas cooled demonstration plant under construction is a type of modular pebble bed reactor. The flowing spherical fuel element composed reactor core is one of important characters. Due to its favorable geometry, on-load refueling is realized in HTR-PM. The Fuel Handling and Storage System (FHSS) is an important system to realize this function. Fuel spheres are removed from the bottom of the reactor continuously and transported through the FHSS while the reactor is operated at full power. Through the FHSS, burn-up of fuel spheres is measured by burn-up and measuring devices first. If the targeted burn-up has not been reached the unburned fuel spheres will be reloaded to the reactor from the top of it to recycle, meanwhile the burnout fuel elements will be delivered to the spent fuel storage tank. The schematic diagram of the FHSS is shown in figure 1.

Full Scope Simulator is an important part of the HTR-PM demonstration power plant. It is very important to improve the safety of nuclear power plant operation by simulator training. Operator must pass the simulator training to get manipulate license.

As the first full scope simulator of HTR-PM demonstration power plant, FSS can be applied in

design verification and operation procedure testing, besides the operator training.

The FHSS is an uniqueness system of the HTR-PM Plant. The simulation accuracy of the FHSS is directly related to the accuracy of full scope simulator and the key is the simulation of the pneumatic conveying. The fuel sphere pneumatic conveying is different to bulk pneumatic conveying commonly used in general industry. The diameter of the spherical fuel element is close to the pipeline diameter, 60mm for fuel sphere outside diameter and 62mm for pipeline inside diameter, diameter ratio close to 0.97, so called “nearly equal diameter” fuel sphere pneumatic conveying.

This paper will focus on fuel sphere pneumatic conveying process in pebble bed reactor. A dynamic model of fuel sphere pneumatic conveying was established to study the motion characteristics of fuel element. The FHSS model tool is shown and the preliminary system unit is included in the paper.

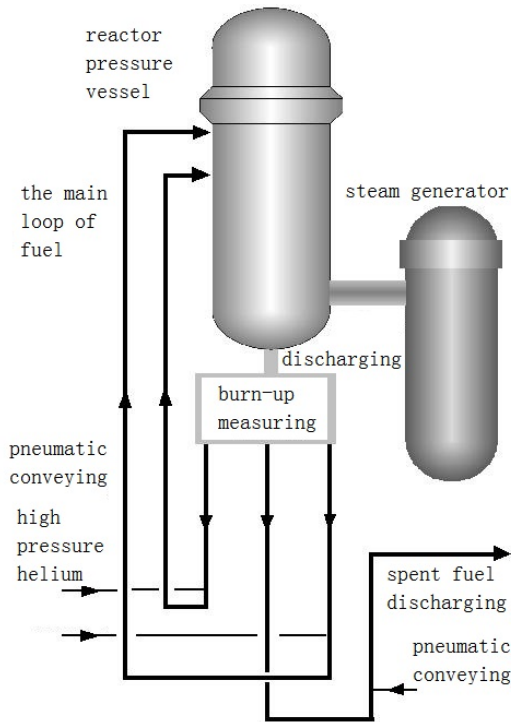


Fig. 1: The schematic diagram of the FHSS

## II. THE FHSS MODEL

### II.A. Pneumatic thrust of pneumatic conveying

In the full power operation condition, the pressure of helium for pneumatic conveying is 7.2MPa, 50~60°C for the temperature and 6m/s for the helium velocity. According to the above parameters Reynolds number of the flow over fuel sphere is calculated:

$$\text{Re} = \frac{uD_b\rho_g}{\mu} = 1.72 \times 10^5 \quad (1)$$

Where,  $u$  is helium velocity,  $m/s$ ;  $D_b$  is fuel sphere diameter,  $m$ ;  $\mu$  is dynamic viscosity,  $N \cdot s/m^2$ ;  $\rho_g$  is helium density,  $kg/m^3$ .

Therefore, “nearly equal diameter” pneumatic conveying process in sphere flows pipeline is large Reynolds number flow. According to feature of this type pneumatic conveying, the following assumptions are made:

(1) The boundary layer separation occur on the surface of sphere earlier, so the point of flow separation is approximately on the equator line of sphere.

(2) As the turbulent flow in pipeline, the drag coefficient of the flow over fuel sphere is irrelevant to Reynolds number.

(3) Differential pressure of the flow is the main cause of Pneumatic thrust. The frictional drag between Helium and sphere is not considered.

Under certain assumptions, Pneumatic thrust  $F$  of “nearly equal diameter” pneumatic conveying is:

$$F = \frac{1}{2}CA_b\rho_g(v_g - v_b)^2 \quad (2)$$

$$F = \Delta P \cdot A_s \quad (3)$$

Where,  $C$  is drag coefficient of fuel sphere;  $A_b$  is cross area of fuel sphere,  $m^2$ ;  $\rho_g$  is Helium density,  $kg/m^3$ ;  $v_g$  is Helium velocity,  $m/s$ ;  $v_b$  is fuel sphere velocity;  $\Delta P$  is differential pressure of before and after fuel sphere,  $MPa$ ;  $A_s$  is cross area of pipeline,  $m^2$ .

The drag coefficient of fuel sphere flow in pipeline can be acquired from the following experiential formula.

$$C = \frac{1}{[(1-k) + 0.5(1-k)^3]^2} \quad (4)$$

$$k = D_b / D_s \quad (5)$$

Where,  $D_b$  is fuel sphere diameter,  $m$ ;  $D_s$  is pipeline diameter,  $m$ .

### II.B. Motion analysis of fuel sphere

A single fuel element in pneumatic conveying, according to the requirements of the different transport process and the structure of the different section, shows different motion state, including acceleration, uniform motion and slowdown. The pipeline of pneumatic conveying is composed of bending pipes and straight pipes. The following simplifications are made:

- (1) The bending pipe is simplified as piecewise straight pipe;
- (2) The radial motion and collisions of fuel sphere are ignored.

A typical pipe element with a sphere is shown in Figure 2.

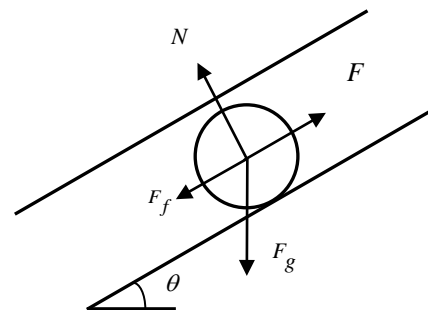


Fig. 2: Forces Exerted on a Sphere in a Pipe  
Here,  $F$  is the drag force, and  $F_f$  is the sliding frictional force.

The net force on the sphere is parallel to the pipe,

$$m \frac{dv_b}{dt} = \frac{1}{2} CA_b \rho_g (v_g - v_b)^2 - mg \sin \theta - fmg \cos \theta \quad (6)$$

Where,  $m$  is mass of fuel sphere, kg;  $f$  is friction coefficient;  $\theta$  is the horizontal inclination of the pipe relative to the horizontal axis.

When accelerated velocity is zero and fuel sphere velocity is zero, the helium velocity is called critical velocity.

$$\text{Critical condition: } \frac{dv_b}{dt} = 0, \quad v_b = 0$$

$$v_c = \sqrt{\frac{2mg(f \cos \theta + \sin \theta)}{CA_b \rho_g}} \quad (7)$$

The maximum speed of fuel sphere:

$$v_f = v_g - \sqrt{\frac{2mg(f \cos \theta + \sin \theta)}{CA_b \rho_g}} \quad (8)$$

### II.C Admittance calculation of pneumatic conveying pipeline

In fluid network, the relation of flow rate and pressure in pipeline without fuel sphere can be written as:

$$G = A_{pass} \cdot \sqrt{\rho_g \cdot (\Delta P + \rho_g g \Delta h)} \quad (9)$$

Here,  $A_{pass}$  is admittance,  $m^2$ , relating to cross area and resistance coefficient;  $\Delta h$  is height difference of import and export pipeline,  $m$ .

For the gas flowing in pipeline, the height difference is neglected. So differential pressure could be expressed as flow rate:

$$\Delta P = \frac{G^2}{A_{pass}^2 \rho_g} \quad (10)$$

On the basis of the hypothesis of “nearly equal diameter” pneumatic conveying process, helium flow frictional resistance effect on loss in gas energy is ignored. Combining equation (2) and equation (3) yields:

$$\Delta P = \frac{1}{2} \frac{CA_b}{A_s} \rho_g (v_g - v_b)^2 \quad (11)$$

Transform into:

$$\Delta P = C_1 \cdot \frac{1}{2} \rho_g v_g^2 \quad (12)$$

$$C_1 = C \cdot \frac{A_b}{A_s} \left( \frac{v_g - v_b}{v_g} \right)^2 \quad (13)$$

Differential pressure of helium flow is expressed with helium flow rate of pneumatic conveying:

$$\Delta P = \frac{G^2}{A_1^2 \rho_g} \quad (14)$$

$$A_1 = A_s \cdot \sqrt{\frac{2}{C_1}} \quad (15)$$

### II.E. Model test

Using the pneumatic conveying motion model above, motion characteristics of fuel sphere flowing in pipeline and the effect of fuel sphere on helium velocity are analyzed.

Table 1 lists the basic parameters using in the model.

name of parameter	unit	value
diameter of sphere	mm	60
density of sphere	kg·m <sup>-3</sup>	1730
diameter of pipeline	mm	62
total length of pipeline	m	40
horizontal inclination of the pipeline	°	0~90
friction coefficient of pipeline	—	0.41
Helium inlet pressure	MPa	7.01
Helium inlet temperature	°C	60
Helium outlet pressure	MPa	7
Helium flow rate	kg/s	0.18

Table 1: Basic parameters used in model.

Figure 3 shows the simplified sphere flow pipeline. The sphere flows pipe is compose with three pipes with different length and horizontal inclination.

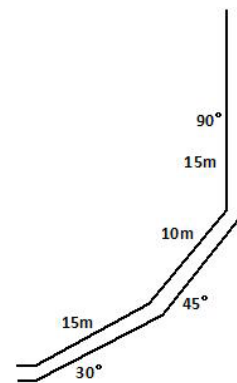


Fig. 3: The simplified sphere flow pipeline.

Figure 4 illustrates the fuel sphere velocity and Helium velocity changing along with the pipeline length. There are four stages for pneumatic conveying of the fuel element.

In the first stages, the fuel sphere enters into the pneumatic conveying pipeline at a speed of zero. Then the Helium flow decelerate and the fuel sphere accelerate. When the pneumatic conveying thrust is

equal to the fuel sphere resistance, the fuel element is accelerated to maximum speed and the system reaches an equilibrium state.

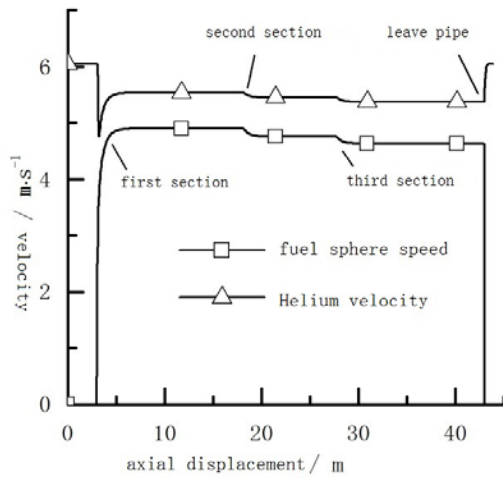


Fig. 4: Fuel sphere speed and Helium velocity

In the second stages, the fuel sphere leaves the first pipeline and enters into the second pipeline. As the horizontal inclination changing from 30° to 45°, the fuel sphere and Helium flow decelerate and reaches a new equilibrium state.

From figure 4, some important parameters of fuel sphere pneumatic conveying are available. The fuel sphere running speed is about 4.63~4.90m/s, which is consistent with the measured result.

### III. THE MODELLING TOOL

According to the theories, the Pebble software modelling tool was developed for the FHSS. The FHSS model tool consists of two parts: the model and the Graphical User Interface (GUI), which is a graphical user front-end to build and test an FHSS configuration. The model is formalized by utilizing Object-Oriented Design (OOD) methodology, which is subject to the real-time platform of the 3KEYmaster Simulation System.

Sphere flow system could be considered as discrete system based on time series. The network topology relation between each device is indicated with the pipeline. All components in a simulated FHSS network are calculated one by one in a sequential order without network solving method. Gravitational fall and pneumatic conveying processes are simulated in pipeline, also the storage function. Generalization is also used in individual classes. For example, the tank has the same features as a buffer and a spent fuel tank.

Users use the Pebble GUI to configure an FHSS model and integrate it with 3KEYmaster for testing. The FHSS model will couple of thermal hydraulics (Flowbase) to simulate pneumatic conveying process. Malfunctions include two types: special malfunctions

and general malfunction. Special malfunctions are introduced from the instructor station, while general malfunctions are integrated into the Pebble tool. The Pebble icons are used to generate the simulation drawing. An icon represents a component in the FHSS. Figure 5 displays the icon component representation.

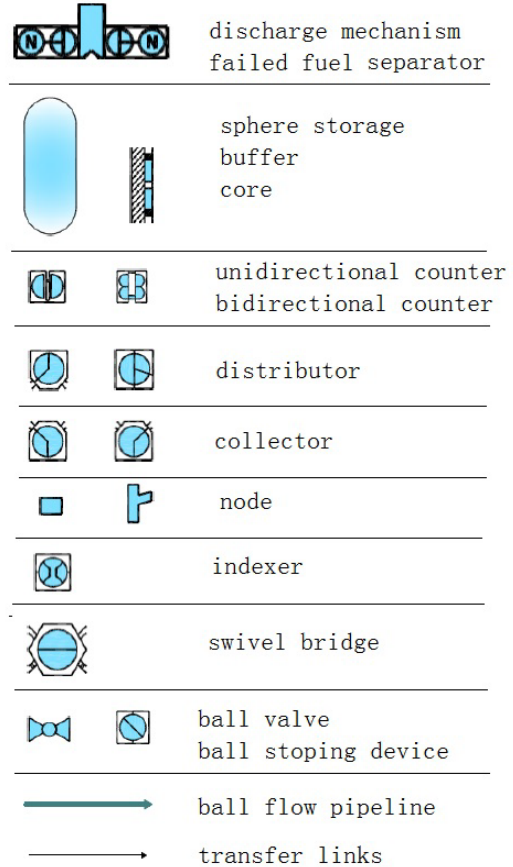


Fig. 5: Icon components for the FHSS

Functional tests for all modular components were done to ensure that functions were implemented as required. To achieve this goal, the targeted component was tested with a configuration of a number of other relevant components. All components shown in figure 5 were tested.

The test configuration as an example is shown in figure 6. The configuration includes two tanks, three pipes, one buffer, ball valve and an indexer. Figure 6a show the initial test configuration. Figure 6b is a snapshot of the test result after simulation.

In figure 6a, the sphere tank contains 100 spheres, and releases 10 spheres in figure 6b. The indexer indexes 7 spheres. The first five spheres arrived in the sphere tank with a capacity of five spheres. Other incoming spheres accumulated in pipeline 3. The remaining 3 spheres stayed in the buffer upstream to the indexer.

The results demonstrated the validity of the Pebble model physics and implementations. Figure 7 shows a larger configuration for detailed analysis of

sphere travelling, including pneumatic conveying process.

is an invaluable tool for the further understanding and operation of the HTR-PM plant.

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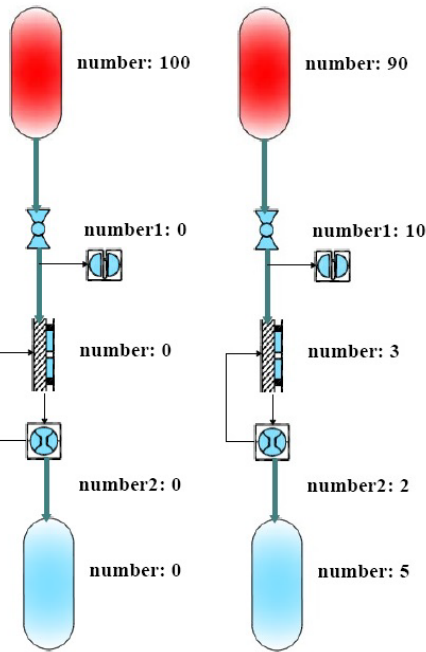


Fig. 6: Test configuration

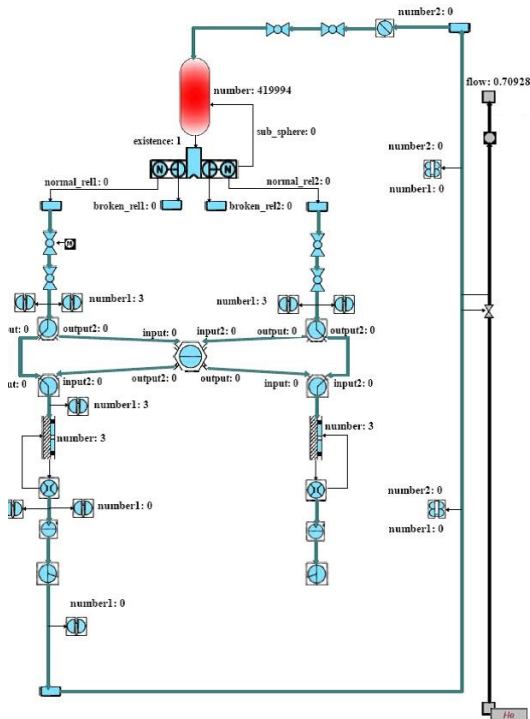


Fig.7 Larger configuration for test

III. CONCLUSION

Fuel sphere pneumatic conveying process is analyzed in this paper. The FHSS model which is a new design concept for the Fuel Handling System was developed using Pneumatic conveying theory. The FHSS model has been tested rigorously during the development phase. This test model of the FHSS