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The Cross-Flow Mixing Analysis of Quasi-Static Pebble Flow in Pebble Bed Reactor

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Abstract –*In the pebble bed reactor, large number of fuel pebbles' movement law and moving state can affect the reactor's design, operation and safety directly. Therefore the pebble flow, which is based on the theory of particle streaming, is one of the most important research subjects of the pebble bed reactor engineering. The in-core pebble flow is a very slow particle flow (or called quasi-static particle flow), which is very different from the usual particle motion. How to accurately describe the characteristics of in-core pebble flow is a central issue for this subject. Due to the presence of random flow, the cross-mixing phenomenon will occur inevitably. In the present paper, the mixing phenomenon of pebble flow is generalized on the basis of experiment results. The pebble flow cross-mixing probability serves as the parameter which describes both the regularity and the randomness of pebble flow. The results are provided in the form of diagrammatic presentation.*

I. INTRODUCTION

High temperature gas-cooled reactor (HTR) is considered as one of the candidates for the next generation advanced nuclear reactors, and is designed to be the uranium-based, graphite-moderated and helium-cooled reactor. HTR-PM [1], which is developed by INET, Tsinghua University, has been approved to be one of the National Special Grand Science-technology Projects of China. HTR-PM is a pebble bed type and modular construction reactor. The reactor core is a pebble bed which is filled with spherical coated fuel pebbles. The fuel pebbles travel through the core from top to bottom in a very low speed under gravity and their positions at a time are determined by the flow pattern of the pebble bed. The pebbles are drained out from the discharge hole at the bottom of the core and new pebbles are reinserted into the core at the top.

In addition to the gravity-driven longitudinal quasi-static flow, the pebbles inevitably radially flow inside the core. The radial flow is caused by the randomness of pebble flow. The cross-mixing of pebbles in different regions within the core will occur as a result of radial flow, and increase the randomness degree of pebble flow. Since the burnup of each fuel pebble may be different, the cross-mixing will affect the core physics, the heat transfer, the core design and other factors. The cross-mixing phenomenon of high temperature reactor core is studied in the present paper. The research bases and mathematical method are introduced, and the obtained calculated results are provided by the form of probability of pebble flow between different regions of the reactor core. In section 2, the research bases, including the pebble flow experiment and the pebble-spindle theory, are introduced. In section 3, the mathematical method for describing the cross-mixing phenomenon is provided. In section 4, there are the results and discussions.

II. RESEARCH BASES

II.A. Pebble Flow Experiment

Fig. 1 shows the photos and description of pebble flow experiment rig in INET [2]. The main design parameters of the facility are collected in Table 1. The experimental rig is designed with reference to the actual engineering design of pebble bed high temperature reactor at the scale of 1:5, and is a two-dimensional approximation compared with the actual three-dimensional cylindrical core. Some experimental results on the pebble flow stream lines and distributions will be given in the next section.

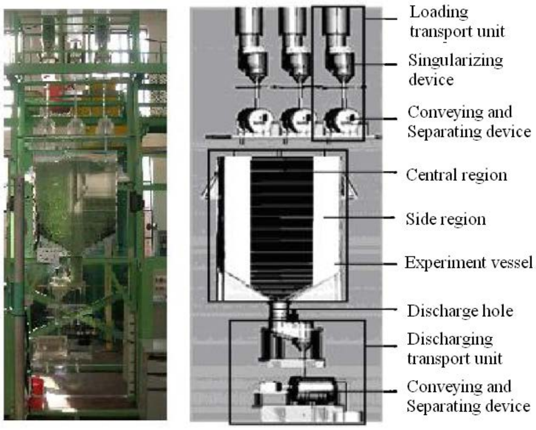

Fig. 1: Pebble flow experiment rig in INET.

Table 1: The main design parameters of the pebble flow experiment rig.

Experiment vessel	Width	600mm
	Height	2200mm
	Thickness	120mm
	Base cone angle	30°
	Material	Plexiglass
Experiment ball	Diameter	12mm
	Quantity	150,000
	Material	Glass

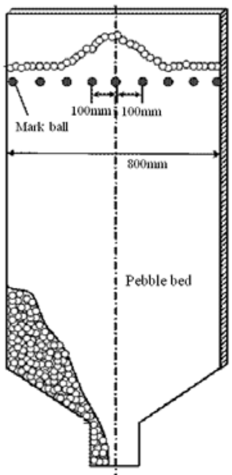

Fig. 2: The quantitative experimental method of pebble flow.

II.B. Pebble-Spindle Theory

If an experiment ball is added into the experimental vessel at a radial position on the top, the movement of the ball in the pebble bed may be limited within a small radial region. Some related pebble flow experiments have verified this statement. Fig. 2 is a schematic that indicates the quantitative experimental method of pebble flow. Nine different symmetrical radial positions are set on the top of pebble bed and mark balls are added into vessel at each position. The movement of the mark balls through the whole experimental vessel (on behalf of the reactor core) can reflect the overall movement condition of the pebble bed. Meanwhile, the mark balls are repeated added for several times at each position. The motion information of a large number of mark balls from the same starting position can be obtained by recording the trajectory and the movement time of the mark balls [3][4].

The trajectory distributions of pebble flow obtained from quantitative experiments are shown in Figure 3. Only right half of the core is analyzed with consideration of the symmetry. The radial position on the top are identified as id0~id4 from middle to right side. The results show that: 1) the mark balls move with randomly and dispersedly; 2) but under the present experimental conditions the mark balls which are added at the same radial position will substantially move in a corresponding area, almost never run out of the area. The confidence interval of the area is usually defined as 95%. The area is designated as “pebble-spindle” due to its spindle shape, and the corresponding research method is named “pebble-spindle theory”. At any height position, the radial position of a mark ball can be fitted by Gaussian probability density function:

$$p(x;\mu,\sigma)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \qquad \text{(eq. 1)}$$

Where μ is the average value of radial position x and σ is the standard deviation. The width of pebble-spindle is 3.92σ due to 95% area is in the range of about [-1.96σ, 1.96σ]. The pebble-spindle width of id0~id4, which stands for the standard deviation σ, are shown in Fig. 4.

III. MATHEMATICAL METHOD FOR DESCRIBING THE CROSS-MIXING PHENOMENON

III.A. The Core Flow Channel Division

In order to study the flow cross-mixing rule between different regions within the core, the core must be divided into several divisions. In the present paper, the core is divided into 20 regions on the height orientation and 5 regions on the radial orientation. On the height orientation, each partition element is uniform with 110mm height. The partition principle on the radial orientation is to ensure that the core area of each element be uniform on the top of the core. The final core division result is shown in Fig. 5. The dividing lines of adjacent flow channels also represent the department's average pebble flow streamline.

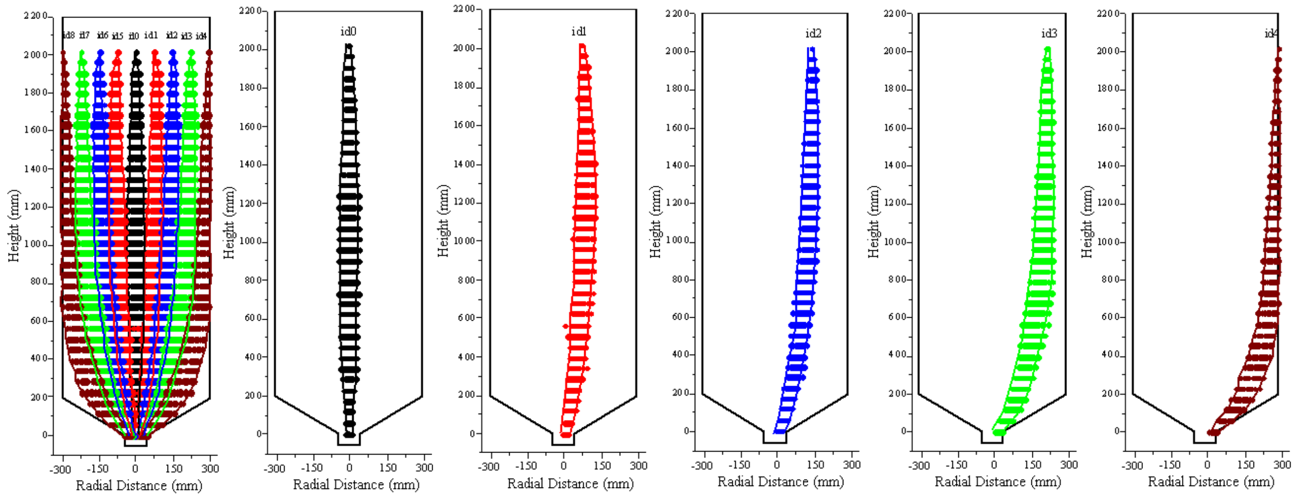

Fig. 3: The pebble-spindle of nine radial positions.

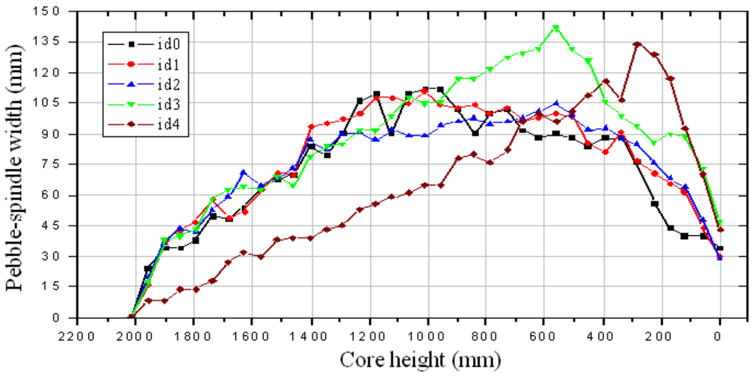

Fig. 4: The pebble-spindle width versus core height.

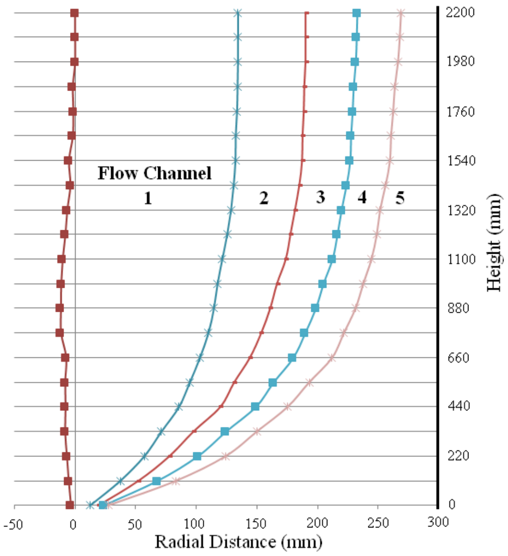

Fig. 5: The core division.

III.B. The Superposition of Gaussian Probability Density

Theoretically, the pebbles in each region of core have chance to flow into every channel below. However, the probability of flowing into the three channels which are directly below is the maximum, as shown in Fig. 6. Therefore the cross-mixing probabilities from one region to all flow channel regions below can be obtained by superimposing the pebble-spindle Gaussian probability density function of the region's boundary:

$$p_i = \frac{\int pdL}{L} \qquad \text{(eq. 2)}$$

Where p_i represents the flow probability from the region to all channels below, and L is the side length of the region. p is the Gaussian probability density function which can be gained by Eq.(1) with μ and σ data from Fig. 5 and Fig.4, respectively.

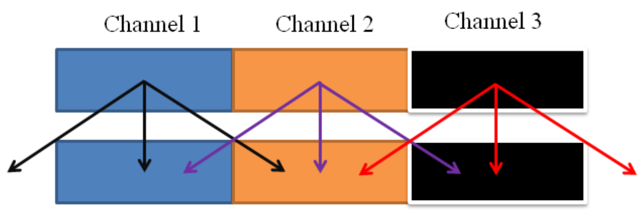

Fig. 6: The schematic of cross-mixing between adjacent channels.

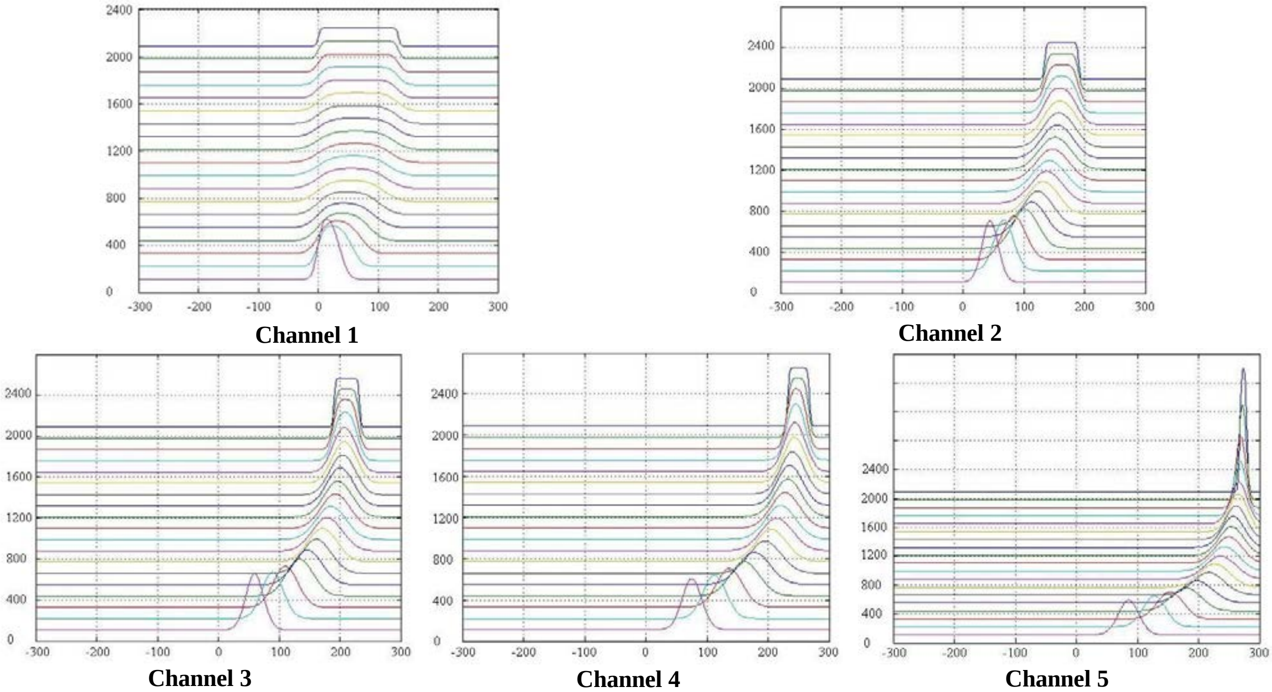

Fig. 7: The cross-mixing probability results.

IV. RESULTS AND DISCUSSIONS

IV.A. The Cross-Mixing Results

The cross-mixing results are summarized in Fig. 7. The results clearly show the statistical pattern of pebble flow:

1) The pebbles flow from top to bottom in the core, driven by gravity. The appearance of streamline is closely related to the shape of the outlet and adjacent areas of core side.

2) In any region, the majority of pebbles move into the region directly below, and more than 99.9% of pebbles flow into the closest three lower channels. This indicates that the regularity of pebble flow: the pebbles will only flow into the directly lower and adjacent channels and almost never appear in any farther channel.

3) In any flow channel, the closer to the outlet, the greater the radial displacement chance of the pebble, and the possibility of pebble's moving to adjacent channels is greater. This is because of the special outlet boundary shape increases the pebble's horizontal speed. On the other hand it is also related to the channel division, the channel close to the outlet is narrower.

4) There is no big deviation between the results of different channels. At any height, the flow values of different channels are very close to each other. This indicates that the radial orientation homogeneity of pebble flow is pretty high. The deviation of curves of each channel in Fig. 7 is due to the difference of flow channel dimensions.

IV.B. Discussions

Pebble flow is one of the principal issues for the design of the pebble bed reactor. The flow cross-mixing directly affects the physical and thermal design of the reactor core. The fuel pebbles are driven by gravity and moves from top to the bottom in a very low speed, thus the pebble flow can be considered as quasi-static flow. There exist both regularity and randomness for the pebble flow. Due to the presence of random flow, the cross-mixing phenomenon will occur inevitably. In this paper, the pebble-spindle theory, which can describe the pebble flow quantitatively, is introduced. On the basis of pebble-spindle theory, the pebble flow cross-mixing probability is calculated by using experimental results. The cross-mixing probability calculation results reveal both regularity and randomness of pebble, and will have a significant impact on the physics computing of pebble bed reactor core.

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