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An Evaluation on the Pebble Flow Velocity in PBMR Core by Using Modified Kinematic Model

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1. Introduction

PBMR core is filled with a large number of pebbles, which are randomly piled up in the core region. During the process of the fuel loading and extraction, the pebbles flow downward through the core. The fuel burn-up is affected by the local powers and the residence times in the core. It is noted that the pebble velocity depends on their positions and it affects the residence times of the pebbles. Therefore, it is an important issue that the pebble velocity affects the neutronic behavior in the reactor.

In this study, a modified kinematic equation and its point kernel approach were proposed to evaluate the velocity distribution in the PBMR core.

2. Methods

Continuum kinematic model proposed by Nedderman, et al. [1] is widely used for the analysis of the gravity-induced flow. Although the model has no theoretical justification, it has various advantages which are the simplicity to use, easy to refine, and the applicability in case of the slow granular flow. Nevertheless, the kinematic model for the analysis of the pebble flow has some problems. The diffusion length constant in the model does not only depend on the properties of the pebble but also on the geometry of the reactor core [2, 3]. And, the velocity distributions are not well matched in some regions in the kinematic model [3]. It also has a difficulty to analyze the complex geometries such as PBMR, which has an annular core with three defuel chutes.

The kinematic model proposed by Nedderman is derived from the relationship between the horizontal velocity and vertical velocity given as following:

$$\frac{\partial v_z}{\partial z} = B\nabla^2 v_z \qquad (1)$$

where, v_z*= vertical velocity*
B= diffusion coefficient

In this study, it is assumed that the pebble flow has compressibility caused by the wall friction. For the application of the wall friction effect, a velocity reduction coefficient, which has a ($dv_z/(v_z dz)$) dimension, is assumed in this study. It is assumed that the velocity reduction coefficient is not changed by the vertical location due to the law of inertia. With the assumptions, Eq. (1) can be replaced as Eq. (2) by adding the two frictional terms.

$$\frac{\partial v_z}{\partial z} = B\nabla^2 v_z - f_b v_z H(r-b(r,z))H(h-z) - f_w v_z H(r-w)H(z-h) \qquad (2)$$

where, f_b, f_w *= velocity reduction coefficients for the conical wall and cylindrical wall frictions*
b(r,z) = a bottom boundary in the cone region
h = a height of cone region
H = a Heaviside function

The Eq. (2) has a difficulty to evaluate the pebble flow velocity for the annular core. Hence, we introduce a point kernel method, which is commonly used to solve the reactor shielding problems. To apply the point kernel method, it is assumed that the core region is divided by a cubic unit lattice and the point kernels are located at the centers of the divided regions. The center of the each divided region is expressed as the (*i*,*j*,*k*). The pebble velocity profile at (*i*,*j*,*k*) is influenced by the lower layer, (*k*-1). Therefore, the diffusion term in Eq. (2) is approximated as below equation:

$$v_z(i,j,k) = v_z(i,j,k-1) + B\Delta z \sum_{i',j'}^{n,m} \left\{ \frac{v_z(i',j',k-1) - v_z(i,j,k-1)}{\Delta r^2(i',j',k-1)} \right\} \qquad (3)$$
$$-\Delta z f_b v_z H(r-b(r,z))H(h-z) - \Delta z f_w v_z H(r-w)H(z-h)$$

where, $\Delta r(i',j',k-1)$ *= distance between the datum point kernel (i,j,k-1) and other point kernel (i',j',k-1).*

The proposed method uses the coefficients which are diffusion length (*B*) and wall velocity reduction coefficient (f_b, f_w). Various velocity distributions can be simulated by the changes of the coefficients; therefore, the problems, which are the distortion of the velocity distribution, can be solved by using this method.

3. Experiments and Results

The pebble flow experiments were performed to get the diffusion length and velocity reduction coefficients. A half model of a cylindrical core was designed as shown in Fig. 1. The radius of the cylindrical core is 14 cm and the cone angle is 45°. The exit diameter is 4 cm and 6 mm plastic balls are used for the experiment. The red plastic balls are located at the points which are the interesting locations for the velocity estimation.

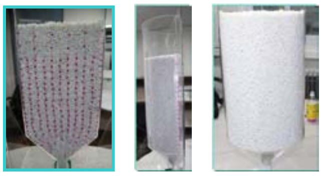


Fig. 1. Half Model Configuration of Cylindrical Core

The velocities from the cylindrical region were estimated after the small amount extraction of the plastic balls. The results of relative velocities normalized on the maximum values in each layer were shown in Fig. 2.

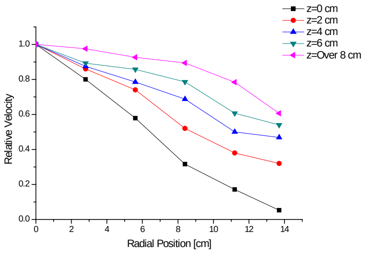


Fig. 2. Velocity Profile from the Half Model Experiment

For the reconstruction of the experiment result, the velocity profile was evaluated by the proposed method at B=0.013, f_w=0.6, and f_b=0.7.

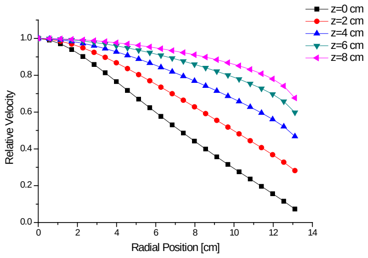
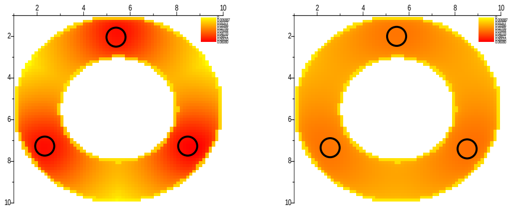
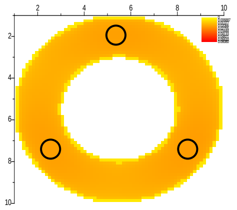


Fig. 3. Velocity Profile of Cylindrical Core Reconstructed by the Proposed Method

By using the coefficients chosen in above, the velocity distribution of PBMR annular core was evaluated. The inner radius and outer radius of the core is 100 cm and 185 cm, respectively. The height of the core is 1011.7 cm and cone angle is 45^o. Three exit chutes were located at r=144 cm. The results with the different heights in the active core were shown in Fig. 4.



(a) z= 0 cm (b) z= 57 cm



(c) z=114 cm

Fig. 4. Reconstructed Velocity Distributions on the Different Heights

At z=0 cm, the velocities at the centers of the exit chutes have maximum values and the velocity profile is dominantly affected by angular position; however, the angular velocity profile was converged as the increase of the z-axial position. The other results over z=100 cm show that velocity distributions were converged and the velocities depend on the radial positions. For the verification of the radial velocity distribution results, an experiment with 1/6 core model was performed. The results evaluated by experiment and proposed method were given in Fig. 5. The results show that the result with proposed method agrees well within 5% with the experiment result.

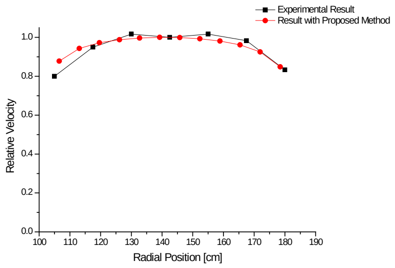


Fig. 5. Velocity Profile as the Different Radial Position over z =100 cm

4. Conclusions

This study is for the evaluation of relative pebble velocity in PBMR core. The modified kinematic model with the point kernel approximation method was proposed. The pebble flow experiment was performed to get the coefficients used in the proposed method. The velocity distribution in the PBMR core was evaluated and it was compared with the experiment result. It shows that the velocity distribution evaluated by the proposed method can properly simulate the pebble flow phenomenon. The problems of kinematic model referred in Chapter 2 can be solved with the proposed method. Therefore, it is expected that the results of the velocity distributions can be utilized for the accurate analysis of the reactor core characteristics as well as the burn-up calculation.

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