博士論文（要約）

Investigation of Debris Bed Coolability and Re-Criticality under the Self-Leveling Behavior of Mixed Solid Particles

(固体粒子のセルフレベリングによるデブリ冷却と再臨界に関する研究)

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Investigation of Debris Bed Coolability and Re-Criticality under the Self-Leveling Behavior of Mixed Solid Particles

(Abridged Version)

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Abstract

In a postulated core-disruptive accident (CDA) in Japan sodium-cooled fast breeder reactor (JSFR), the debris bed will be piled up to form a conical shape on a core support structure in the lower inlet plenum of the reactor vessel. The in-vessel retention (IVR) of CDA is of prime importance in enhancing safety characteristics of JSFR. In the heat-removal phase, IVR failure is dominated by thermal boundary failures. One of the main factors inducing thermal boundary failure is the incompleteness of stable coolability due to the debris bed exceeding the coolable limit.

In order to achieve the stable and effective cooling of debris bed with decay-heat removal, its thickness should be suppressed below the coolable limit by the enhancement of debris dispersion. For this purpose, the multi-layer debris tray is introduced to the JSFR design, on which the debris will migrate from the upper-layer tray to the lower tray, in cases where the coolable-limit thickness is exceeded. The preliminary evaluation by DEBNET code suggests that the relocated molten material would be stably cooled in the reactor vessel by fragmentation and debris-dispersion on the multi-layer debris tray, and the phenomena of thermal boundary failure due to the incompleteness of stable cooling could be avoided by the installation of the multi-layer debris tray. Even the result from the simulating calculation has uncertainty, the behavior of self-leveling will still be initialized to help the debris bed particles re-distributing and suppressed the height of debris bed again. The effectiveness of self-leveling behaviors on stable cooling for the debris bed has also been investigated in order to give further robustness to the present CDA scenario from the viewpoint of achieving IVR.

However, these previous analysis on the debris bed coolability and the probability of re-criticality is under the assumption of the debris bed with homogeneous distribution. In the real situation, the debris bed is a mixed-density debris bed. Therefore, when these mixed-density debris particles start to re-distribute during the phenomena of self-leveling, a debris bed with heterogeneous distribution will be formed. Furthermore, the heavier fuel particles would possibility form a stratified distribution, because , compared with the lighter structure particles, the heavier fuel particles will tend to sink to the bottom of the debris bed during the self-leveling. Under this condition, the capability of coolability and the probability of re-criticality could deviate from the previous study which is based on the assumption of homogeneous

distribution. Therefore, the objective of this study is to clarify in which conditions the debris bed will obtain stable cooling considering the effect of debris bed particle stratification during self-leveling on the generation of criticality.

To achieve this goal, both the neutronics model and CFD-DEM model should be built up for the final reactor scale study.

For the aspect of building neutronics model, through the neutronics calculation (via SERPENT) to evaluate the k-eff eigenvalue on three alternative configurations, it was found that the debris bed with a stratified distribution or centralized distribution have higher probability to attain the status of re-criticality, compared with the debris bed with homogeneous distribution. Therefore, it will be an potential issue when the mixed-density debris bed is under the self-leveling behavior, because a configuration which has higher possibility to be criticality is of possibility.

For the aspect of building CFD-DEM model, after a series of the sensitivity studies, CFD-DEM model had been verified by experiments under the cases of mixed-density particles bed. The verified CFD-DEM model can correctly track the heavy particles movement in the light particles bed with the water-injection. In addition, since the experiments is for simulating g phenomena of self-leveling in JSFR and have done the non-dimensional analysis, the verified CFD-DEM model is with the capability to be applied on it.

Finally, the reactor scale case of 35% of JSFR total fuel inventory is been chosen for being applied on the neutronics model and CFD-DEM model at the same time. The mixed-density debris bed is set as the stratified distribution, because it can compared the result with the previous study using the homogeneous distribution. When the self-leveling is processing, the temperature and the position information of these debris particles are successfully collected, and the k-eff eigen value shows a trend of decreasing. Therefore, self-leveling effect had been quantitively confirmed, even under the case of stratified distribution.

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1 Introduction

1.1 Background

In the construction of the CDA scenario for Japan sodium-cooled fast reactor (JSFR), at first, a most probable sequence was investigated taking into account the various phenomena appearing in the event progression and the various design measures to be applied to the device designs. According to the core disruption status, the whole sequence was categorized into the following four phases: (1) initiating phase, (2) early-discharge phase, (3)material-relocation phase and (4) heat-removal phase. The "early-discharge phase" means a phase in which the molten fuel could be discharged, before the formation of a large-scale molten-core pool, by an adequate design measure such as FAIDUS.

In the heat-removal phase, the debris bed will be piled up to form a conical shape on a core support structure in the lower inlet plenum of the reactor vessel. The key point of thermal boundary failure is the incompleteness of stable cooling due to the thickness of debris bed beyond the coolable limit.
In order to achieve the stable and effective cooling of debris bed with decay-heat removal, its thickness should be suppressed below the coolable limit by the enhancement of debris dispersion. For this purpose, the multi-layer debris tray is introduced to the JSFR design.

The previous evaluation suggests that the relocated core materials would be stably cooled in the reactor vessel by fragmentation and debris-dispersion on the multi-layer debris tray, and the thermal boundary failure due to the incompleteness of stable cooling could be avoided by the installation of the multi-layer debris tray.

The self-leveling, which is a mechanism flattening the debris bed by the disturbing from the heated coolant, can decrease the thickness of the debris bed, in order to attain the stable cooling and avoid the re-criticality. The effectiveness of self-leveling behaviors on stable cooling for the debris bed has also been investigated in order to give further robustness to the present CDA scenario from the viewpoint of achieving IVR.

1.2 Objective

The previous study about the coolability of the debris bed in JSFR have shown that the debris bed can attain the stable cooling when it evenly distributed on the multi-layer debris catcher. However, the research is based on the assumption of homogeneous distribution and using decay heat as the heat source.

However, in the real case, the debris bed contains mixed-density debris particles, including the heavier fuel particles and lighter structure particles. When the debris particles are re-distributed due to the external force (ex. Self-leveling), compared to the lighter structure particles, the heavier fuel particles will tend to sink to the bottom due to the difference od density. Finally, the debris bed would possible to form the heterogeneous distribution. For instance, the debris bed would form the stratified distribution, or even accumulate to some position in the debris bed.

The heterogeneous distribution of the debris bed would affect the possibility of re-criticality. Moreover, if the situation of the re-criticality happened, the fission power will be the heat source, and it will be the main factor to affect the previous assessment on the capability of the debris bed coolability.

Therefore, the objective of this study is to clarify in which conditions the debris bed will obtain stable cooling considering the effect of debris bed particle stratification during self-leveling on the generation of criticality.

The research structure is as follows. First of all, to study and investigate the mechanism of self-leveling is essential. In order to simulate the particle-fulid interaction under the phenomena of self-leveling, validating the CFD-DEM model is important. In this stage, the case without boiling will be focused on, because the previous study on the debris bed located on the multi-layer debris catcher is without the boiling. The way to validate CFD-DEM model is obtaining the data from the water-injection experiments, which is for simulating the phenomena of self-leveling. Another target is to build the capability of neutronics calculation on the different configuration of debris bed. Finally, the target is to apply the CFD-DEM model and neutronics model on a reactor scale case. Via this multi-physics simulation, the issue of coolability and re-criticality can be analyzed on the debris bed with heterogeneous distribution.

2 Methodology to solve self-leveling phenomena

Neutronics: Because the debris bed configuration will affect the k-eff and heat source, neutronics code will be used to calculate the heat source for the following CFD calculation.

CFD: In order to estimate the debris bed coolability, CFD will be used to calculate flow pattern and temperature distribution in the liquid sodium and the debris bed.

DEM: For the issue of the interaction between the fluid phase and particles, it can be achieved by coupling with the computational fluid dynamic (CFD) method through the drag force term. CFD-DEM, this hybrid computation method, can be expected as a suitable approach to treat on the simulation of self-leveling.

3 Neutronics model

3.1 SERPENT code: neutronics algorithm

SERPENT is used to calculate the fission reaction rate distribution in the fuel region to create a heat source for thermal-hydraulic coupling[14]. It also calculates the eigenvalue of the model to assess the reactivity effects of fuel and moderator temperature. SERPENT features accurate 3D geometry modeling and the best available, continuous nuclear data and physics, along with $S(\alpha,\beta)$ thermal scattering tables. Neutronic data is from the ENDF/B-VII.

3.2 Calculations

3.2.1 Case explanations

In this chapter, the main aims are to compare the possibility of re-criticality, and the heat source distribution between the homogeneous distribution and different heterogeneous distributions in the debris bed.

In this chapter, the stratified distribution model and centralized distribution model have been built. The difference between the stratified distribution model and centralized model is the fuel particles distribution. In the stratified distribution model, the fuel particles are set to the bottom layer of the conical debris bed, and the structure particles are put on the upper layer of the conical debris bed. Nonetheless, in the centralized distribution model, all the fuel particles are located to the center of the conical debris bed, and the fuel particles are surrounded by the structure particles.

3.2.2 Results and discussion

For the debris bed with 100% of JSFR fuel inventory and core structure, all the three distribution model attain the status of re-criticality. However, it still can be observed that the heterogeneous model has a trend of higher probability to induce re-criticality, especially on the centralized distribution model.

For the debris bed with only 35% of total JSFR fuel inventory and core structure, it can avoid the status of re-criticality. However, in the stratified distribution model and centralized model, both of them attain the status of re-criticality. These results presents that the debris bed concerning heterogeneous distribution model has a higher probability to meet the status of re-criticality, compared with the homogeneous distribution model.

In order to investigate the geometry effects on k-eff value for the debris bed, a series tests have been done, including different parameters of the fuel content, debris bed inclined angle, and the porosity on the conical debris bed. These tests are based on the conception of using homogeneous model.

According to these series of tests, it can be observed that, for a debris bed with being heterogenous, the fuel distribution will affect the probability of re-criticality, especially for the debris bed with obvious stratified distribution model or centralized model. Besides, based on the investigation of the relationship between the debris bed geometry and the probability of re-criticality, it can be observed that the one with lower porosity and higher inclined angle tend to escalate the probability of re-criticality.

4 Fluid dynamics model

In this chapter, the first step is to examine self-leveling and the characteristic of the debris bed with density-particle distribution. To do so, a multi-density particles bed will be set, and the movement of a heavier particle will be tracked under the situation of water injection from the bottom of the particles bed in order to simulate the phenomena of the self-leveling. Finally, the movement data of the heavier particle will be applied to validate the CFD-DEM model.

4.1 Experiments

4.1.1 Non- dimensional analysis

The experiment aims to simulate the self-leveling phenomena on the debris bed with mixed-density particles in JSFR for validation the CFD-DEM model. Self-leveling, which is a mechanism flattening the debris bed by surrounding coolant disturbing due to being heated, is a crucial factor on the analysis of CDA due to the relocation of the melting core. To simulate this phenomena, setting a mixed-density particles bed with flow disturbing to observe the heavier particle movement is necessary.

A transparent container is as the lower plenum. In order to observe the movement of particles, the water will be chosen as the coolant covering the particles bed, instead of using liquid sodium. For the mixed-density particles bed, the Fluorinated Ethylene Propylene (FEP) (density = 2000 kg/m^3) particles will be implemented as the lighter density particles. And a stain steel spherical particle (density = 7870 kg/m^3) will be put on the top of the particles bed. As for the FEP particle, since its refractive index is close to that of water at visible wavelengths, the characteristic of being transparent in the water can be applied on the tracking the movement of the steel ball[22], even steel ball is in the middle of FEP particles. Considering the density ratio in the real case, in the designed experiment, the density ratio is higher than the real situation. Therefore, the shape of FEP particles will choose cylinder shape to increase the resistance from other FEP particles collision, instead of using the spherical FEP particles. Finally, the water will be injected from the bottom of the container to disturb the particles bed. Therefore, to decide the inlet velocity of water is important.

4.1.2 Experimental setup

The transparent rectangular tank is with a height of 300 mm, 90mm in width, and 90 mm in depth. Water will be drawn from the water tank by the water pump, and the flow rate can be adjusted by the valve, recorded by the following flow meter. Finally, water will be injected from the center of bottom via a tube with a height of 5 mm and with an inner diameter of 5 mm. The Fluorinated Ethylene Propylene (FEP) (density = 2000 kg/m^3) cylindrical particles, which is with a height of 5 mm and a diameter of 5 mm, are put into the transparent rectangular tank. A steel spherical particle (density = 7870 kg/m^3), whose diameter is 8 mm, is put on the top of FEP cylindrical particles. On the front side and right side, there are two digital video camera for recording the trajectory of the particles movement.

Compared with most of researches without applying FEP material, for the topic of the simulating self-leveling behavior with mixed-density particles bed, this experiment provide much more details of an individual particle movement, instead of only observing the change of shape on the debris bed. It is also beneficial for validating the CFD-DEM coupling algorithm. The position of the steel ball can be recorded, and the related coordinates, as well as the velocity data can be extracted by the post processing via ImageJ, which is a public domain Java image processing program.

4.1.3 Experimental case explanations

The experiments can be divided to Case1, Case2 and Case3, respectively. Under different initial conditions of the three cases, the water will be injection on the center of the bottom surface of the multi-density particles bed.

The aim of performing Case1 and Case2 is to compare the effect of water-injection flowrate. Case1 is utilized the higher water-injection flowrate of 3.25 L/min, compared with the water-injection flowrate of 2.75 L/min in Case2. Both Case1 and Case2 have the same number of lighter FEP particles (900), the same height of particles bed (30mm), and the same height of water surface of 60 mm. A heavier steel particle is set on the center of the upper surface of the lighter FEP particles bed in both Case1 and Case2.

The aim of comparing Case1 and Case3 is to investigate the effect of the height of particles bed as. As in Figure 4.4, in Case3, the height of lighter FEP particles bed is higher than Case1, and the number of the lighter FEP particles and the height of the lighter FEP particles bed are 1700 and 50mm, respectively. The water surface of Case3(100mm) is also higher than the Case1(60mm). In both Case1 and Case3, a heavier steel particle is put on the center of the upper surface of the lighter FEP particles bed.

4.1.4 Experimental results and discussion

For the purpose of describing the movement of the heavier metal particle, the original point is set to the cent her of the bottom side of the particles bed. The x-axis is along bottom side in the front view, and the y-axis is along to the bottom side in the side view. In addition, the z-axis is set to along the direction of height of the particles bed.

For Case1, in the beginning, the heavier metal particle actually fall down along this space between the lighter FEP particles. However, when the heavier steel particle goes downwards, because the momentum exchange from injected water to heavier particle is too high, the heavier steel particle goes up and down violently in the z-direction, instead of directly falling down and being settled to the bottom. Besides, in the x-direction and y-direction, the position of the heavier metal particle is also randomly distributed during the water-injection. Finally, the heavier metal particle is located at the upper surface of the lighter FEP particles bed away from the center of this particles bed.

In Case2, the lower flowrate of the water-injection (2.7 L/min) also pushes the light FEP particles to create the space, which can let the heavier steel particle fall down along these created space. In the beginning, the heavier steel particle goes downwards along the z-direction. Following which, the momentum exchange from water to the heavier steel particle makes it goes up and down, as in Case1. In the x-direction and y-direction, the movement of the heavier steel particle is also randomly distributed during water-injection.

However, in Case2, since the flowrate of water-injection is smaller than the flowrate in Case1, the momentum exchange from water to the heavier steel particle is not so large as in Case1. Therefore, no matter in the x-direction, y-direction and z-direction, in Case2 the movement of the heavier steel particle is not so violent as Case1. For example, the movement of the heavier steel particle in the z-direction in Case2 is all below the upper surface of the lighter FEP particles bed. Nonetheless, along the z-direction in Case1, the arrangement of movement of the heavier steel particle is even over the upper the upper surface of the lighter FEP particles bed obviously.

In Case3, even the heavier steel particle is located at the higher initial position of the upper surface of lighter FEP particles bed (50mm), the water-injection still can push the light FEP particles to create the space, which can let the heavier steel particle fall down along these displacement. The heavier steel particle goes downwards gradually in the beginning. After the heavier steel particle sinks to a certain depth, the following movement of the heavier steel particle will also start to move randomly in the x, y, z-direction. However, the momentum exchange from water to the heavier steel particle will be diluted with the increase of the height of the FEP particles bed, the range of the movement of the heavier steel particle in Case3 will smaller than the Case1.

Therefore, with the water-injection, we can observe the momentum exchange from water to particle will create the particle displacement. Because the heavier steel particle is with the higher density than the FEP particle, it tends to go downwards along the displacement in the lighter FEP particles bed.

The range of heavier movement is related to the momentum exchange from water to particles. In addition, quantity of the momentum exchange is related to the flowrate of the water-injection, and the position of the particle. Therefore, the higher flow rate of water-injection and the particle position which is closer to the position of the water-injection, as Case1, will make the range of particle movement wider.

In Case1, the movement of the heavier steel particle can be recorded, and the related coordinates, as well as the velocity data can be extracted by the post processing via ImageJ, which is a public domain Java image processing program. The first step for extracting position data is the calibration via calculating the ratio between the known length and the number of pixels to obtain the real length per pixel.

For Case1, the x-axis is along the bottom side of the particles bed of the front view. The y-axis is along the bottom side of the particles bed of the side view. The z-axis is along the height of the particles bed. The original position (x,y,z = 0,0,0) is set at the center of the bottom of the particles bed. In the beginning, the position of the heavier steel particle is located at the center of the upper surface of the lighter FEP particles bed (0mm, 0mm, 30mm). In the z-direction, with the water-injection, the heavier steel particle goes up and down frequently (6 times within 1 second). The moving range is from 10mm below the upper surface of the lighter FEP particles bed to around 30mm above the upper surface of the particles bed.

On the other hand, the result also presented the random movement of the heavier steel particle in both x-direction and y-direction. In the x-direction, the movement range of the heavier steel particle is around 20mm from the center of the lighter FEP particles bed. In the y-direction, the movement range of the heavier steel particle is about 10 mm from the center of the lighter FEP particles bed. The difference of the moving range between x-direction and y-direction is caused by the random distribution of FEP particles. Finally, the heavier steel particle stops, and is located at the upper surface of the lighter FEP particles bed.

Because the movement of the heavier steel particle is randomly in the x, y, z direction, several times of experiments has been done in order to obtain the statistics data to analyze. For the purpose of providing data for validating the following CFD-DEM model, to transform these random distribution data in a statistics form will be an appropriate way as a benchmark material.

In the z-direction, the position data of the heavier steel particle can be arranged to a form of probability distribution. The highest probability interval is located at the 30 mm ~ 35 mm where is the initial position of the heavier steel particle. From here, the position probability distribution extends to the highest position interval of the 50 mm ~ 55 mm, and lowest position interval of 15mm ~ 20 mm. However, most of time the position probability distribution is distributed in the interval of 20 mm to 45 mm when the heavier steel particle goes up and down. Moreover, from the data of the position probability distribution, compared to the range of above the upper surface of the lighter FEP particles bed (30 mm ~ 45 mm), the heavier steel particle tends to move within the range below the upper surface of the particles bed (20 mm ~ 30 mm).

However, validating CFD-DEM model by x-direction or y-direction data independently would cause misjudge, because the effect of the water injection is spreading on the x-y surface. Therefore, it is better to find a way to connect data on the x-y direction. The study uses the non-dimensional parameter to analysis the characteristics of the heavier steel particle movement in the x and y direction. Via this conception, it can assess the effect of injecting flow on the tracked particle. In conclusion, The numeralized data will be the benchmark material for validation of the CFD-DEM model by comparing the heavier particle movement on along z-direction and on the xy-surface, respectively.

4.2 CFD-DEM

4.2.1 CFD algorithms

The CFD code STAR-CCM+ [30] is used to calculate temperature and density distributions for debris bed simulations. STAR-CCM+ models fluid flow and heat transfer, as well as heat transfer in solids, for complex three-dimensional geometries. It solves the Navier-Stokes equations discretized using the finite volume approach for steady state and time-dependent problems. STAR-CCM+ can represent solid, liquid, gaseous, and porous media. Heat may be transferred via conduction, radiation, and convection. STAR-CCM+ models both single and multi-phase flow, with the ability to model boiling and cavitation phase changes.

Most of the physics represented in a core set of fundamental laws, including conservation of mass, conservation of momentum, and conservation of energy.

4.2.2 DEM algorithms

Contact force formulation in DEM is generated based on the spring-dashpot model. The spring generates repulsive force pushing particles apart and the dashpot represents viscous damping and allows simulation of collision types other than perfectly elastic.

At the point of contact, The forces are modeled as a pair of spring-dashpot oscillators. A parallel linear spring-dashpot model represents the normal force, and another parallel linear spring-dashpot represents the tangential direction of force with respect to the contact plane normal vector. In both, the spring accounts for the elastic part of the response, and the dashpot accounts for energy dissipation during collision.

However, in order to activate the DEM calculation, DEM particles should initialized and introduced in to the fluid domain. Particles enter the fluid domain through injectors at one or more discrete locations. An injector defines the size and the velocity vector distribution of the particles. For unsteady simulations, the frequency will be another parameter to determine how to initialize the DEM particles. For heat and mass transfer effects, particle temperature and composition are also specified.

4.2.3 CFD-DEM coupling algorithms

In the CFD-DEM coupling system, the mode of two-way coupling also been introduced in this study. It is available to simulate the interactions between the particles and the continuous phase as one-way coupling or two-way coupling. The coupling refers to the way that momentum, heat, and mass are exchanged between the phases.

With one-way coupling, only the continuous phase influences the dispersed phase, but not in the reverse direction. However, two-way coupling, the effects of the dispersed phase on the continuous phase such as displacement, interphase momentum, mass, and heat transfer are taken into account. The displacement of the continuous phase by the dispersed phase is accounted for through the volume fraction. With the two-way coupling model, the reverse effect is accounted for, and Lagrangian source terms appear in continuous phase equations. Typically, this effect becomes more important at higher particle loadings.

The volume fraction of a Lagrangian phase is the fraction of the local cell volume which that phase occupies. The volume fraction $\emptyset_c$ of all Lagrangian phases for which the two-way coupling is active is accumulated. This volume is seen as a void by the continuous phase. The available volume fraction for the continuous phase (corresponding to the void fraction) η is defined as the ratio of volume that is occupied by all continuous fluid phases to the total cell volume.

4.2.4 CFD-DEM simulation conditions

The CFD-DEM mode will be validated by simulating the water-injection experiment. Case1 is the target to be simulated. This is based on mode of 3-dimension, implicit unsteady (Time step = 0.01s). For the aspect of CFD, a rectangular tank is been set as the flow region, and the working fluid is water. The bottom side of this tank is 90mm x 90mm, and the height of water surface is 60cm. The position of the water-injection is set at the center of the bottom surface, with a tube diameter of 5mm. The original point is set at the center of the bottom surface. For the boundary condition, the upper surface is set as the constant pressure outlet (1 atm), and the center of the bottom is set as the velocity inlet(2.7m/s), respectively. The turbulent model (K-Epsilon turbulence model) is also been applied. The equation of state applies the constant density.

In the flow region, 2 types of DEM particles will be put into the flow region. On one hand, 900 cylindrical particles with the diameter of 5mm and height of 5mm are for simulating the FEP particles (density = 2000 kg/m3)v. On the other hand, a spherical particle with a diameter of 8 mm also is set on the top of the FEP particles bed for simulating steel particle (density = 7870 kg/m3). For simulating the collision between particles, the linear spring model is been introduced. The Linear Spring model calculates contact between particles or between particles and a wall, based on the relationship found in linear springs.

For simulating the force between the fluid and particles, pressure gradient force model, particle shear lift force model, and drag force model are been introduced.

Regarding the drag coefficient, there are different models which will be validated by comparing with the experimental data. The describing of these drag force coefficient model are as below:

In order to implement the mode of two-way coupling in the CFD-DEM calculation effectively, the mesh size in CFD should not be much smaller than the diameter of the particle size, because the mesh size in CFD cannot calculate void fraction correctly, which is an critical factor on the mass and momentum transfer from particle to fluid.

However, in my case, the mesh size, which is determined by the mesh sensitivity study, is smaller than the particle diameter. Therefore, the cluster cell should be introduced.

4.2.5 CFD-DEM validation

In this section, the first step is to consider the CFD part via doing the mesh sensitivity study without considering the DEM calculation. Following which, in order to start the DEM calculation, the DEM particles should be introduced into the calculation phenomena. Finally, for the validation of CFD-DEM model, the further sensitivity study will be investigated on the cluster size and the model of the drag force coefficient model.

Before starting to calculating on CFD-DEM calculation, processing the DEM particles initialization to introduce the DEM particles into the CFD regime via particle injector is necessary. The first step is introducing 900 FEP particles into the container by the random injector. By doing so, the random injector distributes 900 lighter FEP particles among the space of the container randomly, and then these 900 lighter FEP particles will fall down and pile up to form a lighter FEP particles bed.

The next step is to introduce the heavier steel ball on the top of the lighter FEP particles bed via point injector. The point injector will generate a particle on a certain position and let it fall down. In this case, position of the point injector is set on the top of center of the upper lighter FEP particles bed. After the heavier steel particle is generated, it will fall down and stop on the upper surface of the lighter FEP particles bed, in order to create the initial condition for the following DEM calculation.

After the stage of particle initialization, the water flow will start to inject into the lighter FEP particles bed from the bottom surface of it. The data of the water velocity distribution, and the movement of the particles will be observed based on the CFD-DEM model.

For the purpose of validating CFD-DEM model, a series of parameter sensitivity study will be investigated by comparing CFD-DEM model simulations with the experimental result of Case1, including the term of the cluster cell size and the term of the drag force coefficient model.

The first term of the parameter sensitivity study is focusing on the parameter of the cluster cell size. For calculating the movement of particles accurately in CFD-DEM coupling model, the mesh size should not smaller than the particle diameter. However, since the CFD mesh size of 1 mm calculated from the former mesh sensitivity study is far way smaller than the DEM particles diameter (8mm for heavier steel particle, 5mm for lighter FEP), the cluster cell, which can cluster the original mesh into the larger cluster cell, should be introduced.

From the consideration of the diameter of the steel particle, the cluster size of 4 mm and 8 mm have been chosen to apply on CFD-DEM model , respectively. The results present the comparison of the heavier steel particle movement between experimental result, CFD-DEM simulation with the cluster size of 4mm and the CFD-DEM simulation with the cluster size of 8 mm. The characteristic of the movement of the heavier steel particle in the Case1 is going up and down violently. In the simulation with the cluster cell size of 4 mm, although the lighter FEP particles is been driven up, the heavier steel particle only move in the x-direction and y-direction, without any obvious movement in the z-direction. However, in the simulation result with the cluster size of 8mm, not only in the x-direction and y-direction, but also in the z-direction the heavier steel particle have an obvious movement, including sinking into the particles bed and going up above the upper surface of the particles bed.

Except for observing the movement of the heavier steel particle, the change of the void fraction of lighter FEP particles bed can also be observed. The definition of the void fraction in these two simulation is the ratio of volume of the water to the total volume in a cluster cell. With the increase of the size of the cluster cell, the void fraction around particles can be estimated more accurately, and the drag force contributed from flow f to particles can be calculated more accurately.

For the simulation whose cluster cell size is 4mm, the change of void fraction only occurs around the spot of the water-injection. However, when the cluster cell size increases to 8 mm, the change of the void fraction is spreading to the whole area of FEP particles bed during the time of water-injection.

The data of the movement of the heavier steel particle is also extracted for the further validation of CFD-DEM model. The results show, in z-direction, the comparison of the position probability distribution between the experimental result and the simulations with the different cluster cell size of 4 mm and 8 mm, respectively.

For the simulation with 4 mm of the cluster cell size, the highest position probability is located at the interval between the 30 mm ~35 mm, which is the same result of the experiment. However, at the higher and lower interval, it shows an obvious deviation from the experimental results, with the error of 71.78%.

For the simulation with 8 mm of the cluster cell size, the highest position probability is also located at the interval between the 30 mm ~35 mm. Moreover, at the higher and lower interval, the simulation with 8 mm of the cluster cell size shows an less deviation from the experimental results, with the error of 53.72%.

For considering the movement of the heavier steel particle on the x-y surface, The non-dimensional analysis between experiments and simulations with different cluster cell size has been checked. If the points are accumulated at the corner of the bottom-left, it means the momentum exchange from the flow to particle is not the dominant factor as to the movement of the particle. On the other hand, it the points tend to extend to other three corners, the momentum exchange from the flow to particle is the dominant factor as to the movement of the particle.

The second term of the parameter sensitivity study is focusing on the drag force coefficient model.

For tracking the movement of particles accurately in CFD-DEM coupling model, different drag force model will affect the estimation of the drag force, which is the force from the flow to the particles. In this case, because the case is including the particles bed which is with high number density, the drag force coefficient model should consider the effect of the change of the void fraction during the water-injection. Hence, the model of De Felice model and Gidaspow model have been chosen to compare. However, in the simulation result with Gidaspow model, the heavier steel particle not only sinks into the FEP particles bed along the space between the FEP particles, but also goes up violently due to the momentum exchange from the flow.

For the simulation with De Felice model, the highest position probability is located at the interval between the 30 mm ~ 35 mm, which is the same result of the experiment. However, at the higher and lower interval, it shows the deviation from the experimental results, with the error of 53.72%. On the other hand, for the simulation using Gidaspow model, the highest position probability is also located at the interval between the 30 mm ~ 35 mm. Moreover, at the higher and lower interval, the simulation with Gidaspow model shows an much smaller deviation from the experimental results, with the error of 34.40%.

Finally, it shows that, if the cluster cell size which is larger and closer to the diameter of DEM particles tend to present the similar results with the experiment, and 8mm of the cluster cell size will be chosen for the following simulation with the Gidaspow model for calculating drag force coefficient.

4.3 Summary

In the aspect of building CFD-DEM model, a series experiments which aim to simulate self-leveling have done. A heavier steel particle put on the top of FEP particles bed, which is transparent in the water for helping people to observe the movement of the heavier particle movement, as the initial setup. However, the heavier particle, which is the tracked target in the lighter FEP particles bed, is moving randomly along x,y,z direction during water-injection.

In order to use these data as the benchmark materials on CFD-DEM validation, along the z-direction, the location data of the heavier steel particle is arranged to the probability distribution. On the other hand, the position data on the x-y surface is also been arranged to a form of none-dimensional analysis.

These data is applied on the CFD-DEM validation. Regarding the validation, it focus on the issue of cluster cell size and the model of generating drag force coefficient. The reason for doing the sensitivity study on the cluster size is because the mesh size is far smaller than the size of the particles in the simulation. Therefore, in order to estimate the momentum exchange more appropriately in the CFD-DEM model, the cluster cell, which accumulate the original mesh to turn into a lager unit, should be applied.

In last section, the cluster size chooses the one which is closer to the diameter of particle size. On the other hand, the Di Felice model and Gidaspow model are also been tested for determining which model can appropriately simulate the behavior of self-leveling. Finally, because the Gidaspow model shows a better result via comparing with the experiments data, the one will be used for the further reactor scale simulation.

5 Coolability calculation

5.1 Case explanations

Because the previous study has proved that, via setting 3-layers debris catcher, the debris bed with 1/3 of total JSFR fuel inventory and structure can attain the stable cooling and avoid re-criticality. However, previous study is under the assumption of the homogenous distribution debris bed model. But in the real case, when the debris particles are piled up to form the debris bed, it is possibly to form a stratified distribution configuration due to the density difference between particles. Therefore, in this chapter, the capability of keeping stable cooling and avoid re-criticality will be investigated on the debris bed with stratified distribution.

5.2 Simulation conditions

5.2.1 CFD-DEM

The target is to analysis the debris bed coolability and the issue of re-criticality on the first layer of three-layer debris catcher in the lower plenum of JSFR. The target geometry assumes the cylinder to simulate that the debris bed is located between the first layer of debris catcher and the cold leg. On the top of flow region, there are four cold leg s as the location of the inlet velocity boundary. In the center of the of the top, there is the outlet as the pressure outlet. In order to simulate the case on one of the 3-layer debris catcher, the debris bed is use the parameter as the Case2 with the stratified distribution model in Chapter 3, with 35% of the total JSFR fuel inventory and 35% of the total structure in the reactor core. The stratified debris bed model composed of 2385 fuel particles (red particles) and 1378 structure particles(blue particles).

In this case, the study uses STAR-CCM+ to simulate the phenomena of the debris bed in the first layer of the debris catcher. In CFD part, this simulation is under the 3-dimension, implicit unsteady calculation. The time step for implicit unsteady calculation is set as 0.01s. The working flow is liquid sodium with the initial temperature of 900k and initial pressure of 1atm. For the equation of state regarding the liquid sodium, the density of liquid sodium is calculated by polynomial approximation.

Particles collision and the interaction between the liquid sodium and the particles will be calculated by CFD-DEM model. For the part of DEM, the particles-particles interaction will applied the linear spring model, and the flow-particles interaction will apply Gidaspow model to calculate drag force coefficient. In this simulation, fuel particles is the heat source (3.1×10^7 w/m^3, 7% of the JSFR operating power) for simulating the decay heat generating, with the initial temperature of 900k. For a multiple flow regime phase interaction, the calculation of the interphase heat transfer is applied Rans-Marshall model to calculate heat transfer coefficient.

5.2.2 Neutronics

Re-criticality is the another essential issue to assure regarding safety concerning on the debris bed. When the fuel particles and structure particles move during the CFD-DEM calculation, the debris particles position and the geometry of the debris bed will change. It will affect the probability of the re-criticality. Therefore, using neutronics calculation to track the change of k-eff is important. In this study, every 0.1s in the CFD-DEM calculation, every debris particle' position will be extracted via using Java language on STAR-CCM+ first. Following which, using Python to transfer the data to the .inp file, which is a form of file to provide information of particle position to apply on Serpent, which is a Monte-Carlo neutronics simulation tool. Via this position data transfer, it can process over 10,000 particles once for all.

The debris geometry, the number of fuel and structure particles, and the material parameters are as the same as the Case2 in chapter3. The cross section data library is ENDF B/VII (900K). The number of tracking neutrons is 10000. The total iteration and invalid iteration are 200 and 10, respectively. The boundary condition is set as reflective.

5.3 Simulation results and discussions

Debris particles disperse toward to the boundary of the debris catcher gradually, and the inclined angle of the debris bed keeps decreasing. For the liquid sodium, although it is not obvious in the beginning, after the liquid is heated by the surface of the fuel particles, the liquid sodium will start to go upward to the outlet. Therefore, the gravity and the liquid sodium upwards flow will drag the surface debris particles to leave the debris bed surface and disperse gradually.

The debris bed with stratified distribution will induce the state of re-criticality. However, with the particle dispersion, the geometry buckling is decreasing . Therefore, the k-eff is decreasing with the change of the geometry of the debris bed. Finally, after 1s, the debris bed is attain the status of sub-criticality.

The cross section of the particles temperature distribution has been tracked. In the beginning, because the fuel particles can generate decay heat as the heat source, the temperature of the lower layer of fuel particles will increase quickly. And then, the liquid sodium starts to take heat from the heat source on the surface of the debris bed. Hence, the temperature in center of the fuel layer begins to higher the outsider. On the other hand, compared with the thermal conductivity of liquid sodium (76w/m-k), the structure particle's thermal conductivity (30w/m-k) is lower than it. Therefore, the decay heat preferred to be taken from the liquid sodium rather than the structure particles, and this is the reason why the structure particles are almost not increase the temperature.

The cross section of the liquid sodium temperature distribution are also been tracked. Because the temperature of the center fuel particle is higher than the fuel particles located at boundary of the debris bed, the liquid sodium located at the center is with the highest temperature as well. When the liquid sodium is heated up, it could go upwards because of the decrease of the density. However, at the current stage, the density change of liquid sodium is not obvious (900k: 801 kg/m^3, 907k: 794 kg/m^3, from polynomial approximation). Especially for the liquid sodium which is located in the center of the debris bed, it is easy to meet pressure drop to intervene to leave the inside of the debris bed due to the porous structure. Therefore, the liquid sodium in the debris bed could not be easy to leave there at the current temperature increase.

5.4 Summary

In this chapter, both the thermal-hydraulic aspects and the neutronics evaluation have been investigated with tracking moving mixed-density particles on the heterogeneous stratified distributed debris bed. Even the composition are the same for the debris bed, the debris bed with stratified distribution still presents the potential issues on the coolability and re-criticality, compared the previous study applying the homogeneous distribution model.

For the flow of the liquid sodium inside the debris bed, if the debris bed is homogeneous distribution, the upper layer will also generate heat, and the upper layer of insider liquid sodium will be easy to leave the debris bed and also can drag the bottom layer of the inside liquid sodium. However, the debris bed with stratified distribution, the bottom layer of the liquid sodium become hard to be drag to the apex of the debris bed, especially this is the porous structure. Therefore, the situation could intervene the heat transfer.

For the surface flow on the debris bed, compared with the homogeneous distribution debris bed, the heating surface is lower in the debris bed with stratified distribution. But with the debris particles dispersing, the heating surface will increase gradually. For the issue of the re-criticality, the debris bed configuration is an important factor. If the stratified distribution in the debris bed is formed during the debris bed is piling up, it would possibly to meet the accident of re-criticality. Fortunately, according to the calculation analysis, after the debris particles dispersing for the debris bed with stratified distribution, it would decrease the geometry bucking of the debris bed, and avoid re-criticality.

6 Conclusions

6.1 Summary

The aim of this study is to investigate coolability and the re-criticality on the debris bed with the mixed-density heterogeneous configuration during the behavior of self-leveling. In order to achieve this target, on one hand, the neutronics model, which can calculate the k-eff eigenvalue to estimate the debris bed is re-criticality or not, is been built via testing on different types of configurations of debris bed, including homogeneous distribution model, stratified distribution model and centralized distribution model. On the other hand, the model of CFD-DEM model, which is been implemented to simulate the interaction between flow and particles, is also validated via a series experiments for simulating self-leveling phenomena. Finally, a complete reactor scale case has been done applying the CFD-DEM model and neutronics model at the same time to evaluate the capability of the coolability and the probability of re-criticality on a stratified distribution debris bed in JSFR phenomena.

For the aspect of building neutronics model, the results present that the previous study on the debris bed would underestimate the probability of attaining the status of re-criticality on the debris bed, because the previous study is based on the assumption of homogeneous distribution model. In the consideration of the real case of mixed-density debris bed, after the re-distribution of the debris particles, a debris bed with stratified distribution or centralized distribution could be expected. Through the neutronics model to evaluate the k-eff eigenvalue on these three different configurations, it found the debris bed with a stratified distribution or centralized distribution have higher probability to attain the status of re-criticality, compared the debris bed with homogeneous distribution. Therefore, it is an potential issue when the mixed-density debris bed is under the self-leveling because a configuration which has higher possibility to be criticality is possible.

In the aspect of building CFD-DEM model, a series experiments which aim to simulate self-leveling have done. A heavier steel particle put on the top of FEP particles bed, which is transparent in the water for helping people to observe the movement of the heavier particle movement, as the initial setup. However, the heavier particle, which is the tracked target in the lighter FEP particles bed, is moving randomly along x,y,z direction during water-injection. In order to use these data as the benchmark materials on CFD-DEM validation, along the z-direction, the location data of the heavier steel particle is arranged to the probability distribution. On the other hand, the position data on the x-y surface is also been arranged to a form of none-dimensional analysis. These data is applied on the CFD-DEM validation. Regarding the validation, it focus on the issue of cluster cell size and the model of generating drag force coefficient. The reason for doing the sensitivity study on the cluster size is because the mesh size is far smaller than the size of the particles in the simulation. Therefore, in order to estimate the momentum exchange more appropriately in the CFD-DEM model, the cluster cell, which accumulate the original mesh to turn into a lager unit, should be applied. Finally the cluster size choose the one which is closer to the diameter of particle size. On the other hand, the Di Felice model and Gidaspow model are also been tested for deciding which model can appropriately simulate the behavior of self-leveling. Finally, because the Gidaspow model shows a better result via comparing with the experiments data, the one will be used for the further reactor scale simulation.

Finally, the reactor scale case of 35% of JSFR total fuel inventory is been chosen for applying the neutronics model and CFD-DEM model at the same time. The mixed-density debris bed is set as the stratified distribution, because it can compared the result with the previous study using the homogeneous distribution. Although the previous study shows that the type of debris bed in the debris bed can keep stable cooling and avoiding re-criticality, in the stratified distribution case, the re-criticality occurs in the beginning. Nonetheless, k-eff decreases with the particle dispersing with time passing. For the issue of the coolability, although the temperature of debris bed particle and the liquid sodium are not over the boiling temperature. However, the liquid sodium flow both on the surface and located inside the debris bed show the different results compared with the homogeneous debris bed. The liquid sodium located at the lower fuel particle layer is hard to flow out, which can help cooling.

6.2 Conclusion

In this study, after a series of the sensitivity studies, CFD-DEM model had been verified by experiments under the cases of mixed-density particles bed. The verified CFD-DEM model can correctly track the heavy particles movement in the light particles bed with the water-injection. In addition, since the experiments is for simulating g phenomena of self-leveling in JSFR and have done the non-dimensional analysis, the verified CFD-DEM model is with the capability to be applied on it.

For the neutronic model, because the previous estimations on the issues of debris bed re-criticality is based on the assumption of homogeneous distribution, different heterogeneous distribution had been investigated. The results present that the debris bed with heterogeneous distribution has higher probability to attain the re-criticality than the debris bed with homogeneous distribution.

Finally, regarding the issue of coolability and re-criticality on the debris bed, a reactor scale case had been checked by the verified CFD-DEM model and neutronics model. When the self-leveling is processing , the temperature is below the boiling point, and the k-eff eigen value shows a trend of decreasing. Therefore, self-leveling effect had been quantitively confirmed, even under the case of stratified distribution.

6.3 Future work

1. The on-line coupling system between the neutronics model and CFD-DEM model:

The issue of the current calculation is the off-line coupling. So, in order to increase the accuracy and the applicability on the criticality and coolability analysis, one thing is applying the dynamics analysis, instead of only using statics calculation in neutronics model. The reason for planning to implement dynamics neutroncis calculation is that it can provide the fission power data which is different from the statics calculation. If the fission power distribution can be applied, even the debris bed attain the status of criticality, the neutronics model can provide the fission power data to CFD-DEM model for the heat source data. Another thing is to build up the interiteration coupling system between neutronics and CFD- DEM model. With the criteria of the convergence for both of two, it surely can provide more accurate and more reliable results for the relative calculations.

The planed is as following describing. In the beginning, the neutronics model will be used to calculate the case is criticality or not. If it is criticality, the heat source for the following CFD-DEM calculation will use the fission power heat. However, the heat source will be set as decay heat for the following CFD-DEM calculation. In the CFD-DEM calculation, if the particles' position or the temperature changes, the current result of particle position information will sent to the neutronics model to calculate the k-eff eigenvalue again. Until there is no change for the CFD-DEM calculation, the all circulation in this coupled system is being done.

2. IVR analysis:

The conception of deriving IVR failure probability is as following describing. In the step1, for a certain amount of the melting fuel, the possible types of the debris beds can be generated by these parameters (ex: shape, inclined angle, porosity, etc.). In the step2, for each possible type of these debris beds, the coolability analysis will be done in order to evaluate if it satisfies the IVR criteria or not. In the step3, an IVR failure probability (the number of cases which do not satisfy the IVR criteria / the number of total cases) for this amount of the molten fuel can be derived from the former calculated results. In this preliminary test, if the highest liquid sodium temperature in the debris bed is over the boiling temperature, it will be treat as the case which is not satisfied the IVR criteria.

In the step4, each IVR failure probability (derived by the same way of step1~step3) will be recorded.

Following which, in the step5, these calculated IVR failure probability data can do the lognormal cumulative distribution function (CDF) fitting (lognormal distribution is a continuous probability distribution of a random variable whose logarithm is normally distributed). Therefore, a mean value will be derived from the lognormal CDF, and the mean value can be treated as the mean IVR failure mass. These mean IVR failure mass can also provide effective references for optimizing the performance of this multi-layer debris tray design in JSFR in the future.