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CFD Investigations of Subcooled Flow Boiling in a Random Pebble Bed

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A new concept of nuclear reactors, Pebble Bed Water Reactor (PBWR), has attracted wide attention due to the advantages in the inherent safety performance, high conversion efficiency and low power density design. In this paper, the RPI wall boiling model was applied to solve the local flow and heat transfer of subcooled flow boiling in a random pebble bed with the tube diameter to particle diameter ratio D/d of 4. The effects of inlet temperature and particle diameter on the subcooled flow boiling characteristics were analysed. It was found that the hot spots and bubbles began to appear at the downstream of the contact points between neighbour pebbles or between pebbles and tube wall. With a higher inlet temperature, the onset of boiling occurred earlier and the void fraction near walls increases obviously. With a smaller pebble diameter, the onset of boiling was delayed and the bubbles occupied a smaller fraction of pebble surfaces. This study can provide useful information to the design of the PBWR.

1. Introduction

Pebble Bed Water Reactor (PBWR), combining the most mature water-cooled reactor technology with the excellent performance of triple coated (TRISO) type fuel elements, has many advantages such as the inherent safety performance, high conversion efficiency and low power density design. Some concept reactors have been presented by different research institutions.

In a typical PBWR, the reactor core is composed of thousands of pebble fuel elements. The diameters of pebble fuels range from 2 mm to 10 mm (Li et al., 2012). Take the BWR-PB (Pebble Bed Boiling Water Reactor) for example, the coolant water enters at the bottom of the reactor core. The coolant flows though the pores formed by the fuel pebbles, and takes away a large amount of heat produced in the fuel particles. Then the coolant water is heated to be overheat steam, which goes out at the top of the core. It covers all the boiling regimes, including convective heat transfer of water, subcooled nucleate boiling, nucleate boiling, film boiling and convective heat transfer of steam. The flow and heat transfer in a pebble bed is very complicated. The random packing structure makes it even more complicated.

The boiling in a pebble bed have been widely investigated. Wang et al. (2004) studied bubble behaviour during boiling in bead-packed structures. The experimental results evinced that the dynamic bubble behaviour was significantly influenced by the bead-packed structure. Dry phenomenon was difficult to emerge due to the behaviour of the replenished liquid caused by special pore geometry. Chen et al. (2016) studied the dry-out phenomena in packed beds and developed a new model for the Wallis coefficient. Zhou et al. (2015) studied the nucleate boiling characteristics of deionized water and some typical self-rewetting fluids in spherical glass beads packed bed. The results showed that the heat transfer during nucleate boiling can not only be enhanced by the porous structures, but also be enhanced by increasing the number of carbon atoms of the alcohols.

All the above studies were focused on the pool boiling in a pebble bed in the background of the nuclear reactor severely damaged without water. And much less studies were about the flow boiling in the pebble beds. Xu et al. (2014a, b) studied flow boiling heat transfer characteristics of volumetrically heated packed

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beds. A new correlation was developed to predict the ONB heat flux in a volumetrically heated pebble bed. The nucleate boiling was firstly observed in the contact surface. Structures of contact surface had great impacts on the bubble shapes, departure diameter and frequency. Bai et al. (2009) studied boiling two-phase flow in different porous channels composed of particles with diameters of 4 mm, 6 mm and 8 mm. It was found that bubbles and slugs deformed, coalesced and broke up more frequently, and increased in both number and size with the increase of the heat flux.

To the authors' knowledge, no data has been found in the open literature on the subcooled flow boiling in the pebble bed based on the pore scale. In this paper, the RPI model proposed by Kurul and Podowski (1991) was used to solve the local flow and heat transfer of subcooled flow boiling in a pebble bed. The distributions of velocity, temperature and void fraction were obtained. The effects of inlet temperature and pebble diameter on the subcooled flow boiling characteristics were analyzed to better understand the thermal-hydraulics of the subcooled flow boiling in a pebble bed.

2. Physical model and numerical methods

2.1 Physical model and grid systems

The computational domain is shown in Figure 1. There are three sections: inlet section, packed section and outlet section. The packed section is generated with the discrete element method (DEM). With DEM, the particle falls into a cylindrical tube one by one under the gravity force. The packing method has been validated in the work of Yang et al. (2016). There are 140 pebbles in the packed section with the tube diameter to pebble diameter ratio D/d of 4. The porosity of the packed section is 0.45. It is to note that there is a through pore in the center of the packed section. The geometry parameters are listed in Table 1.

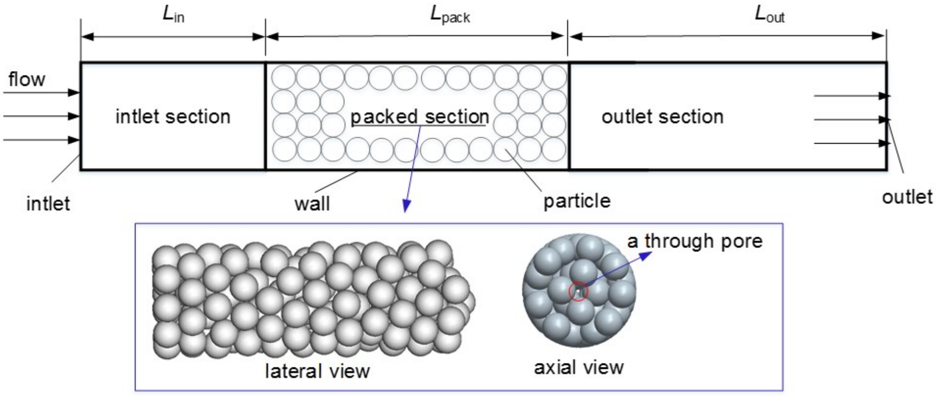


Figure 1: Computational domain

Table 1: Geometry parameters

Parameters	Value
Pebble diameter (d), mm	6, 2
Inlet section length	10d
Outlet section length	30d
Packed section length	10.6d
Tube diameter to particle diameter ratio D/d	4

The constant heat flux is specified at the particle surface. The inlet coolant velocity and temperature are assumed to be constant. The tube walls of all sections are set to be adiabatic and non-slip wall boundary. The calculation parameters are based on the data used by Li et al. (2012). The operated pressure is 10 MPa with the saturated temperature 584.15 K. Three simulations are carried out to investigate the effects of inlet temperature and pebble diameter on the subcooled flow boiling characteristics in the pebble bed. The key parameters of three simulating cases are listed in Table 2.

In the present work, the tetrahedral grids are constructed, as shown in Figure 2. The short cylinder brides are used to improve the mesh quality near the contact points between spheres or between spheres and tube wall (Bu et al., 2014b). The setting of the mesh generation is same to that of Yang et al. (2016). The maximal element size for the main flow computational domain is limited to d_p/20. The grids are refined near the contact regions. The grid elements qualities are all above 0.2. The grid system with 8,528,081 cells is used as the final grid in the later calculations.

Table 2: Parameters of simulating cases

	Inlet velocity, m/s	Inlet temperature, K	Pebble diameter, mm	Re
Case 1	0.06	523	6	2,690
Case 2	0.06	543	6	2817
Case 3	0.06	523	2	897

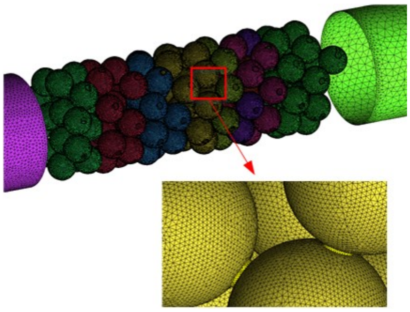


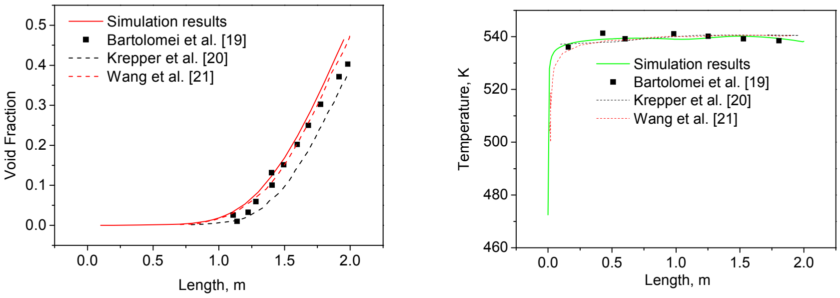
Figure 2: Grid systems and contact modifications

2.2 Numerical methods

A two-fluid Eulerian approach is used for mathematical description of the subcooled flow boiling in the pebble bed. The liquid is regarded as a continuous phase while the vapor is regarded as a dispersed one. The conservation equations for mass, momentum, and energy are solved by the commercial software code ANSYS CFX 14.0. The thermal physical properties of water and vapour are taken from IAPWS-IF97.

It is seen from Table 2 that the Reynolds number of all cases is greater than 400, indicating the turbulent flow (Bu et al., 2014a). The RNG k- ε turbulence model with scalable wall function has been applied to the liquid phase. A disperse phase zero-equation turbulence model with Sato Enhanced Turbulence Transfer model is used for the vapour phase. The drag force which is flow-regime dependent, is modelled according to the correlation by Ishii and Zuber. The applied turbulent dispersion force is based on the Favre average of the interfacial drag force. The influence of lift force and wall lubrication force on the void fraction profile can be ignored due to the small size of the pores. The two-resistance model for inter-phase heat transfer is employed. RPI wall boiling model is used to capture subcooled boiling phenomena in the pebble bed (ANSYS 14.0).

To validate the numerical method, the subcooled boiling flow in a heated tube is performed based on the experiment (Bartolomei et al., 1982). The simulation results are compared with the experimental results and numerical results by Krepper et al. (2007) and Wang et al. (2014). It is seen from Figure 3 that the simulation results agree well with the published results. The average error of simulation results is about 2.4 % compared with the results by Wang et al. (2014).



(a) void fraction *(b) wall temperature*

Figure 3: Validation of the numerical methods

3. Results and discussion

3.1 Local flow and heat transfer characteristics

As shown in Figure 4, a middle plane and a pebble layer are selected to analyse the local flow and heat transfer characteristics in the pebble bed. The velocity and temperature distributions at the middle plane for the Case 1 are shown in Figure 5. It is obvious that the flow in random pebble bed is rather complexed. The flow characteristics are tightly related with local pore structure. The velocity is relatively greater at the through pore and some areas near wall, where the local porosity is relatively high. The fluid is gradually heated by the particle surfaces. The average fluid temperature at the outlet is 542 K**,** much less than the saturated temperature.

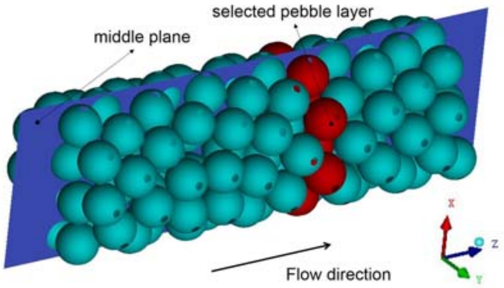
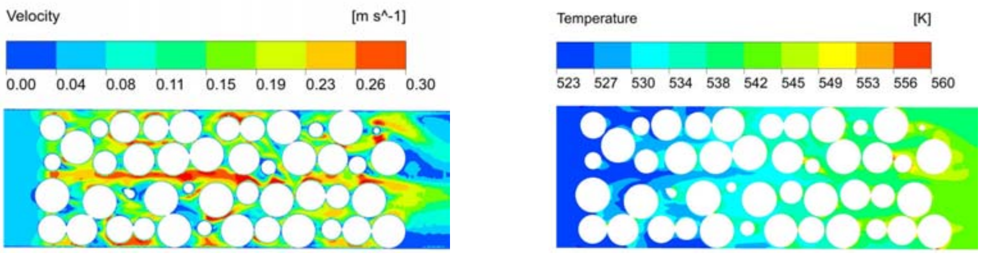


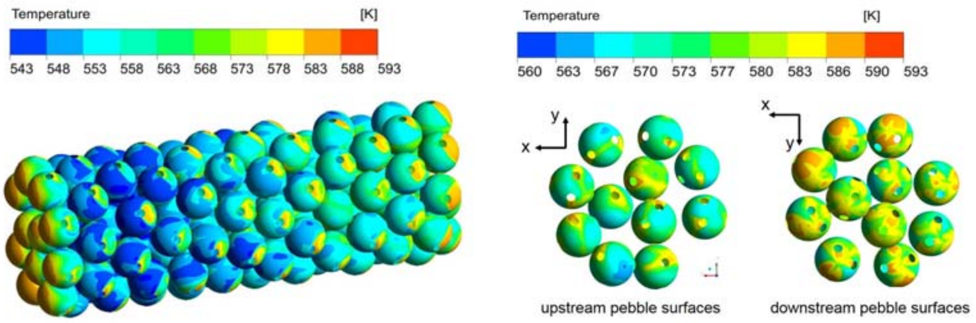
Figure 4: Locations of a selected middle plane and pebble layer



(a) velocity distribution *(b) temperature distribution*

Figure 5: Velocity and temperature distributions in the middle plane for Case 1

The temperature distributions at whole pebble surfaces are shown in Figure 6. It is obvious that the wall temperatures at the pebble surfaces are quite nonuniform. The hot spots are located at the downstream of the contact points between neighbor pebbles. It is interesting that the temperature at the upstream of the first pebble layer is rather high. It is seen from Figure 6(b) that the temperatures at downstream pebble surfaces are much higher compared to those at the upstream pebble surfaces. The reason may be that flow separation and flow recirculation exists in the downstream pebble surface and the heat transfer gets weaker between coolant and pebble surface. The maximum temperature at the pebble surfaces can reach 588 K, which is 4 K over the saturated temperature.



(a) the whole pebble bed *(b) the selected pebble layer*

Figure 6: Pebble surface temperature for Case 1

The void fraction distributions at pebble surfaces for Case 1 are shown in Figure 7. The bubbles begin to appear near the contact points between pebbles or between pebbles and tube wall, where the velocity is rather low and the temperature is comparatively high. Therefore, it is easy to achieve the degree of superheat to generate bubbles. However, the void fraction is very low (less than 0.1) and the bubbles only occupy a very small fraction of the last several pebble surfaces. The subcooled boiling is very weak for Case 1.

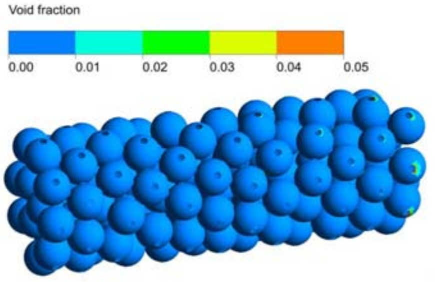
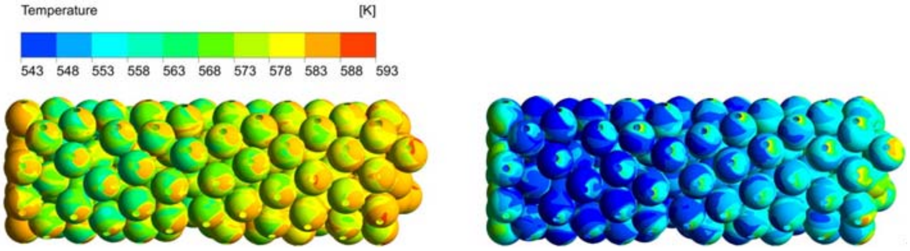


Figure 7: Void fractions at pebble surfaces for Case 1

3.2 Effects of inlet temperature and pebble diameter

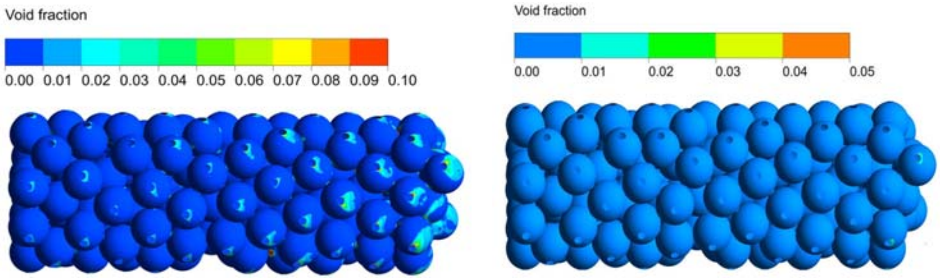
The temperature distributions at pebble surfaces for Case 2 and Case 3 are shown in Figure 8. When the inlet temperature increases by 20 K, the temperatures at the pebble surface are obviously getting higher. The average temperature at pebble surfaces for Case 1 is 558 K, while that for Case 2 is 577 K. The temperature rise of the average temperature at pebble surface approximately synchronizes with the temperature increases of the inlet temperature. The maximum temperature at the pebble surface for Case 2 is 588 K, which is same to that for Case 1. When the pebble diameter decreases to 2 mm, the average pebble surface temperature decreases to 551 K. The maximum temperature at the pebble surface for Case 3 is 588 K and appears at the contact points, which is same to that for Case 1 and Case 2. The temperatures of hot spots for these cases do not exceed 588 K, which is 4 K over that saturated temperature. The reason is that it begins to generate bubbles when the superheat at pebble surface is 4 K. The heat transfer is greatly enhanced due to the vaporization and the hot spots tend to maintain at a constant temperature, with a quite large margin of the maximum fuel temperature limit 1,600 °C.



a) Case 2 *(b) Case 3*

Figure 8: Temperature distributions at pebble surfaces

The void fractions at pebble surfaces for Case 2 and Case 3 are shown in Figure 9. Similar to that in Case 1, the bubbles began to appear at the contact points downstream between pebbles or between pebbles and tube wall for the two cases. With the increased inlet temperature, it is very obvious that the area of void fraction pebble surfaces gets larger. The bubbles begin to generate at the first pebble layer, indicating that the onset of subcooled boiling is getting earlier when compared with that for Case 1. However, the void fraction is very low and the subcooled boiling is still weak for Case 2. When the pebble diameter decreases to 2 mm, the void fraction is lower and the bubbles occupy a smaller fraction of the last several pebble surfaces when compared with that for Case 1. As mentioned above, the subcooled boiling is rather weak for the three cases.



a) Case 2 *(b) Case 3*

Figure 9: Void fraction at pebble surfaces

4. Conclusions

The subcooled boiling in a random pebble bed with the tube diameter to particle diameter ratio D/d of 4 is numerically studied in this paper. The effects of inlet temperature and pebble diameter on the subcooled flow boiling characteristics are analysed. The main findings are listed as below:

[1] The flow and heat transfer characteristics are tightly related with local pore structure. The velocity is relatively greater, where the local porosity is relatively high. The temperature distributions at the pebble surfaces are quite nonuniform. The temperatures at downstream pebble surfaces are much higher compared to those at the upstream pebble surfaces. The hot spots are located at the downstream of the contact points between neighbour pebbles or between pebbles and tube wall. Therefore, the bubbles began to appear at the contact points.

[2] The subcooled flow boiling is greatly influenced by the inlet temperature and pebble diameter. Increasing the inlet temperature and pebble diameter could promote the subcooled boiling and bubbles may appear at the first pebble layer. However, the temperatures of hot spots do not exceed 588 K, which is 4 K over that saturated temperature. The reason is that the heat transfer is greatly enhanced due to the vaporization.

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