Study on the Curved Channel Model in the Initial Core Loading of Pebble Bed High Temperature Reactors

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Abstract. Continuous on-line fuel cycling is the essential feature of the pebble bed high temperature reactor (PB-HTR). The flow speed of the fuel pebbles in a PB-HTR presents a radial distribution in the reactor core, mainly due to the friction between the pebbles and the wall and the conical structure at the core bottom. In the VSOP fuel shuffling model, the simulation of unequal pebble flow speed is achieved by dividing the reactor core into some vertical flow channels with different numbers of the equal-volume regions in each channel. However, the fuel shuffling with equal-volume batches bring complexity when dealing with the change of fuel composition, such as the fuel fraction of fuel-graphite pebble mixture, during the initial core loading and early running-in phase. In this work, a curved channel model with unequal flow speed and the bottom cone is established based on the DEM simulation of pebble flow in the HTR-PM. The batch-wise fuel shuffling strategy is adapted to fit the complex situation during mixing and re-assigning the discharged fuels by employing a rounding strategy for the actual volume of fuels with similar irradiation history. The key of the adapted strategy is to divide the total number of the mixed batches with similar irradiation history by the number of flow channels, and round the quotient as the number of reloaded batches in each top region. The fuel loading process to build up the initial core, accompanied by the low-power reactor running to compensate the reactivity provided by the fresh fuels, is simulated by using the fuel shuffling model mentioned above. On the other hand, the simulation on the same process with an effective cylindrical core mesh and straight flow channels is carried out, in which dividing and rounding the batch numbers are unneeded. The results of both models are compared, indicating that the curved channel model presents less core reactivity and shorter fuel loading period than those of the cylindrical model. From the point of view of fidelity, the former is more suitable for the simulation of initial core loading process. The results in this work are important for enhancing the economy of fuel cycling of PB-HTRs.

1. Introduction
High temperature gas-cooled reactors (HTGRs) present the unique feature of the spherical fuel elements with diameter of 6 cm flowing downward within the pebble bed reactor core. The simulation of the fuel pebble flow is important to the neutronics calculations since the on-line fuel recycling is carried out all the time. In the model of the well-verified PB-HTR code V.S.O.P. [1], the simulation of pebble flow is carried out by dividing the pebble bed into several vertical channels. Each channel is then divided into some regions with equal volumes in the axial direction, as shown in Fig. 1.
During the pebble flow simulation, all the fuels in the regions can be simultaneously shuffled to the next regions in the corresponding channels or to the so-called “storage boxes” representing the fuels in the discharge tube under the pebble bed core for a certain time interval, i.e., the shuffling cycle. The fuels in one single region are subdivided into some equal-volume logical parts named “batches”, which are the basic units of fuel content in PB-HTR neutronics calculations and represent the fuels with different irradiation histories. The pebble flow speed varies in the radial direction, mainly due to the friction between the pebbles and the wall and the conical structure at the core bottom. Consequently, the pebbles near the core axis move faster than those near the side reflector. The radial difference of pebble speed can be simulated by assigning the region number proportional to the fuel residence time for each channel in the V.S.O.P. model.

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For the core physics design of the HTR-PM, sufficient precision can be achieved by using the simple cylindrical channel model, i.e., the region numbers of all the channels are equal and the bottom cone structure is replaced by an effective cylinder with the same volume, since the pebble flow speed values at different radial position are similar. In this work, the model with curved channels and bottom cone structure is called “the curved channel model”, while the model with cylindrical channels is called “the cylindrical channel model”. Both models are equally suitable for the fuel shuffling of the equilibrium core because the batches in a region are all filled with fuels and present the regular pattern from the shortest irradiation period to the longest one. On the other hand, circumstance becomes complicated when the curved channel model is utilized for the initial core and running-in phase. As shown in Fig. 2, the front of regions filled with fuel-graphite pebble mixture in the central channel reaches the core bottom earlier than those in outer channels. Therefore, the fuel-graphite pebble mixture in the central-bottom region will be mixed with the graphite pebbles in the bottom regions of
other channels, and be equally divided into all the channels when reloaded to the core top. Unfortunately, the volume of reloaded batches is usually unequal to that of the original batches. Hence, one has to deal with the “fractional batches” for most of the cases of the curved channel model, which is the most challenging feature in the curved channel model.

| 7:8G | 7:8G | 7:8G | 7:8G | 0:15G |
|------|------|------|------|-------|
| 7:8G | 7:8G | 7:8G | 7:8G | 0:15G |
| 7:8G | 7:8G | 0:15G | 0:15G |
| 7:8G | 7:8G | 0:15G | 0:15G |
| 7:8G | 0:15G | 0:15G | 0:15G |
| 7:8G | 0:15G | 0:15G | 0:15G |

Figure 2. An example of the logical layout of regions near the core bottom. The columns represent the channels, while a single row corresponds to the pebbles unloaded within a certain period. The figure in each region represents the ratio of fuel pebbles to graphite pebbles. The subscripts of number mean the pass number of fuels and the subscripts of G mean the graphite pebbles.

2. Analysis Models
In this work, the curved channel model and cylindrical model based on the HTR-PM are established as reference models based on the HTR-PM. The active core of the HTR-PM can be equivalent to a cylinder with the diameter of 150 cm and the height of 1100 cm according to the volume equivalence, which bases the cylindrical channel model in this work. On the other hand, a more realistic model, namely the curved channel model with an upper cylinder and a bottom cone structure is established based on the actual layout of the reactor core. In the hypothetical models of this work, the active core is divided into 5 channels. In the curved channel model, the region numbers of the channels from core axis to reflector are set as 20, 21, 23, 25 and 26, respectively, while the cylindrical channel model also contains 5 channels with 23 regions for each channel. The ratio of fuel pebble number to the graphite pebble number is set as 7:8, and the fuel-graphite pebble mixture are filled in the top 9 regions in each channel of both models while the lower parts are both filled with graphite pebbles. In order to load more fuel-graphite mixture, depletion must be introduced to compensate the further reactivity introduced by the loading of more fuels. In this work, the reactor power is set as 10% reactor full power (RFP), i.e., 25MW. Another boundary condition for the calculations is the reactor can be operated at full power when the whole cores are totally filled with the pebble mixture.

| 7:8G | 7:8G | 7:8G | 7:8G | 0:15G |
|------|------|------|------|-------|
| 7:8G | 7:8G | 7:8G | 7:8G | 0:15G |
| 7:8G | 7:8G | 0:15G | 0:15G |
| 7:8G | 7:8G | 0:15G | 0:15G |
| 7:8G | 0:15G | 0:15G | 0:15G |
| 7:8G | 0:15G | 0:15G | 0:15G |

Figure 3. The logical layout of regions near the core bottom of the curved channel model in this work. The boundary of fuel shuffling strategy change is between the uncolored regions and green-colored ones. The right column presents the fractional fuel batches to be reloaded to core top.
Since the ratio of fuel pebble number to the graphite pebble number is set as 7:8, it is natural to divide one region into 15 batches for both models. For the initial core loading process, the general fuel shuffling strategy is unloading the graphite pebbles from the core bottom, recycling 8/15 of them to the core top and loading fresh fuel pebbles with number of 7/15 of the unloaded pebbles to ensure the reloaded fuel to graphite ratio equal to 7:8. For the fuel shuffling simulation of the cylindrical channel model, the recycled batches with the same batch serial number from 5 bottom regions are mixed into one composition called “storage box” before they are divided evenly back to 5 top regions. This strategy ensures no mixing between fuel pebbles and graphite pebbles, as well as no mixing between fuels with different refueling history.

The logical layout of regions near the core bottom of the curved channel model is shown in Fig. 3, containing the batch numbers of fuels and graphite pebbles which should be assigned to the top regions under the restriction of equal batch volumes. Unfortunately, the fractional batch numbers are unacceptable in V.S.O.P. However, the sums of the fractional batch numbers are integers equal to the actual batch number sum of fuels and graphite pebbles divided by the channel number. On the other hand, the same integer sums as those mentioned above can be achieved by rounding the fractional batch numbers. Hence, the rounded batch numbers can be treated as the recycled batch numbers in the fuel shuffling simulations, for example, 61:9, 41:11, 31:12 and 11:14, corresponding the fractional batch numbers in Fig. 3.

The refueling strategy should be decided after rounding the batch numbers for each layer. For the cylindrical model, 3 batches of graphite pebbles will be replaced by 3 batches of fuels after all the graphite pebbles unloaded from the core, i.e., the initial core, resulting the reloaded fuel to graphite ratio of 10:5. There should be a mandatory boundary between the fuel shuffling strategies before and after the initial core, which is presented by color difference in Fig. 3 for the curved channel model. Consequently, the actual graphite batch number to be replaced for each region is determined by both the shuffling strategy and the rounded batch numbers. For example, 61:9, 41:11, 31:12 and 11:14, corresponding the fractional batch numbers in Fig. 3.

3. Results and Discussions

In order to investigate the difference between the cylindrical channel model and the curved channel model, simulations for both models are carried out. As mentioned above, the final core state after 10% RFP operation along with fuel loading must be able to reach 100% RFP with proper control rod position. Hence, the irradiation period and the control rod position have to be adjusted carefully.

The evolution of average control rod position (CRP) during the initial core loading process is illustrated in Figure 4. The initial CRP values and the final CRP values are similar for both models, indicating that the initial and final excess reactivity values are also similar for both models. That is the natural results of the requirement of full power operation for the final state. However, the irradiation period of cylindrical channel model is significantly longer than that of curved channel model (about 8% longer), which means the reactor can be depleted less for the latter than the former. It should be considered that there are three kinds of reactivity increment/decrement which satisfy the equation below

\[ \rho^{+}_{\text{load}} = \rho^{+}_{\text{burn}} + \rho^{+}_{\text{rod}} \]

in which \( \rho^{+}_{\text{load}} \) is the reactivity increment originated from fuel loading, \( \rho^{+}_{\text{burn}} \) is the reactivity decrement from fuel depletion and \( \rho^{+}_{\text{rod}} \) is the reactivity decrement from control rod insertion. Since the depth values of control rod insertion in both models are quite similar, it is reasonable to consider the \( \rho^{+}_{\text{burn}} \) values in both models are also similar. Consequently, the reactivity increment \( \rho^{+}_{\text{load}} \) in the curved channel model, corresponding to the less depletion, is less than that in the cylindrical channel model.
The results of irradiation period can be explained as below. For the final state of the cylindrical model, the whole reactor core is totally filled with fuel-graphite pebble mixture with fuel to graphite ratio of 7:8. On the other hand, there exist some pure graphite zones around the outer bottom of the core in the final state of the curved channel model. Moreover, the fuel pebbles reloaded near the end of final state of the curved channel model contain some irradiated fuel pebbles, corresponding to the fuels in the green zones in Fig. 3. Those facts indicate that the final state of the curved channel model presents not only less fuel pebbles, but less fresh fuel pebbles than that of the cylindrical channel model. Consequently, the former can be depleted for a shorter period than the latter to obtain the same excess reactivity.

Moreover, it can be observed through the evolution of the CRP values that there exists depletion with remarkable variable speed during the loading process in the curved channel model. For the earlier refueling cycles, the increase values of insertion depth of control rods are much larger than those for the latter cycles. These results reveal that the accumulation of reactivity in the earlier cycles is larger than in the latter cycles, which can also explain by the lack of fuel pebbles, especially fresh fuel pebbles, during the latter process of the curved channel model.

On the other hand, a calculation test is performed to evaluate the calculation error of the rounding process. The $k_{eff}$ values, corresponding to 1 batch and 2 batches of fuels reloaded to the core when reloading the bottom layer of mixtures in Fig. 3, are calculated, as listed in Table 1. Both values are quite close to each other and the reactivity difference is only 2.8 pcm, which may only be treated as calculation error and is definitely negligible. Similarly, the discrepancy of reactivity introduced by rounding 1.4 batches of fuels to 1 batch of fuels must be also negligible. Hence, the batch number rounding in the curved channel model is sufficiently accurate since the total batch number of the whole reactor core maintains unvaried.

| Reloaded batch number | $k_{eff}$ value | Difference of reactivity (pcm) |
|-----------------------|----------------|-------------------------------|
| 1                     | 1.001599       | 2.8                           |
| 2                     | 1.001571       | --                            |
Compared with the cylindrical channel model, the curved channel model provides higher fidelity. It means that the errors on estimating the period length of initial core loading with the simpler model of cylindrical channels can be corrected by the curved channel model. Since the length of commissioning process, including the initial core loading process, is highly related to the cost of the plant operation, the accurate determination of the initial core loading period length is important to the cost control of fuel cycling of PB-HTRs.

4. Conclusions
In this work, a curved channel model for the HTR-PM core design is established, with 5 vertical pebble flow channels in radial direction and the equal-volume region numbers for channels from inside to outside of 20, 21, 23, 25 and 26. These region numbers are proportional to the averaged passing-through time in the channels derived from the DEM simulations of the pebble flow. Compared with the traditional cylindrical channel models, the curved channel models encounter complicated situation when dealing with the refueling process before reaching equilibrium core, such as the running-in phase and the initial core loading. The main challenge is the possible fractional batch numbers after the refueling process, which can be solved by rounding the fractional batch numbers.

The simulation of initial core loading process with the curved channel model mentioned above is implemented in this work, based on the solution of rounding fractional batch numbers. It is revealed that the irradiation period of cylindrical channel model is about 8% longer than that of curved channel model, which can be explained by the difference of distribution of fuels and graphite pebbles between the both models. Furthermore, the error of batch number rounding process is analyzed and proved negligible for the keff results. The fidelity of the curved channel models is important for the design and analysis on the complicated refueling process of PB-HTRs. The analysis upon the running-in phase will be focused in the future works.

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References
[1] H. J. Rütten, K. A. Haas, H. Brockmann and W. Scherer, “VSOP (99/05) computer code system for reactor physics and fuel cycle simulation”, Jül-4189, Forschungszentrum Jülich (2005).