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SCOPING STUDY ON THE OPTIMUM FUEL COMPOSITION AND FUELING SCHEME OF A PEBBLE-BED HTGR

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ABSTRACT

An optimum fuel composition is a very important parameter in the operation of a pebble bed high temperature gas-cooled reactor (HTGR). In the present scoping study, the optimum ranges of heavy metal (HM) loading per pebble and the uranium enrichment are investigated. The HM loading range covers 4 to 10 g per pebble, while the uranium enrichment covers 5 to 20 w/o. Two fuel loading schemes typical to pebble-bed HTGRs are also investigated, i.e. the OTTO and multi-pass schemes. All calculations are carried out using BATAN-MPASS, a general in-core fuel management code dedicated for pebble-bed type HTGRs. The reference reactor design case is adopted from the German 200 MWth HTR-Module but with core height of half of the original design. Other design parameters follow the original HTR-Module design. The results of the scoping study show that, for both once-through-then-out (OTTO) and multi-pass fueling schemes, the optimal HM loading per pebble is around 7 g HM/ball. Increasing the uranium enrichment minimizes the fissile loading however higher enrichment than 15 w/o is not effective anymore. The multi-pass fueling scheme shows lower fissile loading requirement and a significantly lower axial power peaking than the OTTO scheme. It can be concluded that the optimum range of HM loading and uranium enrichment are found to be around 7 g per pebble and 15 w/o. In addition the multi-pass fueling scheme shows superior burnup and safety characteristics than the OTTO fueling scheme.

Keywords: optimum fuel composition, fuel loading scheme, pebble-bed HTGR, HTR-Module, Batan-MPASS.

INTRODUCTION

An optimum fuel composition and fuel loading scheme in the operation of a pebble-bed high temperature gas-cooled reactor (HTGR) are very important design parameters since they will directly affect the fuel cost, new and spent fuel storage capacity as well as other back-end environmental burden. A scoping study on the fuel composition parameters, namely heavy metal (HM) loading per pebble and uranium enrichment, and on the fuel loading scheme, i.e. once-through-then-out (OTTO) and multi-pass, is conducted. The main goal of this study is to obtain optimum range of HM loading per pebble and uranium enrichment for the both of OTTO and multi-pass schemes. The HM loading per pebble strongly affects the neutron moderation while the uranium enrichment is correlated directly with the achievable discharge burnup. The fuel loading schemes, on the other hand, will influence the overall burnup performance as well as the axial power profile which is an important safety aspect.

In the past, Liem (1996) has proposed a two-step design procedure for small-sized pebble bed HTGRs [1]. The German 200 MWth HTR-Module [2] was taken as the reference case for designing smaller-sized pebble-bed HTGRs. In the first step of the design procedure, keeping the core diameter (D) constant, the core height (H) is reduced until the burnup performance starts to deteriorate considerably. It has been found that the HTR-Module original core height can be reduced to its half value with negligible penalty on the burnup performance, that is, from around 9 m to 4.8 m. This core dimension is taken as the reference case for the present scoping study while keeping other design parameters identical with the ones of the original HTR-Module. The main reason to choose the above-mentioned height is the use of OTTO fueling scheme (HTR-Module considered only multi-pass fueling scheme) where the bottom half of the 9 m core produces almost no power. We aim at a more compact core design where the core pressure drop is expected to be much lower. In addition, from the point of view of xenon stability, the shorter core height is expected to improve the stability against xenon. The neutron migration length (M) is estimated to be approximately 25 cm, so that the H/M ratio decreased from 36 to 18, i.e. to more stable regime which allow higher level of thermal neutron flux in the core. However, reducing the active core volume resulted in a higher average power density.

It should be noted also that the fuel compositions used in the two-step design procedure in Ref [1] were identical with the HTR-Module (7 g/pebble, 8 w/o enrichment), and no effort has been conducted to check whether the fuel composition is optimum. The vendor of HTR-Module may have conducted a similar scoping study however the results are not available in open publications. Hence, this work is expected to contribute in providing engineering arguments of optimum fuel composition not only for the HTR-Module but also for smaller-sized pebble-bed HTGRs derived from the design.

METHODOLOGY

The reactor core main parameters used in the present scoping study are shown in the Table-1. For other main design parameters, readers should consult Ref. [2]. For the multi-pass fuel loading scheme, the number of passes is 8 times.

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The scoping study is conducted over HM loading in the range of 4 to 10 g per pebble and uranium enrichment in the range of 5 to 20 w/o for OTTO and multi-pass fuel loading schemes. Fissile loading requirement per unit of generated energy (kg per GWD), which directly affects the fuel cost, is taken as the objective function to be evaluated and compared for the present scoping study. All calculations results have converged to a critical, equilibrium core condition with the prescribed thermal-hydraulic design parameters.

Table-1. Reactor core main parameters.

Parameters	Value
Thermal power (MWth)	200
Core height (cm)	480
Core diameter (cm)	300
Void height (above the core, cm)	94
System pressure (bar)	60
Helium inlet temperature (C)	250
Helium outlet temperature (C)	700
Coated fuel particle	TRISO LEU UO_2

The pebble fuel movement, burnup and core criticality calculations are carried out by BATAN-MPASS [3], a general in-core fuel management code for pebble-bed HTGRs, featured with many automatic equilibrium and criticality searching options as well as thermal-hydraulic module. The code has been validated with the German HTR-Module design, the validation results have also been used as a comparative solution for other code [4].

The cross-sections (4 energy groups) and their self-shielding factors as a function of temperature and composition were prepared using several parts of the VSOP code system [5]: ZUT-DGL, THERMOS and GAM. Group constants for the cavity at the top of the core are determined according to the method developed by Gerwin and Scherer [6]. Using their method, different axial and radial diffusion coefficients can be obtained. The detail discussion of the in-core thermal-hydraulic model used in the BATAN-MPASS code was already given by Liem and Sekimoto [7].

RESULTS AND DISCUSSIONS

Figures-1 and 2 show the calculated fissile loading requirement as a function of HM loading for OTTO and multi-pass schemes, respectively. It is obvious from Figure-1 that the optimum HM loading and enrichment are found in the range of around 7 g per pebble and 10 – 15 w/o, respectively, for OTTO fuel loading scheme. On the other hand, the optimum HM loading and enrichment for the multi-pass fuel loading scheme (Figure-2) are found around 7 g per pebble and 15w/o, respectively.

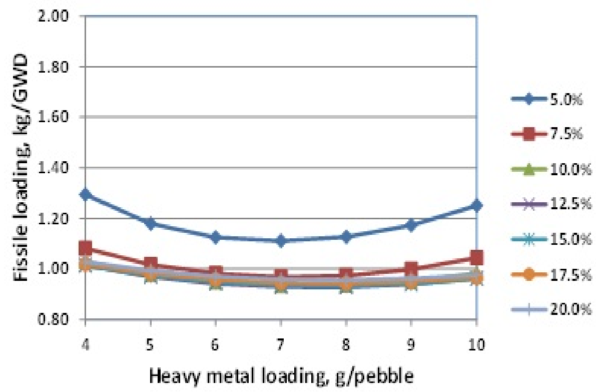

Figure-1. Fissile loading requirement as a function of HM loading for OTTO fuel loading scheme.

The multi-pass HTR-Module [2] adopted 7 g per pebble and 8 w/o enrichment for its fuel composition. Our optimization result shows the same HM loading but higher enrichment (15 w/o). The HTR-Module fuel enrichment may be set based on the aimed discharge burnup of 80 GWd/t. Recent development of TRISO coated particle fuel technology allows much higher discharge burnup.

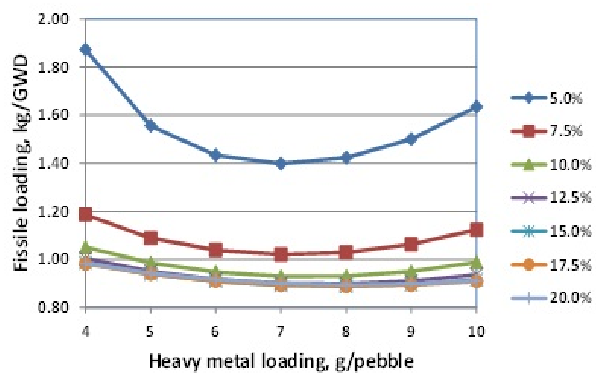

Figure-2. Fissile loading requirement as a function of HM loading for multi-pass fuel loading scheme.

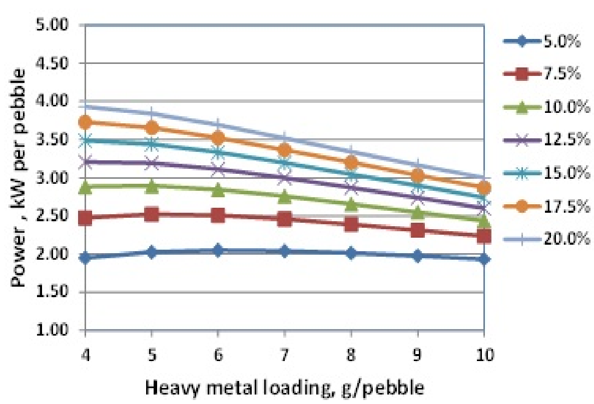

Figure-3. Maximum power per pebble as a function of HM loading for OTTO fuel loading scheme.

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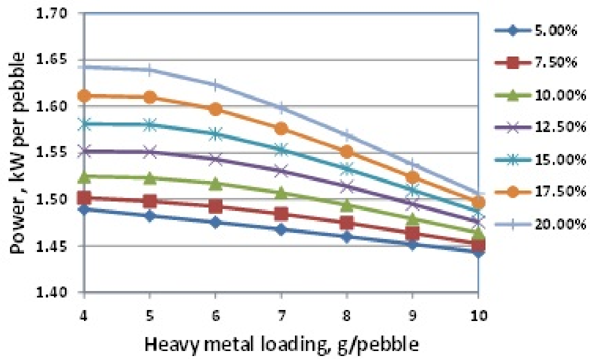

Figure-4. Maximum power per pebble as a function of HM loading for multi-pass fuel loading scheme.

For the both fuel loading schemes, increasing the uranium enrichment minimizes the fissile loading requirement however enrichment higher than 15 w/o is not effective anymore. For uranium enrichment of 15 w/o, the discharge burnup of OTTO and multi-pass fueling scheme is 164 GWd/t and 173 GWd/t, respectively. Needless to say, the multi-pass scheme shows lower fissile loading requirement than the OTTO one in the optimum ranges.
Figures-3 and 4 show the maximum power per pebble for OTTO and multi-pass fueling scheme, respectively. For both fueling scheme, as will be shown later, the power peak is located along the axial central axis of the core. Therefore, the axial power peaking factor will determine the core overall power peaking factor, i.e. the maximum power per pebble at the peak location. In general, as the HM loading increases the maximum power per pebble decreases. In the contrary, as the fuel enrichment increases the maximum power per pebble also increases.

The multi-pass fuel loading scheme shows much lower power per pebble and this is expected to affect the reactor safety during severe accidents such as a depressurization accident.

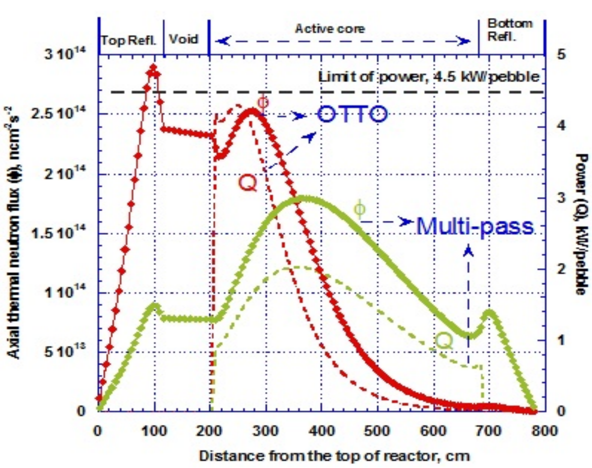

Figure-5. Axial distributions of thermal neutron flux and power density for OTTO and multi-pass fueling schemes (optimal fuel composition).

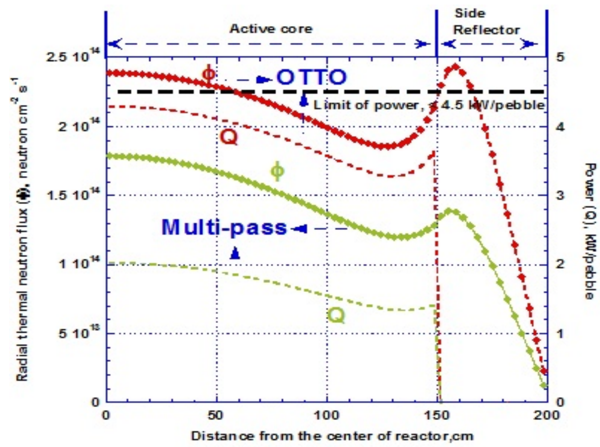

Figure-6. Radial distributions of thermal neutron flux and power density for OTTO and multi-pass fueling schemes (optimal fuel composition).

The axial and radial distributions of thermal neutron flux and power density for OTTO and multi-pass fueling scheme are shown in Figure-5 and 6, respectively. The figures correspond to the optimal fuel composition cases. From Figure-5 one can observe that for OTTO fueling scheme, not only the severe power peak at the upper part of the core but the neutron flux at the upper reflector is also significantly higher than that of multi-pass fueling scheme. The power density peak of OTTO fueling scheme is just below the limit value (4.5 kW/pebble). The radial distributions shown in Figure-6 confirm that the power peak location is at the core central axis.

CONCLUSIONS

A scoping study on the optimum fuel composition (HM loading per pebble and uranium enrichment) for a 200 MWth pebble-bed reactor with LEU UO2 TRISO fuel under OTTO and multi-pass fueling scheme was conducted using BATAN-MPASS code. The objective function for the optimization is the fissile loading requirement per energy generated (kg/GWd). The optimum HM loading and uranium enrichment are found around 7 g per pebble and around 15 w/o for both OTTO and multi-pass fueling schemes. The multi-pass fueling scheme shows better burnup and safety characteristics than the OTTO fueling scheme.

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