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Physical Design of High-Performance Fuel Assembly Based on Fully Ceramic Microencapsulated Fuel for Supercritical CO_2 Cooled Reactor

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Fully ceramic microencapsulated fuel (FCM) is employed in the supercritical CO_2 (S-CO_2)-cooled reactor as accident tolerant fuel (ATF). Although the fuel and the assembly substrate contain SiC, the assembly cannot be sufficiently moderated due to the weak moderating performance of S-CO_2, which affects the neutronics economy seriously. In this study, a new fuel assembly based on FCM fuel is proposed for the S-CO_2 cooled reactor. Besides, the solid moderator rod is introduced into the design. Although the introduction of moderator rods can effectively improve the moderation performance of S-CO_2 reactor assembly, it will lead to the deterioration of uniform moderation. To further improve the uniform moderation, arrangement of moderator rods and fuel enrichment partition are studied. Finally, the results show clearly that a better balance between uniform moderation and sufficient moderation can be obtained in the high-performance S-CO_2 reactor assembly.

Keywords: supercritical CO_2 cooled reactor, fuel assembly (FA), FCM fuel, sufficient moderation, uniform moderation

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INTRODUCTION

By taking advantage of the appropriate critical pressure, high density, stability, and sluggishness of CO_2 near its critical point, the use of supercritical CO_2(S-CO_2) as a coolant in the direct cycle reactor is evaluated (Ahn et al., 2015; Wu et al., 2020). The S-CO_2–cooled reactor, as a promising innovative reactor, has the advantages of simple system, high thermal efficiency, small volume, and light weight, and it represents an important development direction for nuclear energy innovation and development (Michael, 2004).

Safety and economics are the main objectives of the S-CO_2–cooled reactor. A new fuel concept is referred to as accident-tolerant fuels (ATFs) are capable of mitigating the potential consequences of beyond-design-basis accidents (Bragg-Sitton, 2014). The fully ceramic microencapsulated (FCM) fuel (Terrani et al., 2012) has become one among the ATF options which is based on tristructural isotropic (TRISO) (Bragg-Sitton and Carmack, 2015)–coated particles embedded in silicon carbide (SiC) matrix. FCM fuel borrows from the TRISO particle design from the high-temperature gas reactor (HTGR) technology but uses SiC as a matrix material rather than graphite in HTGR. Benefiting from the multiple barriers of TRISO and SiC matrix, FCM fuel has extremely high radioactivity retention capability compared to that of the conventional standard UO_2 fuel. By the advantages of safety, a new fuel assembly based on the FCM fuel is proposed for the S-CO_2–cooled reactor in this study.

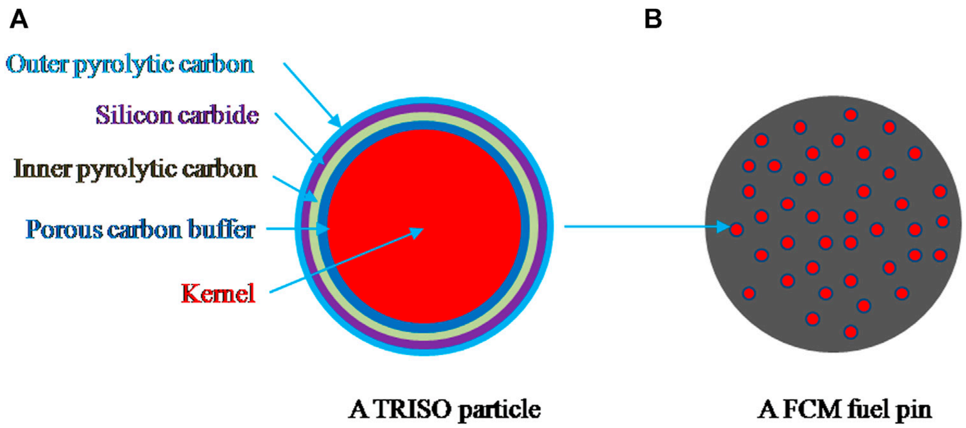

FIGURE 1 | Design of FCM fuel.

TABLE 1 | TRISO particle geometry and composition.

Layer	Radius (mm)	Density (g/cm^3)
Kernel	0.4000	10.41
Porous carbon buffer	0.4500	1.100
Inner pyrolytic carbon	0.4850	1.900
Silicon carbide	0.5200	3.180
Outer pyrolytic carbon	0.5400	1.900

TABLE 2 | FCM fuel design parameters.

Parameter	Value	Unit
Fuel compact outer radius	8.3500	mm
Gas gap outer radius	8.4000	mm
SiC Clad outer radius	8.9000	mm
^{235}U enrichment	19.75%	-
TRISO particle share	40%	-

In further research, although the FCM fuel contains moderation materials such as SiC, the assembly cannot be sufficiently moderated due to the weak moderating performance of S-CO_2, which affects the neutronics economy seriously. The study on improving the deficiency of weak moderating performance is described in this article.

Unlike the light water moderated or heavy water moderated (Zhang et al.,2019; Zhang et al.,2020) nuclear reactors, the S-CO_2 cooled reactor needs specific moderator rods to improve the slow-down of neutrons. The introduction of moderator rods can effectively improve the moderating performance of S-CO_2–cooled reactor, but it will lead to the deterioration of uniform moderation. To further improve the uniform moderation, moderator rod arrangement and fuel enrichment partition method are studied. Finally, this study shows clearly that a better balance between uniform moderation and sufficient moderation can be obtained in the high-performance S-CO_2–cooled reactor assembly.

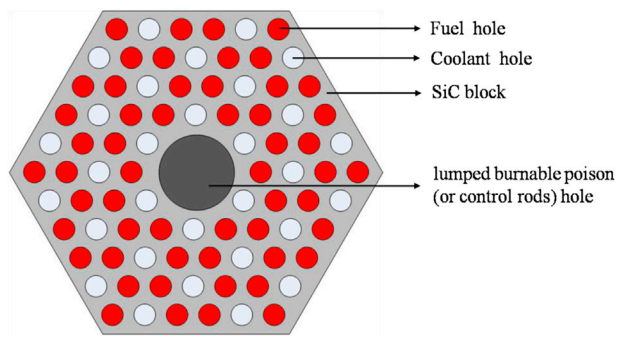

FIGURE 2 | S-CO_2–cooled reactor standard fuel assembly.

TABLE 3 | FCM fuel design parameters.

Parameter	Value	Unit
SiC block length	2,500.00	mm
SiC block width	240.00	mm
Fuel/Coolant hold diameter	18.00	mm
Minimum web thickness	6.00	mm
SiC Clad outer radius	8.90	mm
lumped burnable poison (or control rods) hole diameter	72.00	mm
Fuel hold number	54	-
Coolant hold number	30	-
U weight per assembly	44.48	kg

FULLY CERAMIC MICROENCAPSULATED FUEL ASSEMBLY OF S-CO_2–COOLED REACTOR DESIGN

Standard Fuel Assembly of S-CO_2–Cooled Reactor Design

An FCM fuel with a TRISO particle is shown in **Figure 1**. The TRISO particle geometry and composition are given in **Table 1** and the FCM fuel design parameters are given in **Table 2**. In this

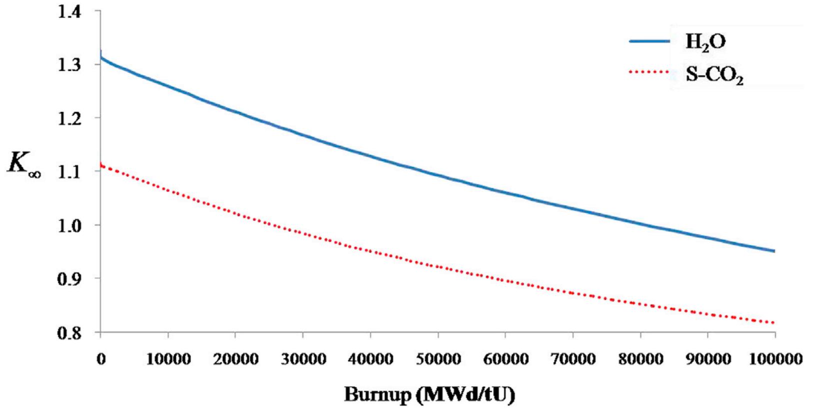

FIGURE 3 | K_∞ versus fuel burn up.

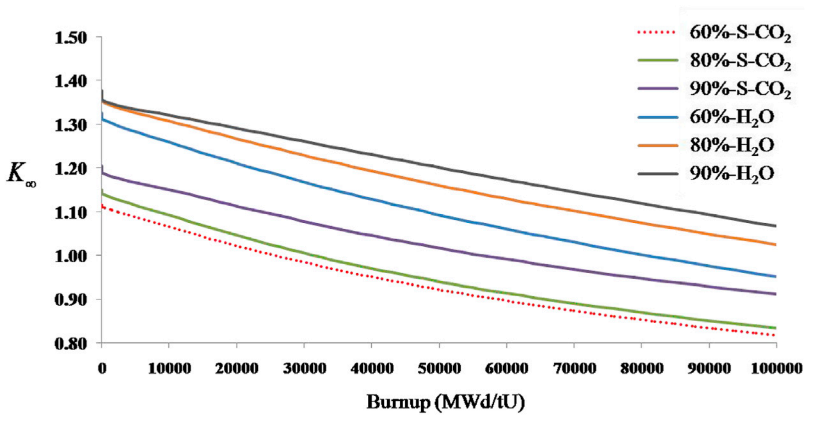

FIGURE 4 | K_∞ by different SiC matrix share versus burn up.

design, the TRISO particles account for 40% of the volume in FCM fuel and the enrichment of ^{235}U reaches 19.75%.

The standard fuel assembly of S-CO_2–cooled reactor in this study is shown in **Figure 2**; it contains SiC block, fuel holes, coolant holes, and lumped burnable poison (or control rods) hole. The assembly design parameters are given in **Table 3**. Each block is a right hexagonal prism with a dimension of 2,500 mm in length and 240 mm across the flats of the hexagonal cross section. Fuel and coolant holes run parallel through the length of the block in a regular triangular pattern of nominally two fuel holes per coolant hole. The pitch of the fuel and coolant hole array is 18 mm. The minimum web thickness between the fuel hold and coolant hole is 6 mm and this web provides an additional barrier to the release of metallic fission products. In order to get an effective control of reactivity, a lumped burnable poison (or control rods) hole (72 mm) is added to the center of standard fuel assembly.

TABLE 4 | $YH_{1.8}$ solid moderator pin geometry and composition.

Layer	Radius (mm)	Material
Kernel	8.4000	$YH_{1.8}$
Cladding	8.9000	stainless steel

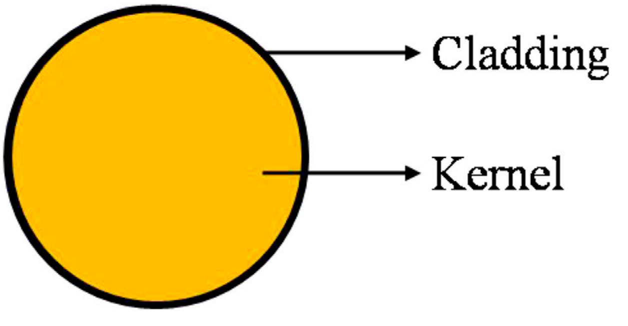

FIGURE 5 | $YH_{1.8}$ solid moderator pin.

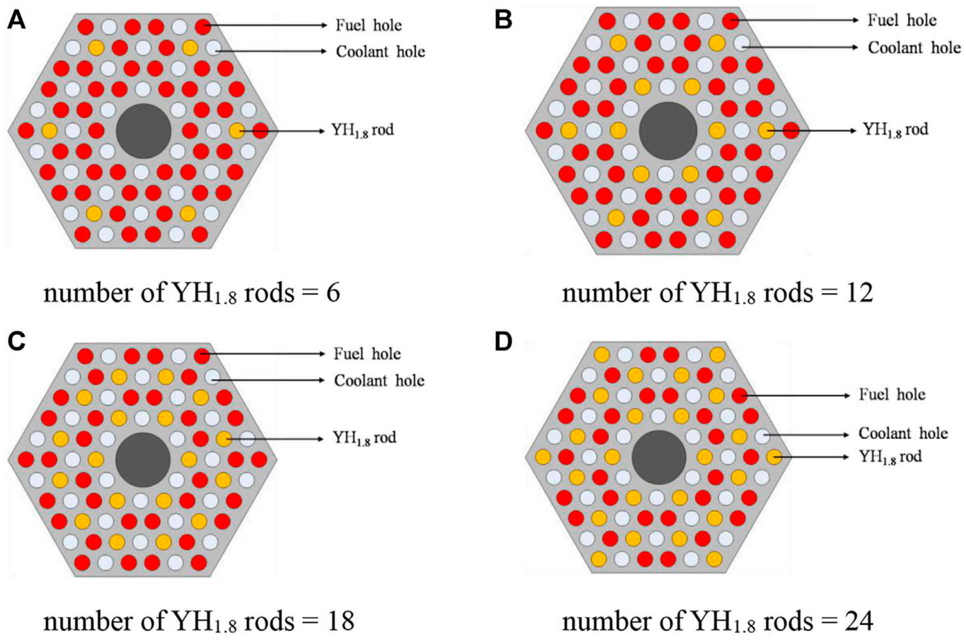

FIGURE 6 | Arrangements of $YH_{1.8}$ solid moderator rods in S-CO_2 assembly.

Neutron Moderating Performance Analysis for the Standard Assembly

To analyze neutron moderating performance for the standard assembly, the light water (H_2O) coolant fuel assembly is used for comparison in standard assembly cooling by S-CO_2. Other than replacing coolant with H_2O, the design parameters remain unchanged to compare S-CO_2 assembly and H_2O assembly in moderating analyses. The calculation in the study is done by using HANDF-E code package developed by the Nuclear Power Institute of China. This code has been used in the analysis of hexagonal assembly because of its high accuracy.

Infinite multiplication factor (K_∞) is the main parameter that characterizes fuel reactivity. In general, moderating performance largely determines the value of K_∞. $K_\infty$of each assembles as fuel burn up varies, as shown in **Figure 3**. $K_\infty$of S-CO_2 assembly is much less than that of H_2O under the same fuel burn up. The calculation results clearly show that S-CO_2 assembly has the defect of insufficient moderating performance.

Neutrons can be moderated in the SiC, and increasing the SiC matrix share of FCM fuel is the most direct way to improve the moderating performance. The SiC matrix share increases from 60 to 80%, or even 90%, and then K_∞ by different SiC matrix share as fuel burn up varies is shown in **Figure 4**. The calculation results clearly show that increasing SiC matrix share is beneficial to enhance moderating performance and improve fuel reactivity. **Figure 4** also presents K_∞ of H_2O assembly by different SiC matrix share as fuel burn up varies. Even if the matrix share changes, K_∞ of H_2O is still much greater than that of S-CO_2. These results show that the method of increasing the SiC matrix share has a limited effect on improving the moderating performance.

In fact, in terms of fuel burn up and core volume, increasing SiC matrix share is not a good idea; it means the TRISO particle share is reduced and fuel burn up will be grow greatly. To reduce fuel burn up, a larger number of assembles will be used in core, resulting in a larger core volume, and the large core volume makes the design of pressure vessels under high temperature and pressure a great challenge. Therefore, the method to improve the moderating performance should minimize the increase in core volume.

TABLE 5 | $YH_{1.8}$ solid moderator rods number setting.

	$YH_{1.8}$ rods number	Fuel rods number	Relative share of fuel
1	0	54	1.000
2	6	48	0.889
3	12	42	0.778
4	18	36	0.667
5	24	30	0.556

NEUTRONICS ANALYSIS FOR THE DESIGN OF $YH_{1.8}$ IN THE STANDARD ASSEMBLY

Because of stronger neutron moderating capacity, metal hydride has been used as a solid moderator in reactors. Yttrium hydride ($YH_{1.8}$) is more suitable to use in the S-CO_2 cooled reactor because it is more stable than zirconium hydride ($ZrH_{1.6}$) at high temperature.

The design of $YH_{1.8}$ solid moderator rod used in this study is shown in **Figure 5**. To reduce the release of hydrogen atoms,

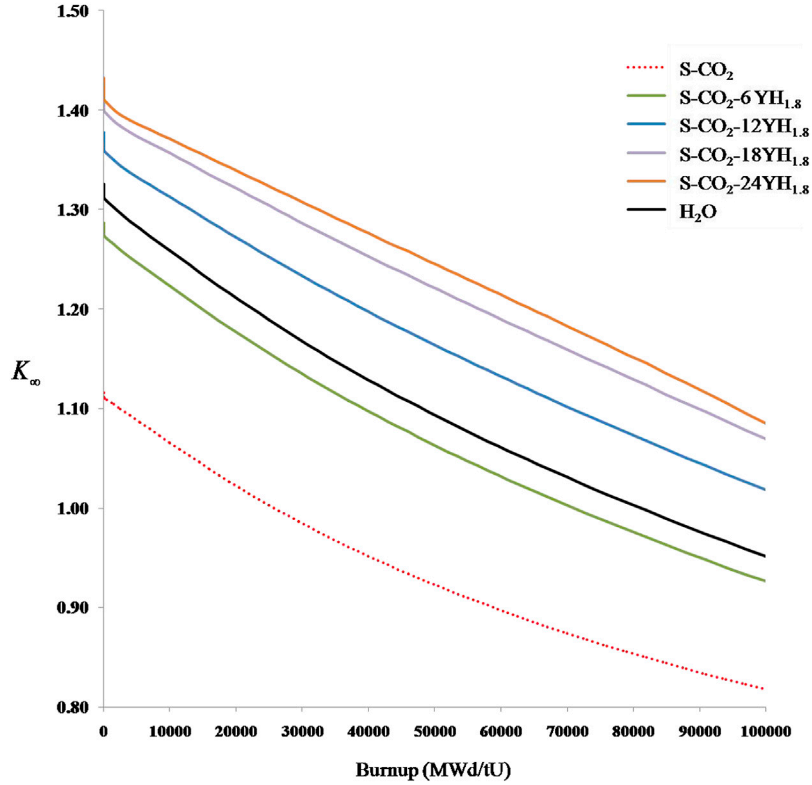

FIGURE 7 | K_∞ by different numbers of $YH_{1.8}$ rods versus burn up.

the solid moderator rod is coated with stainless steel. The $YH_{1.8}$ solid moderator rod geometry and composition are given in **Table 4**.

The moderating method is to insert the $YH_{1.8}$ solid moderator rod into part of fuel holds instead of the FCM fuel. The moderating performance of assembly can be changed by using different number of $YH_{1.8}$ solid moderator rods. The number of $YH_{1.8}$ solid moderator rod analyzed in this study is shown in **Table 5**, and the arrangements of the $YH_{1.8}$ solid moderator rods are shown in **Figure 6**.

K_∞ by different $YH_{1.8}$ solid moderator rod number as fuel burn up varies is shown in **Figure 7**. The calculation results clearly show that adding $YH_{1.8}$ solid moderator rod can significantly enhance moderating performance and then improve the fuel reactivity greatly. K_∞ of H_2O is also described in **Figure 6**. When the number of $YH_{1.8}$ solid moderator rods is greater than 12, the $K_\infty$of S-CO_2 assembly is significantly larger than that of H_2O assembly. These results show that moderating performance can be improved significantly by inserting the $YH_{1.8}$ solid moderator rod. When 12 $YH_{1.8}$ solid

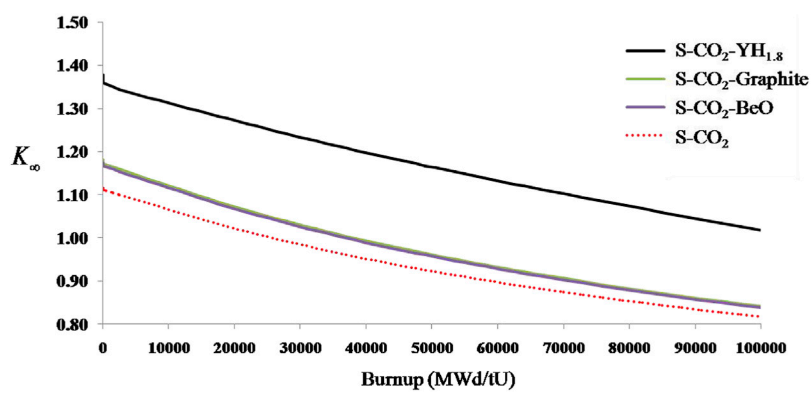

FIGURE 8 | K_∞ by different moderating materials versus burn up.

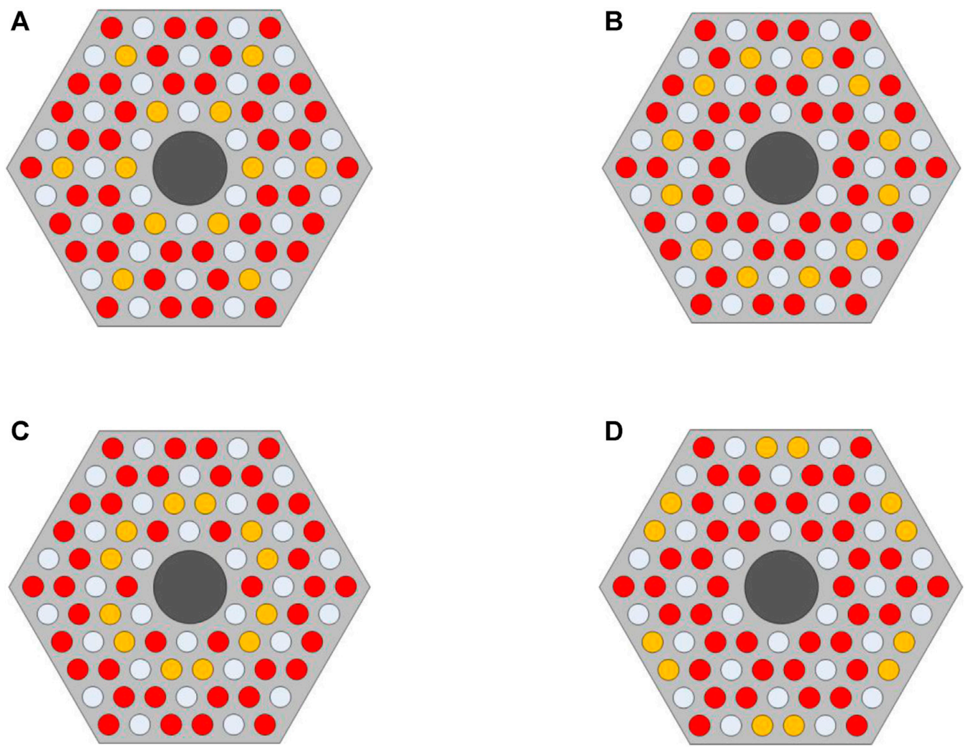

FIGURE 9 | Arrangements of 12 $YH_{1.8}$ solid moderator rods.

moderator rods were inserted, the S-CO_2 assembly was moderated sufficiently and the fuel share was reduced by only 22.2%.

The moderating effect of different materials was further studied. Commonly used moderating materials such as graphite and BeO are used for comparison with $YH_{1.8}$. K_∞ of different moderating materials as fuel burn up varies are shown in **Figure 8**. K_∞ of $YH_{1.8}$ is significantly larger than that of graphite and BeO. The results show that using $YH_{1.8}$ as a moderator is the best choice to improve the moderating performance of S-CO_2 assembly.

UNIFORM MODERATING DESIGN FOR THE S-CO_2 ASSEMBLY

Inserting the $YH_{1.8}$ solid moderator rods cause uneven moderating in the assembly. In order to get uniform moderating, the arrangement of the moderators must be studied.

The moderating effect and the change of fuel share were considered, and then the number of $YH_{1.8}$ solid moderator rods is selected as 12 in this section. The different arrangements of $YH_{1.8}$ solid moderator rods are shown in **Figure 9** and power uneven factor by different solid

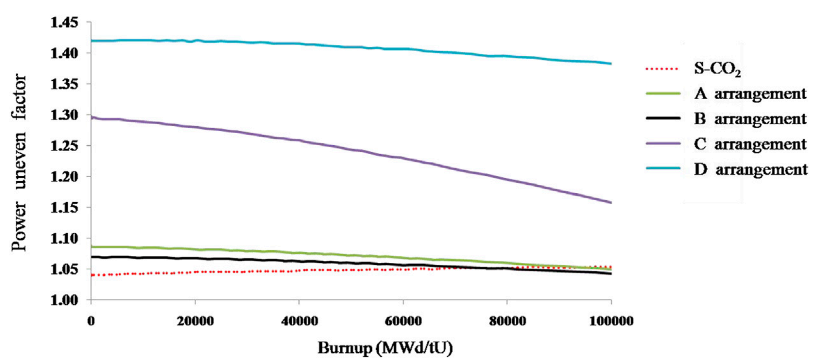

FIGURE 10 | Power uneven factor by different solid moderator arrangements.

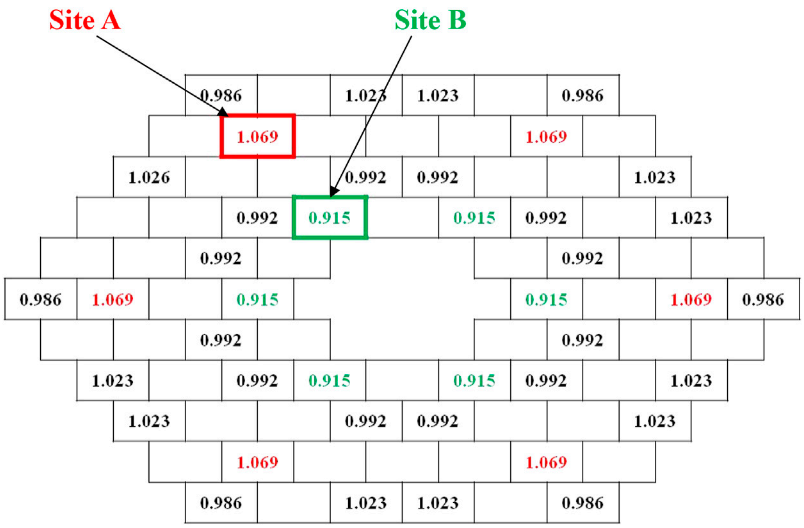

FIGURE 11 | Relative power distribution of S-CO_2 assembly using arrangement B (BOL).

moderator arrangements as fuel burn up varies are shown in **Figure 10**. The arrangement B of solid moderator obtains the lowest uneven factor and becomes the preferred arrangement in this study.

Figure 11 presents the BOL (**B**egin **Of L**ife) relative power distribution of S-CO_2 assembly using arrangement B. **Figure 11** clearly shows that the maximum power is at site A and the minimum power is at site B. In order to further realize the uniform moderating to reduce the power uneven factor, the fuel share of FCM partitioning method is applied in the S-CO_2 assembly design. The fuel share of FCM is reduced from 40 to 35% at site A which have maximum power and the fuel share of FCM is increased from 40 to 45% at site B which have minimum power. In addition, this partitioning method ensures that the fuel weight remains the same in the S-CO_2 assembly. The BOL relative power distribution of S-CO_2 assembly using the partitioning method is shown in **Figure 12**. The relative power at site A decreases from 1.069 to 0.964, the relative power at site B increases from 0.915 to 1.005, and then the uneven factor decreases from 1.069 to 1.028. **Figure 13** presents a power uneven factor by arrangement B with the partitioning method as fuel burn up varies; it shows that the fuel share of the FCM partitioning method can achieve more uniform moderating and power distribution.

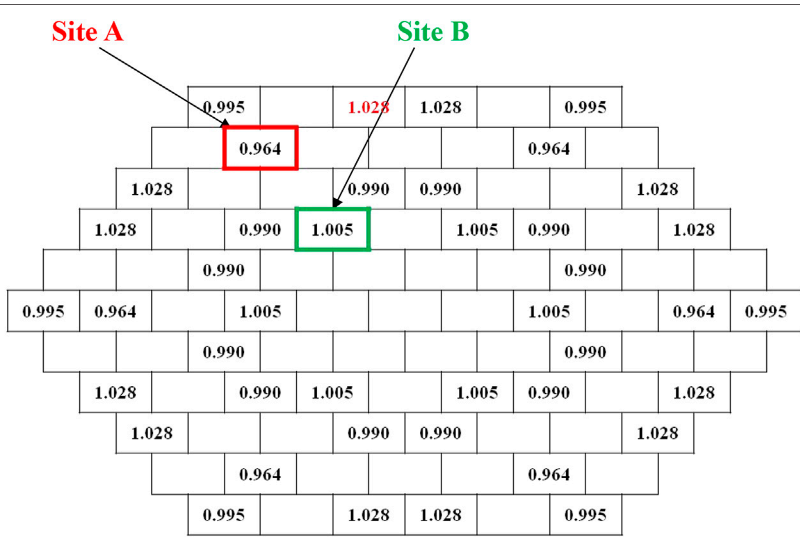

FIGURE 12 | Relative power distribution of S-CO_2 assembly using the partitioning method (BOL).

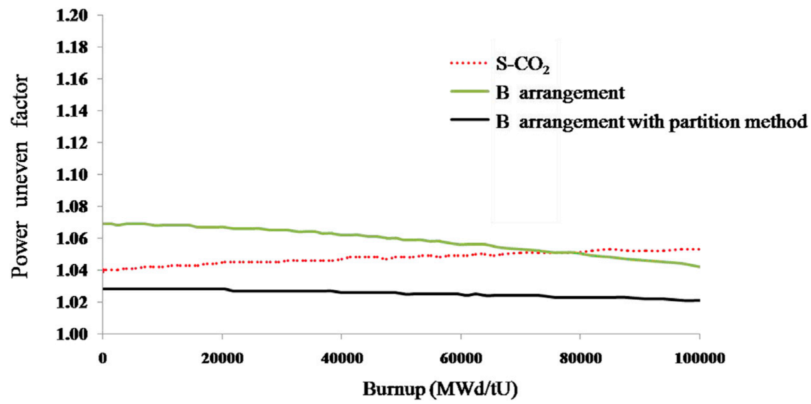

FIGURE 13 | Power uneven factor by arrangement B with the partitioning method.

CONCLUSION

As a new type reactor with development potential, the S-CO_2–cooled reactor has many advantages, such as simple system, high thermal efficiency, and small volume. FCM fuel which is a potential option of ATF is capable to mitigate the potential consequences of beyond-design-basis accidents and become the preferred type of fuel for the S-CO_2–cooled reactor.

In this article, a new fuel assembly design concept based on FCM fuel for S-CO_2–cooled reactor is proposed. Then, the design of $YH_{1.8}$ solid moderator rod was adopted to improve the moderating performance of the fuel assembly. In order to deal with the moderating non-uniformity caused by the moderator, the arrangement of moderators and the method of fuel share partitioning were well studied, and then the high-performance fuel assembly based on FCM fuel for S-CO_2–cooled reactor is proposed at last. The main conclusions of the study are as follows:

1) The fuel assembly based on the FCM fuel for the S-CO_2–cooled reactor was proposed because of the safety advantage. Due to the weak moderating performance of S-CO_2, the neutrons in this assembly cannot be sufficiently moderated and affects the neutronics economy seriously.
2) As it is superior to the method of adjusting the SiC matrix share, the design of $YH_{1.8}$ solid moderator rod is studied. With this design, the assembly can be sufficiently moderated.
3) The arrangement of $YH_{1.8}$ solid moderator rods is proposed, which can effectively improve the uniformity of moderating. The method of fuel share partitioning is studied at last and the fuel assembly is further uniformly moderated.
4) The high-performance fuel assembly based on the FCM fuel which has good safety and economics is suitable for S-CO_2–cooled reactor.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

DL contributed to conceptualization, methodology, and design. LW contributed to conceptualization and methodology. YC performed the calcualtion and analysis. DW funding acquisition and supervision. CZ visualization and investigation.

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