Preliminary Analysis of the Afterheat Removal in Pebble Bed Fluoride Salt Cooled High Temperature Reactors under Accident Conditions

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ABSTRACT

The pebble bed fluoride salt cooled high temperature reactor (PB-FHR) is an advanced reactor program that adopts coated particle fuel embedded within graphite sphere and molten salt coolant. It benefits from the advantages of the existing HTRs and those of the molten salt reactors (MSRs). The use of passive afterheat removal during an accident to enhance full safety is one vital element of the FHR design. The afterheat transfer mechanism in stagnant pebble bed core with molten salt plenum plays a dominate role in afterheat transport from the core to the ultimate heat sink. This complex multiple heat transfer mechanisms in the core can be described by an integrated feature parameter called effective thermal conductivity. It is similar to that of HTRs, but uses a liquid salt as coolant. It is not known whether the liquid salt is a radiation transparent material like helium, as a result, it must keep in mind that the effective thermal conductivity correlation validated by experiments in HTRs could not be directly employed to conduct FHRs' safety analysis. A PB-FHR design is now being planned for construction by the Center for Thorium Molten Salt Reactor System (TMSR) of Chinese Academy of Sciences, in Shanghai Institute of Applied Physics (SINAP), foreseeing the first criticality in 2020. In this study, much emphasis is put on the effect of the effective thermal conductivity on the afterheat removal in stagnant pebble bed core with molten salt plenum. The afterheat removal is based on the capacity of the TRISO coated fuel particles to accept temperatures up to 1600℃without damage, the temperature 1430℃ at which the salt coolant starts to boil, and the too high temperature resulting from heat transport from the core without exceeding the limits on the surrounding metallic structures, which is the most limiting constraint of the PB-FHR design.

KEYWORDS

Pebble bed fluoride salt cooled high temperature reactor, Effective thermal conductivity, Afterheat remova l

1. INTRODUCTION

The pebble bed fluoride salt cooled high temperature reactor (PB-FHR) is an advanced reactor concept that adopts coated particle fuel embedded within graphite sphere and molten salt coolant. It benefits from the advantages of the existing HTRs (e.g. on-line refueling and flexible fuel management) and those of the molten salt reactors (MSRs) (e.g. reactor operation at atmospheric pressure, high power density, excellent heat transfer and transport capability, etc.). This fuel has been demonstrated as a reliable, high temperature fuel in helium-cooled pebble bed reactors in Germany and China. The potential utility of molten salt as heat transfer agents was also demonstrated for nuclear reactors, as the liquid fuel in MSRE program, and several molten salts have been investigated by U.S., Japanese and China. Some necessary knowledge for the operation of FHR has been gained from related research and operational experience of HTRs and MSRs [1]. A PB-FHR design named SF1 has been being planned for construction by the Center for Thorium Molten Salt Reactor System (TMSR) of Chinese Academy of Sciences (CAS), in Shanghai Institute of Applied Physics (SINAP), CAS, foreseeing the first criticality in 2020 [2].

Study of heat transport from the core to the ultimate sink is very important for substantiation of safety and for licensing of FHRs. The afterheat transport from the core to the ultimate heat sink may be divided into four characteristic parts: (a) core - graphite reflector, (b) graphite reflector - reactor vessel, (c) reactor vessel - reactor cavity cooling system, (d) reactor cavity cooling system - ultimate heat sink. One of the remarkable features of PB-FHR is a possibility to remove the residual heat from the core to the graphite reflector due to natural heat transfer processes (conduction, convection, radiation), which can withstand a loss of both coolant and forced cooling without fuel failure or fission product release [3-8]. This complex multiple heat transfer mechanisms in the core can be described by an integrated feature parameter called effective thermal conductivity. The passive afterheat transfer mechanism in stagnant pebble bed with molten salt plenum during a loss of forced cooling accident (LOFC) with scram plays a vital role in afterheat transport from the core to the ultimate heat sink [9-16].

In this study, much emphasis is put on the effect of the effective thermal conductivity on the self-acting removal of the afterheat from a stagnant pebble bed with molten salt plenum. The afterheat removal is based on the capacity of the TRISO coated fuel particles to accept temperatures up to 1600℃ without damage, the temperature 1430℃ at which the salt coolant starts to boil, and the too high temperature resulting from heat transport from the core without exceeding the limits on the surrounding metallic structures, which is the most limiting constraint of the PB-FHR design.

2. Effective thermal conductivity

The core of the PB-FHRs is a packed bed of spherical fuel elements, the heat is transported simultaneously by these types of mechanisms: conduction of spherical, spherical contact area conduction, radiation in void region, conduction of molten salt and free convection of liquid salt [17-20]. Although the phenomena involved are complex, the model of the effective thermal conductivity is based on a simple Fourier conduction rate equation. The heat transfer rate (Q) can be described by:

$$Q = -k_{eff} A \frac{dT}{dx} \tag{1}$$

where k_{eff} denotes the effective thermal conductivity, and A is the relevant area of the pebble bed perpendicular to the temperature gradient through which the heat transfer is taking place. And dT/dx stands for the radial temperature gradient. Evidently, the effective thermal conductivity presents the integrated heat transfer capability of the pebble bed reactor core [20]. It may be expressed as the sum of different types of effective conductivity described as following: (1) solid conduction and radiation between pebbles, (2) conduction through the solid phase and across the contact interface between pebbles, (3) conduction within the interstitial voids filled by the molten salt and the pebble solid conduction, (4) heat transfer through free convection of molten salt.

In the interest of finding a correlating model for predicting the effective thermal conductivity of pebble bed reactor core, a large number of fundamental models have been developed, and some of those have been used in nuclear reactor design and safety analysis, i.e. gas cooled high temperature reactor (HTR) [21-28]. Many of the models are for specific pebble bed reactor core and/or compositions, as well as are based on different boundary conditions. Because of the complexity of the heat transfer process in pebble bed core, some aspects of the models are difficult to be reasonably simplified. Most of experimental studies on the effective thermal conductivity of pebble bed reactor core are related to gas cooled reactor. The fluid considered in studies is mainly gas [29-36]. However, studies on the effective thermal conductivity of the pebble bed reactor core adopting molten salt as coolant is still blank. It is similar to that of HTRs, but uses a liquid salt as coolant. It is not known whether the liquid salt is a radiation transparent material like helium, as a result, it must keep in mind that the effective thermal conductivity correlation validated by experiments in HTRs could not be directly employed to conduct FHRs' transient and accident safety analysis. Accordingly, theoretical and experimental studies on the effective thermal conductivity of FHR have been being conducted by TMSR.

3. Analysis and discussion

In the FHRs' transient and accident safety analysis process, the temperature limits given below need to be considered: the maximum of 1600℃ for TRISO coated fuel particles, the temperature at which the salt coolant starts to boil (1430℃), and the too high temperature without exceeding the limits on the surrounding metallic structures (core barrel, pressure vessel).

As a computational example, the effective thermal conductivity of the FHR is calculated by adopting the empirical model developed for calculating the effective thermal conductivity of the HTRs [37], in which only the gas was replaced by molten salt. In the stagnant pebble bed core with molten salt plenum, since the density of the pebble is slightly smaller than that of liquid salt, the pebbles suspend in the core and contact with each other subjected a small compressive load, so that the area contact conduction could be ignored. Besides, the convection of liquid salt is excluded. The effective thermal conductivities of the FHR calculated are shown in figure 1, where the porosity in pebble bed is 0.4, the pebble emissivity of 0.8 is selected, and the molten salt is regarded as a radiation transparent medium or a radiation opaque medium.

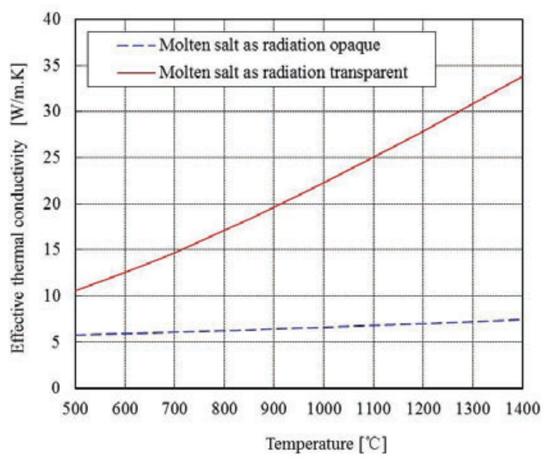


Figure 1 Effective thermal conductivity vary with temperature

The total thermal capacity of the reactor core (ρC_p) is the sum of the thermal capacity of pebble and molten salt. It can be described by:

$$(\rho C_p) = (\rho C_p)_s (1 - \varepsilon) + (\rho C_p)_f \varepsilon \quad (2)$$

where ε denotes the porosity in pebble bed.

As for the SF1 project, with finite element heat conduction codes [38], in which the model would not be able to catch the features of the free convection if it were taking place in the core, the top temperatures in the core, the barrel and the surface of the reactor body vary with time are shown in figure 2, with regarding the influence of the molten salt radiation performance on the temperature. As shown in Figure 2, it can be seen: (1) When the molten salt is regarded as a radiation opaque medium, the top temperature in the core reaches the peak of 1156℃ in 18.4 hours after reactor shutdown, whereas it is 956.6℃ in 7.3 hours after reactor shutdown when the molten salt is regarded as a radiation transparent medium. (2)

When the molten salt is regarded as a radiation opaque medium, the top temperature in the barrel reaches the peak of 728℃ in 13.8 hours after reactor shutdown, whereas it is 740.3℃ in 13.5 hours after reactor shutdown when the molten salt is regarded as a radiation transparent medium. (3) For the two different conditions, the time, of which the top temperature in the barrel is higher than 700℃, is no more than 45 hours.

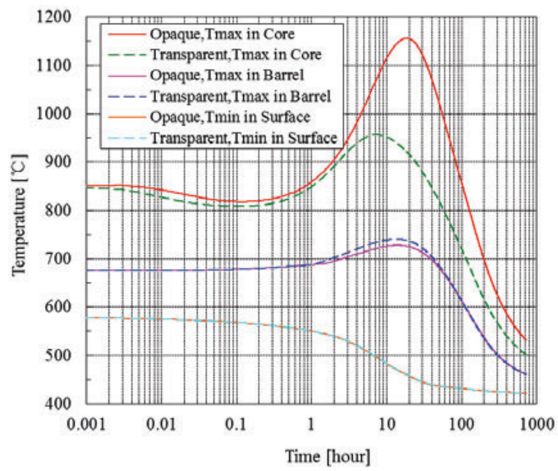
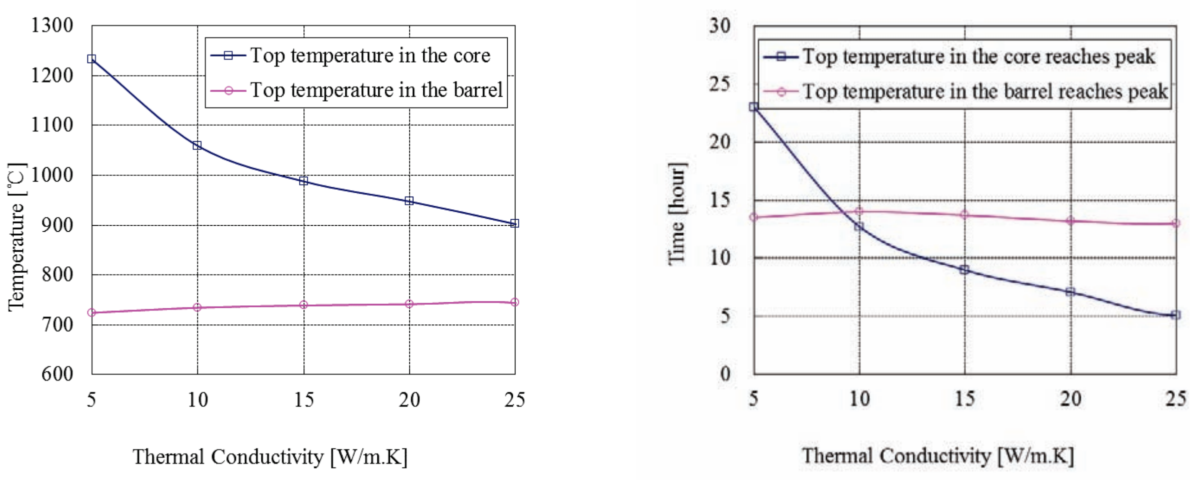


Figure 2 The top temperatures in the core, the barrel and the surface of the reactor body vary with time, with regarding the influence of the molten salt radiation performance on the temperature.

It can be concluded from the above results that the influence of the molten salt radiation performance on the temperature is evident and should be further taken into account. However, how the molten salt influence the radiative heat transfer process is not clear today. The effect of the effective thermal conductivity on the afterheat removal in stagnant pebble bed core with molten salt plenum is conducted.

Figure 3 shows the analysis results regarding the influence of the effective thermal conductivity on the peak temperature in the core and the barrel and their corresponding time after reactor shutdown. As can be seen: (1) when the effective thermal conductivity increases, the top temperature in the core decreases with the time shortening, yet the top temperature in the barrel increases. (2) when the effective thermal conductivity is $5 W/m\cdot\mathrm{K}$, the top temperature in the core is 1232.2℃ in 23.0 hours after reactor shutdown and the barrel is 724.1℃ in 13.5 hours after reactor shutdown. (3) when the effective thermal conductivity is $25 W/m\cdot\mathrm{K}$, the top temperature in the core is 902.2℃ in 5.1 hours after reactor shutdown and the barrel is 743.8℃ in 13.0 hours after reactor shutdown.



(a) (b)

Figure 3 The peak temperature in the core and the barrel and their corresponding time after reactor shutdown vary with the effective thermal conductivity

4. CONCLUSIONS

The effective thermal conductivity is very useful to understand the complex heat transfer phenomena in pebble bed with molten salt plenum. It plays a vital role in FHRs' transient and accident safety analysis. It is very necessary to develop a theoretical model to well predict the effective thermal conductivity for FHRs.

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REFERENCES

1. Piyush Sabharwall, Shannon M. Bragg-Sitton, Carl Stoots. Challenges in the development of high temperature reactors. Energy Conversion and Management, 74 (2013), 574–581.
2. Jiang mianheng, Xu Hongjie, Dai zhiming. The future advanced nuclear energy system——Thorium Molten Salt Reactor System. Bulletin of the Chinese Academy of Sciences, 2012, 27(3): 366-374. [in Chinese]
3. Wang Naxiu, Tian Jian, etc. Pre-conceptual design of a 10MW Pebble-bed Fluoride Salt Coolant high temperature test reactor: Thermal hydraulic design. The Center for Thorium Molten Salt Reactor System (TMSR) of Chinese Academy of Sciences, Technical Report, 2013. [in Chinese]
4. Zhu Zhiyong, Lin Jun, etc. Reactor fuel. The Center for Thorium Molten Salt Reactor System (TMSR) of Chinese Academy of Sciences, Technical Report, 2013. [in Chinese]
5. R. N. Morris, D. A. PetO, D. A. Powers, B. E. Boyark. TRISO-Coated Particle Fuel Phenomenon Identification and Ranking Tables (PIRTs) for Fission Product Transport Due to Manufacturing, Operations, and Accidents. NUREG/CR-6844, Vol. 1. U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, 2004.
6. Tang Chunhe, Tang Yaping, Zhu Junguo, et al. Design and manufacture of fuel element for the 10MW high temperature gas-cooled reactor. Nuclear engineering and design, 2002, 218, 91-102.
7. Wu Zhongxin, Xu Yuanhui, Sun Yuliang. Fuel element, design characteristics and safety features for HTR-10. Tsinghua Science and Technology. 2001, 41(4): 112-115. [in Chinese]

8. Cheng Bihua, Xu Shijiang. The damage rate of coated fuel particles for high temperature gas-cooled reactor. High Technology Letters, 1996, (3): 54-57. [in Chinese]
9. Argo W.B., Smith J. Heat transfer in packed beds. Chemical Engineering Progress, 1957, 49, 443-451.
10. Bahrami M., Yovanovich M.M., Culham J.R. Effective thermal conductivity of rough spherical packed beds. International Journal of Heat and Mass Transfer, 2006, 49, 3691-3701.
11. Achenbach E. Heat and flow characteristics of packed beds. Experimental Thermal and Fluid Sciences, 1995, 10, 17-27.
12. Breitbach G, Barthels H. The radiant heat transfer in the HTR core after failure of the afterheat removal systems. Nuclear Technology, 1980, 49: 392-399.
13. Prasad V, Kladas N, Bandyopadhaya A, et al. Evaluation of correlations for stagnant thermal conductivity of liquid-saturated porous beds of spheres. International Journal of Heat and Mass Transfer, 1989, 32, 1783-1796.
14. Aichlmayr H.T. The effective thermal conductivity of saturated porous media, University of Minnesota, Masters Thesis, 1999.
15. Botterill J S M, Salway A G, Teoman Y. The effective thermal conductivity of high temperature particulate beds. I. Experimental determination. International Journal of Heat Mass Transfer, 1989, 32(3), 585-593.
16. Botteril J S M, Salway A G, Teoman Y. The effective thermal conductivity of high temperature particulate beds. II. Model predictions and the implication of the experimental values. International Journal of Heat Mass Transfer, 1989, 32(3), 595-609.
17. Bauer, R., Schlunder, E.U. Part I: Effective radial thermal conductivity of packings in gas flow. Part II: Thermal conductivity of the packing fraction without gas flow. International Chemical Engineering, 1978, 18, 189-204.
18. Bauer, R. Stagnant packed beds. In: Hewitt, G.F. (Ed.), Hemisphere Handbook of Heat Exchanger Design. Hemisphere Publishing Corporation, 1990, pp. 2.8.1-1-2.8.4-14.
19. Van Antwerpen, W., du Toit, C.G., Rousseau, P.G. A review of correlations to model the packing structure and effective thermal conductivity in packed beds of mono-sized spherical particles. Nuclear Engineering and Design, 2010, 240, 1803-1818.
20. Ren Cheng, Yang Xingtuan, Li Congxin, Sun Yanfei. Progress in Pebble Bed Heat Transfer Test Facility of High Temperature Gas-cooled Reactor. Science Technology and Engineering, 2013, 13(7): 1905-1914. [in Chinese]
21. Aquaro D., Zaccari N. Experimental and numerical analysis on pebble beds used in an ITER test module blanket. Fusion Engineering and Design, 2006, 81, 1-7, 707-712.
22. Jin X.Z., Meyder R. Thermal-hydraulic system study of the helium cooled pebble bed (HCPB) test blanket module (TBM) for ITER using system code RELAP5. Plasma Science and Technology, 2005, 2, 2753-2757.
23. Aquaro D., Zaccari N. Pebble bed thermal-mechanical theoretical model: application at the geometry of test blanket module of ITER-FEAT nuclear fusion reactor. Fusion Engineering and Design, 2005, 75-79, 903-909.
24. Dalle D.M., Sordon G. Heat transfer in pebble beds for fusion blankets, Fusion Technology, 1990, 17, 597-635.
25. Okazaki M., Yamasyki T., Gotoh S. Effective thermal conductivities for granular beds of various binary mixtures. Journal of Chemical Engineering of Japan, 1981, 14, 183-189.
26. Dong Qi, Ye Danian. Particles' specific gravity and conformation and their random accumulation. Chinese Science Bulletin, 1993, 38(1): 54-57. [in Chinese]
27. Guo Renbing. Porosity of regular spheric accumulation. Journal of China University of Geosciences, 1994, 19(4): 503-508. [in Chinese]
28. Zhu Dunzhi. Theory model, numerical simulation and experimental study for spherical flow. Doctoral Dissertation of Tsinghua University, 1991. [in Chinese]
29. Niessen, H.F., Ball, S., Gao, Z. Heat Transport and Afterheat Removal for Gas Cooled Reactors

Under Accident Conditions. IAEA-TECDOC-1163, IAEA, VIENNA, 2000.

30. Niessen, H.F., Ball, S. Data sets of SANA experiment: 1994-199. JUEL-3409, Forschungs zentrum Julich, 1997.
31. Niessen H.F., Ball, S. SANA-1 code-to-experiment summary description of benchmark, 3rd IAEA Research Coordination Meeting on Heat Transport and Afterheat Removal for Gas-cooled Reactors under Accident Conditions, Vienna, Austria, 1995.
32. Liu Jie, Gao Zuying. The effective conductivities of pebble bed in high temperature gas cooled reactor and its application to SANA benchmark experiments. Chinese Journal of Nuclear Science and Engineering, 1999, 19(4): 303-308. [in Chinese]
33. Rousseau, P.G., van Staden, M. Introduction to the PBMR heat transfer testfacility. Nuclear Engineering and Design, 2008, 238, 3060-3072.
34. Rousseau, P.G., Du Toita, C.G., Van Antwerpena, W. et al. Separate effects tests to determine the effective thermal conductivity in the PBMR HTTU test facility. Nuclear Engineering and Design, 2013, http://dx.doi.org/10.1016/j.nucengdes. 2013.12.015.
35. Rousseau, P.G., Du Toit, C.G., Landman, W.A. Validation of a transient thermal-fluid systems CFD model for a packed bed high temperature gas-cooled nuclear reactor. Nuclear Engineering and Design, 2006, 236, 555-564.
36. Du Toit C.G., Rousseau P.G., Greyvenstein G.P., et al. A systems CFD model of a packed bed high temperature gas-cooled nuclear reactor. International Journal of Thermal Sciences, 2006, 45, 70-85.
37. IAEA. Heat Transport and Afterheat Removal for Gas Cooled Reactors Under Accident Conditions, IAEA-TECDOC-1163, 2000: 296-332
38. Wang Naxiu, Tian Jian, etc. Pre-conceptual design of a 10MW Pebble-bed Fluoride Salt Coolant high temperature test reactor: Thermal hydraulic design. The Center for Thorium Molten Salt Reactor System (TMSR) of Chinese Academy of Sciences, Technical Report, 2015. [in Chinese]