Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2023

A Comparative Physics Study on Very Small Reactor Cores (vSMRs) having Different Coolants for Ultra-Long-Life Operation

Seung Nam Lee, Yu Yeon Cho, Ser Gi Hong*
[a]*Department of Nuclear Engineering, Hanyang University,222 Wangsimni-ro, Seongdong-gu, Seoul, 04763*
**Corresponding author: hongsergi@hanyang.ac.kr*

1. Introduction

Recently, many different types of SMRs are being considered in nuclear society. They use different coolants and fuels. They include liquid metal cooled reactors, light water cooled ones, gas cooled ones (thermal and fast spectra), and molten salt cooled ones of liquid molten salt fuels or of solid fuel with molten salt coolants. It should be noted that molten salts and lead, sodium coolants have technical issues due to their chemical interactions with the other parts, such as erosion and corrosion, which need to be carefully considered. For example, most molten salt cooled reactors have high thermal efficiency and can be operated at low pressure; however, they also introduce concerns regarding erosion, and corrosion. Lead coolant benefits from superior neutron economy, and a high boiling point, but it also faces the technical challenges related to erosion, corrosion, and the need for advanced materials to address lead's high melting point. Sodium coolant possesses favorable heat transfer property, and a low melting point, but they raise safety issues due to sodium's chemical reactivity with water and air. Of them, ultra-long-life cores which can be operated without refueling over its life or cycle have been attracted due to its simplicity in the operation, proliferation resistant, and high capacity factor. In particular, it is known that fast spectrum reactors have desirable to achieve ultra-long-life due to high breeding in fuels. Recently, our group have designed lead-cooled nitride fueled vSMR cores rating 35MWt (~10MWe) which has about 1.0m diameter core [1]. vSMRs are referred to the modular reactors which have power rating less than 15 MWe. The vSMR can be operated over 34~43 EFPYs corresponding to 61~78 MWd/kg burnup and have very good safety-related reactivity coefficients. However, to our knowledge, there have been no studies which compare suitability of different types reactors for ultra-long-life operation in vSMR core size.

The objective of this work is to consistently compare the physical characteristics of vSMR cores cooled by several different coolants. The size and power of the cores are fixed and only solid uranium-nitride fuels of different coolants are considered.

2. Computational Methods and Core Model

2.1 Computational Methods

The core depletion calculations were done using the Serpent2 code which is a well-known Monte Carlo neutron transport and depletion calculation code developed by VTT [2]. We used the ENDF/B-VII.r0 point-wise cross section library for neutron transport calculations. Full-core 3-D analysis was performed with preserving fuel pin level heterogeneities and Chebyshev Rational Approximation Method (CRAM) option is used for burnup depletion modeling. Each assembly was considered as a radial depletion zone and the active core is divided into axially eight depletion zones. The depletion time step size is a half year. 100 inactive cycles and 500 active cycles with 50,000 histories for each cycle are used for Monte Carlo transport calculation, which gives ~10 pcm standard deviation in k_{eff} during depletion, while the physics parameters are evaluated using 200 inactive cycles and 1300 active cycles with 100,000 histories each.

2.2 Core Model

The thermal output of core is 35MWt and the core is loaded with uranium nitride fuel rods of 1.6cm outer diameter and 0.55mm thick clad. The fuel rods are arranged in triangular lattice of P/D ratio=1.18 within a fuel bundle. One fuel bundle is comprised of 37 fuel rods and the fuel rods are tied with grid spacers and the fuel bundle has no duct. The core is 130cm and average linear heat generation rate is 104.2W/cm. The total number of fuel rods and fuel bundles in the core are 2664 and 72, respectively. Currently, HT9 was considered as cladding and structural materials. The radial and axial configurations of the core are shown in Fig. 1 and 2, respectively.

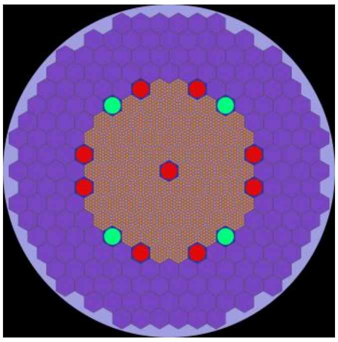

Fig. 1. Radial core configuration

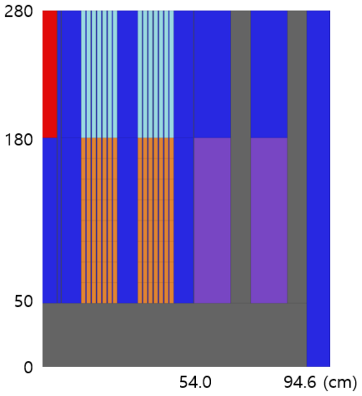

Fig. 2. Axial core configuration

As shown in these figures, the active core is surrounded by lead reflector assemblies. The absorber material for control rods is 40v/o B_4C+60 v/o W which was selected with considering high coolant density [3]. For the uranium nitride fuel, we considered 75% smear density to consider fuel swelling and 150cm long fission gas plenum above fuel to accommodate fission gas release. Actually, the core model was developed for lead coolant in our previous study.

2.3 Core Physics Analysis and Results

We considered seven different coolants which cover two liquid metal coolants (i.e., Na and Pb) and five molten salts (i.e., KCl-$MgCl_2$, FLiNaK, LiF-BeF_2, NaCl-$MgCl_2$, NaF-BeF_2) which are widely considered in molten salt reactors. First, we compared the evolution of k_{eff} as time to check the cycle lengths, which is given in Fig. 3. In this work, the initial uranium enrichments are determined such that the initial k_{eff} is equal to 1.004. Then, we compared the other physics parameters such as reactivity coefficients, cycle length, coolant void reactivity worth, and control rod worth, which are summarized in Table I. From Fig. 3, it is shown that the lead coolant gives the longest cycle length of ~31 EFPYs but all other cases give the shorter cycle lengths than 10.0 EFPYs. The NaCl-$MgCl_2$ and KCL-$MgCl_2$ give next long cycle lengths of 7.5 and 7.0 EFPYs, respectively. Then, the sodium (Na) coolant gives the cycle length of 6.5 EFPYs. The other three cases of molten salts give cycle lengths shorter than 3.0 EFPYs. Also, the core burnups of these cores except for the lead coolant giving 56.7 MWd/kg are much smaller than the burnup of the commercial PWRs. The lead coolant case has the lowest initial uranium enrichment of 12.11wt% while the FLiNaK one gives the highest one of 13.06wt%.

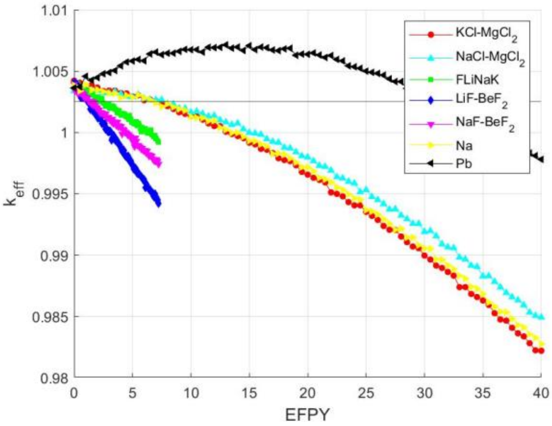

Fig. 3. Comparison of the k_{eff} evolutions of all coolants

Fig. 4 compares neutron spectra of the cores and the integrals of the normalized neutron fluxes for thermal (<0.625 eV), epithermal (0.625 eV~0.1 MeV), and fast (>0.1 MeV) regions are compared in Table II. From these results, it was shown that the KCL-$MgCl_2$ and lead coolants give harder spectra than the others. The spectrum is one of the key factors affecting the reactivity parameters. For example, the LiF-BeF_2 coolant case gives the most negative Doppler coefficient due to its softest spectra. Also, it is noted that the lead and sodium coolant cases give the largest negative coolant void worth for voiding both in active core and fission gas plenum and they also have large reactivity worth of the control assemblies. It is considered that these large reactivity worth of control assemblies are due to the lower absorption in fuels resulted from hard neutron spectral.

3. Conclusions

In this work, we consistently compared the core physics parameters of nitride fueled vSMR cores having different coolants covering liquid metals and molten salts for a fixed core size and fixed fuel and lattice structures. From the analysis, it was shown that the lead cooled core has the longest cycle length and desirable reactivity coefficient while FLiNaK, LiF-BeF_2, and NaF-BeF_2 cooled cores have very short cycle length and so they are not desirable for ultra-long-life or long-life core. Even if we did not try to optimize the cores, it seems that the KCl-$MgCl_2$, NaCl-$MgCl_2$, Na coolants can be used to achieve ultra-long-life by increasing core size and adjusting P/D ratio which will be the next future work.

REFERENCES

[1] Y. Y. Cho and S. G. Hong, "Neutronic Analysis of an Ultra Long Cycle VSMLFR (Very Small Modular Lead-cooled Fast Reactor)", Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 19-20, 2022.

[2] Leppänen, J., et al., "The Serpent Monte Carlo code: Status, development and applications in 2013", Annals of Nuclear Energy, Vol.82, 142-150, 2015.
[3] S. G. Hong, E. Greenspan and Y. I. Kim, "The Encapsulated Nuclear Heat Source (ENHS) Reactor Core Design", Nuclear Technology, Vol. 149, Issue. 1, 22-48, 2005.

Table I: Summary of performance parameters of the reference cores (BOC)

Parameters	KCl-$MgCl_2$	$NaCl$-$MgCl_2$	***FLiNaK***	LiF-BeF_2	NaF-BeF_2	***Na***	***Pb***
Cycle length (EFPY)	7.0	7.5	2.5	1.2	1.4	6.5	31.5
Burnup (MWd/kgU)	12.61	13.51	4.44	2.22	2.52	11.70	56.73
Enrichment (wt%)	12.81%	12.50%	13.06%	12.46%	12.35%	12.47%	12.11%
Doppler effect (pcm/K)	-0.377	-0.457	-0.576	-1.350	-0.924	-0.546	-0.526
Coolant expansion coefficient (pcm/K)	0.00238	0.00143	0.00619	0.00165	0.00019	-0.00069	-0.00018
Coolant void worth (pcm)							
active core	768.7	556.9	2539.7	1953.9	1114.1	-99.4	-4.0
active core + upper plenum	658.2	340.4	2300.7	1494.3	709.7	-260.7	-402.7
Axial expansion (pcm/K)	-0.237	-0.203	-0.192	-0.130	-0.144	-0.218	-0.194
Radial expansion (pcm/K)	-0.568	-0.492	-0.544	-0.311	-0.313	-0.460	-0.433
Control rod worth (pcm)							
primary	9083.6	8949.2	8268.2	7785.3	8037.7	9200.3	8915.5
primary+secondary	10804.0	10655.4	9857.6	9318.0	9610.7	10931.7	10609.1

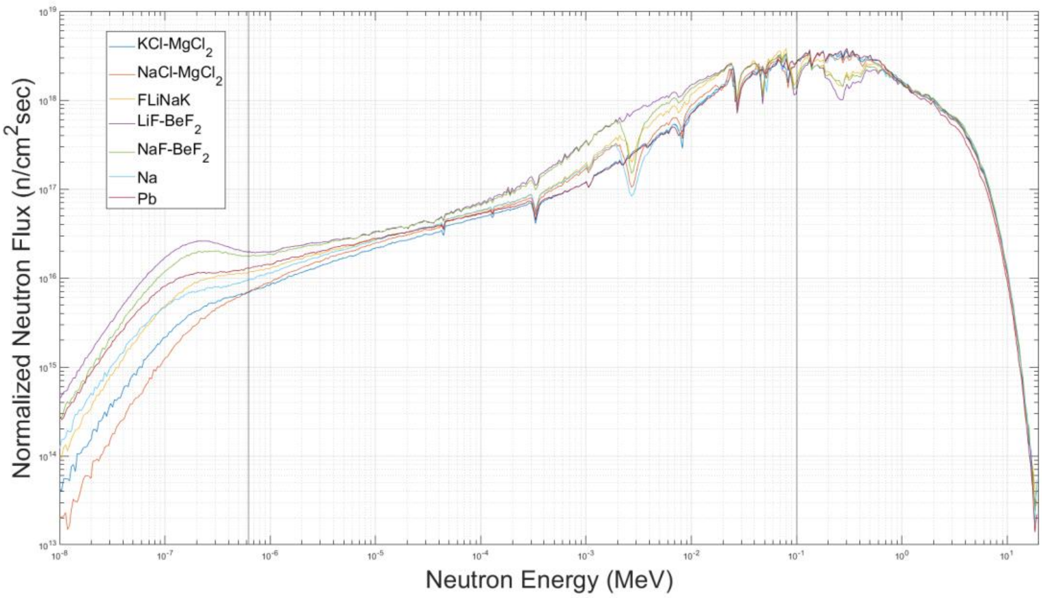

Fig. 4. Normalized neutron spectrum of all coolants

Table II: Normalized neutron flux distributions of all coolants (BOC)

Normalized neutron flux	KCl-$MgCl_2$	$NaCl$-$MgCl_2$	***FLiNaK***	LiF-BeF_2	NaF-BeF_2	***Na***	***Pb***
thermal (<0.625 eV)	2.23E+17	1.70E+17	4.38E+17	1.21E+18	9.29E+17	3.79E+17	5.97E+17
epithermal (0.625 eV - 0.1 MeV)	1.13E+20	1.21E+20	1.49E+20	1.68E+20	1.57E+20	1.17E+20	1.14E+20
fast (>0.1 MeV)	1.92E+20	1.83E+20	1.56E+20	1.35E+20	1.47E+20	1.87E+20	1.90E+20