Neutronic Design of a Liquid Salt-cooled Pebble Bed Reactor (LSPBR)

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Abstract

A renewed interest has been raised for liquid salt cooled nuclear reactors. The excellent heat transfer properties of liquid salt coolants provide several benefits, like lower fuel temperatures, higher coolant outlet temperatures, increased core power density and better decay heat removal. In order to benefit from the on-line refueling capability of a pebble bed reactor, the Liquid Salt Pebble Bed Reactor (LSPBR) is proposed. This is a high temperature pebble-bed reactor with a fuel design similar to existing HTRs, but using a liquid salt as a coolant.

In this paper, the selection criteria for the liquid salt coolant are described. Based on its neutronic properties, LiF-BeF_2 (FLIBE) was selected for the LSPBR. Two designs of the LSPBR were considered: a cylindrical core and an annular core with a graphite inner reflector. Coupled neutronic-thermal hydraulic calculations were performed to obtain the steady state power distribution and the corresponding fuel temperatures. Finally, calculations were performed to investigate the decay heat removal capability in a protected loss-of-forced cooling accident. The maximum allowable power that can be produced with the LSPBR is hereby determined.

KEYWORDS: Liquid salt coolants, negative temperature-reactivity-coefficient, pebble bed, steady state operation, decay heat removal.

1. Introduction

Because of its high efficiency and its inherent safety features the High Temperature Gas-cooled Reactor (HTGR) attracts a lot of attention worldwide. Despite these promising features, the HTGR concept can be improved by using a liquid salt as a coolant instead of helium. Promising liquid salt candidates exist that have excellent heat capacity and heat transfer properties, which allow reactor operation at high power density without any compromise to safety.

Till now, the Oak Ridge National Laboratory (ORNL) has focused on the Advanced High Temperature Reactor (AHTR) [1], which can be considered as the liquid-salt cooled counterpart of the prismatic HTGR. In this paper, we describe the stationary design of a Liquid Salt-cooled Pebble Bed Reactor (LSPBR), which combines the advantages of a pebble-bed HTGR (e.g. on-line refueling and flexible fuel management) with those of the AHTR (e.g. reactor operation at ambient pressure, high power density, lower maximum fuel temperatures, etc). There is one

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major difference between the AHTR and the LSPBR. The first reactor design has some flexibility with regard to the salt volume fraction in the core, as this is a design parameter that can freely be chosen, while the LSPBR has a fixed salt volume fraction of about 39% determined by the random packing volume fraction of the pebble bed. This paper is a condensed version of a MSc Thesis work performed at the Delft University of Technology [2].

2. Selection of the Liquid Salt Coolant and Parameter Design

Several criteria are important for the selection of a liquid salt coolant. Apart from good heat transfer coefficients, a coolant must be chemically inert, have low toxicity, reasonably low melting point and high boiling temperature. Tab. 1 lists the physical properties of the salt mixtures that were selected as candidates for the LSPBR [3].

The coolant salts will moderate and absorb neutrons. When voiding occurs, the reactivity increases due to the reduced absorption and reactivity decreases due to the reduced moderation. For a safe operation of the reactor it is required that the liquid salt coolant does not lead to positive voiding or temperature reactivity effects. These effects can be prevented by using a coolant with a good moderating quality, which can be quantified by the moderating ratio. For all liquid salt mixtures considered, the moderating ratio is shown in Tab. 1. The Σ_a and the Σ_s were calculated by flux weighing in the 0-1 eV and the 1-10^4 eV region, respectively. Clearly, LiF-BeF_2 (FLIBE) has the best moderating ratio of all salts considered.

Table 1: Physical properties and moderating ratio of the selected liquid salts.

Salt (mol %)	Molar mass (g/mol)	Melting point (°C)	Density (g/cm^3), T(°C)	700°C Heat capacity (kJ kg^{-1} K^{-1})	Viscosity (mPa s), T(K)	Moderating Ratio $\xi\Sigma_s / \Sigma_a$
LiF-BeF_2 (66-34)	33.1	458	$2.28 - 4.9 \cdot 10^{-4}$ T	2.38	0.116 exp (3755/T)	63.0
NaF-BeF_2 (57-43)	44.1	360	$2.27 - 3.7 \cdot 10^{-4}$ T	2.18	0.034 exp(5164/T)	9.8
LiF-NaF-KF (46.5-11.5-42)	41.2	454	$2.53 - 7.3 \cdot 10^{-4}$ T	1.88	0.04 exp(4170/T)	1.7
NaF-ZrF_2 (50-50)	104.6	510	$3.79 - 9.3 \cdot 10^{-4}$ T	1.17	0.071 exp(4168/T)	6.7
NaF-KF-ZrF_4 (10-48-42)	102.3	385	$3.45 - 8.9 \cdot 10^{-4}$ T (est.)	1.09 (est.)	0.061 exp(3171/T) (est.)	2.9
LiF-NaF-ZrF_4 (42-29-29)	71.56	460	$3.37 - 8.3 \cdot 10^{-4}$ T	1.47	0.0585 exp(4647/T)	12.5
NaF-$NaBF_4$ (8-92)	104.4	385	$2.25 - 7.1 \cdot 10^{-4}$ T	1.51	0.0877 exp(2240/T)	12.9

2.1 Effect of voiding, temperature and packing fraction on k_∞

To make a selection for the first candidate liquid salt coolant, the effects of the coolants on the neutronics were studied in an infinite array of pebbles. In Tab. 2 the results of the k-infinity calculations for the different salts and Helium are shown. The calculations were performed with a fuel enrichment of 10 % U-235 and with 12 g HM per pebble. For three candidate salts the k_∞ is below unity. The salt $LiF-BeF_2$ (FLIBE) has the highest k_∞ and provides most design freedom.

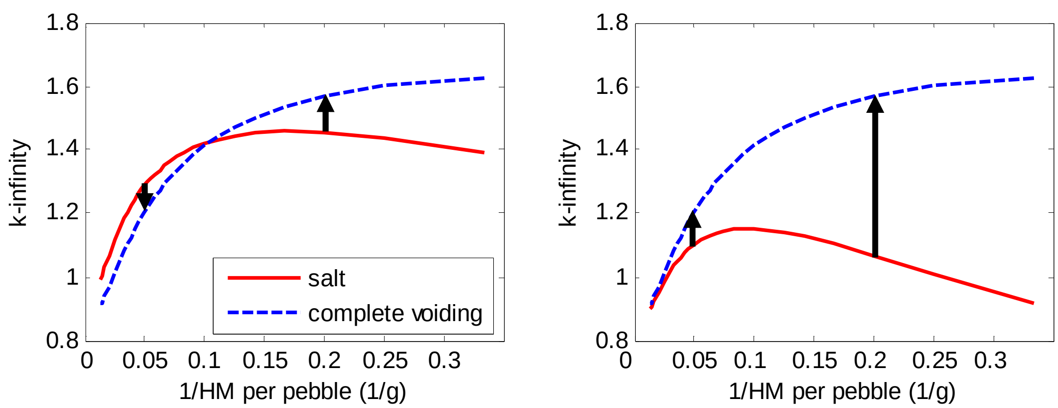
Table 2: The k_∞, reactivity change after complete voiding, and the temperature and packing reactivity coefficients for pebbles containing 12 g uranium with enrichment of 10%.

Salt	k_∞	Reactivity change complete voiding ($)	Fuel & coolant temperature reactivity coefficient (10^{-5} K^{-1})	Packing fraction reactivity coefficient (% $fraction^{-1}$)
$LiF-BeF_2$	1.39	- 2.30	-7.6750	-0.0007
$NaF-BeF_2$	1.11	21.5	-2.5283	0.0086
LiF-NaF-KF	0.71	87.9	8.1400	0.0129
$NaF-ZrF_2$	1.10	23.0	-0.4650	0.0087
$NaF-KF-ZrF_4$	0.81	65.1	5.4200	0.0131
$LiF-NaF-ZrF_4$	1.15	17.7	-1.5333	0.0073
$NaF-NaBF_4$	0.86	56.2	8.3183	0.0125
Helium (7 MPa)	1.36	- 0.11	-8.5783	-0.0003

It can be seen that all salts except $LiF-BeF_2$ (FLIBE) give a positive reactivity increase upon complete voiding. Only for three salts of these, the increase of reactivity can be compensated by the negative fuel temperature feedback.

The density of some salts is higher than that of graphite. A loss of forced cooling accident might therefore lead to floating of fuel pebbles, decreasing the random packing fraction to values below 61 %. In Tab.2 the packing fraction reactivity coefficient is shown for a fuel loading of 12 g per pebble. Only for FLIBE a decrease in packing fraction leads to an increase in k_∞. To avoid this, special measures should be taken like poisoning the top reflector. Also the neutron leakage increases at lower packing fractions, which will lead to a lower k-effective.

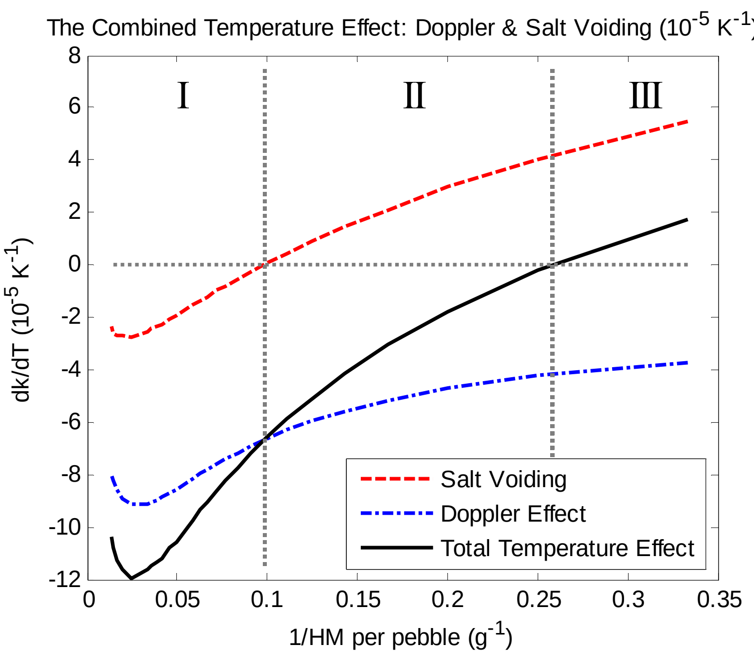
Figure 1: The k_∞ as a function of the fuel loading per pebble for FLIBE (left) and $LiF-NaF-ZrF_4$ (right), both combined with the complete voided case. Upon voiding, the k_∞-curve of the liquid salt moves to that of complete voiding.



All properties in Tab.2 depend on the fuel loading per pebble. In Fig. 1 the k_∞ as a function of the inverse heavy metal content per pebble is shown for two salts. During burnup the fuel loading per pebble decreases (inverse loading increases) and the voiding reactivity coefficient will become positive. Even for FLIBE with a fuel loading less than ~8-9 grams (~0.11-0.13 g^{-1}) per pebble, voiding leads to an increase in k_∞. For all other salts, this is the case at all fuel loadings.

The sum of the coolant and fuel temperature reactivity coefficients remains negative until a fuel loading of ~ 3.9 g HM/pebble (0.26 g^{-1}). In Fig. 2 the temperature reactivity coefficient is shown as a function of the inverse fuel loading. Three regions can be identified: In region I the Doppler reactivity coefficient and the coolant temperature feedback reinforce each other, in region II the coolant temperature coefficient is positive but the Doppler effect is negative and dominant, while in region III the positive coolant temperature coefficient has become dominant. Because LiF-BeF_2 (FLIBE) has the best neutronics properties of all candidates considered till now, it was selected as the leading primary coolant for the LSPBR.

Figure 2: The combined temperature effect, the change in k_∞ per K is shown as a function of salt voiding, the Doppler effect and the combined temperature reactivity coefficient.



2.2 Parameter Design for the LSPBR

As mentioned before, the major difference between the AHTR and the LSPBR is the salt volume fraction in the core. The pressure drop over the packed pebble bed calculated with the Ergun relation [4] does not exceed 1 bar for a pebble bed height less than 800 cm. In Tab.3 some results for the pressure drop calculations are given.

Two different core shapes, both with a height of 750 cm, have been investigated: an annular core with inner reflector with radii of 100 cm and 370 cm, and a cylindrical core with outer radius of 360 cm. The core volumes in both cases are about 300 m^3, and the average power density about 8.3 MW/m^3. The total power equals about 2500 MWth. The salt enters the core at the top at a temperature of 900 °C and will be heated up to 1000 °C at the bottom of the core. To achieve this, the mass flow rate is set to 10478 kg/s.

Table 3: Results of pressure drop calculations for liquid salt coolant FLIBE.

Liquid salt properties in pressure drop calculation for FliBe	**Results**
Density ρ at 950 °C (kg m^{-3})	1815.7
dynamic viscosity μ at 950 °C (mPa s)	$2.50 \cdot 10^{-3}$
heat capacity c_p (kJ kg^{-1} K^{-1})	2.38
Results with H = 7,5 m; core Volume 300 m^3; ΔT = 100 °C; total Power = 2500 MW	
Mass flow (kg s^{-1})	10478
Average coolant velocity (m s^{-1})	0.36
Reynolds number	6300
Pressure drop (MPa)	0.078
Pumping power (kW)	451
Fraction of total electric power of 1300 MW(%)	0.032

3. Steady State Operation and Decay Heat Removal

3.1 Steady State Operation

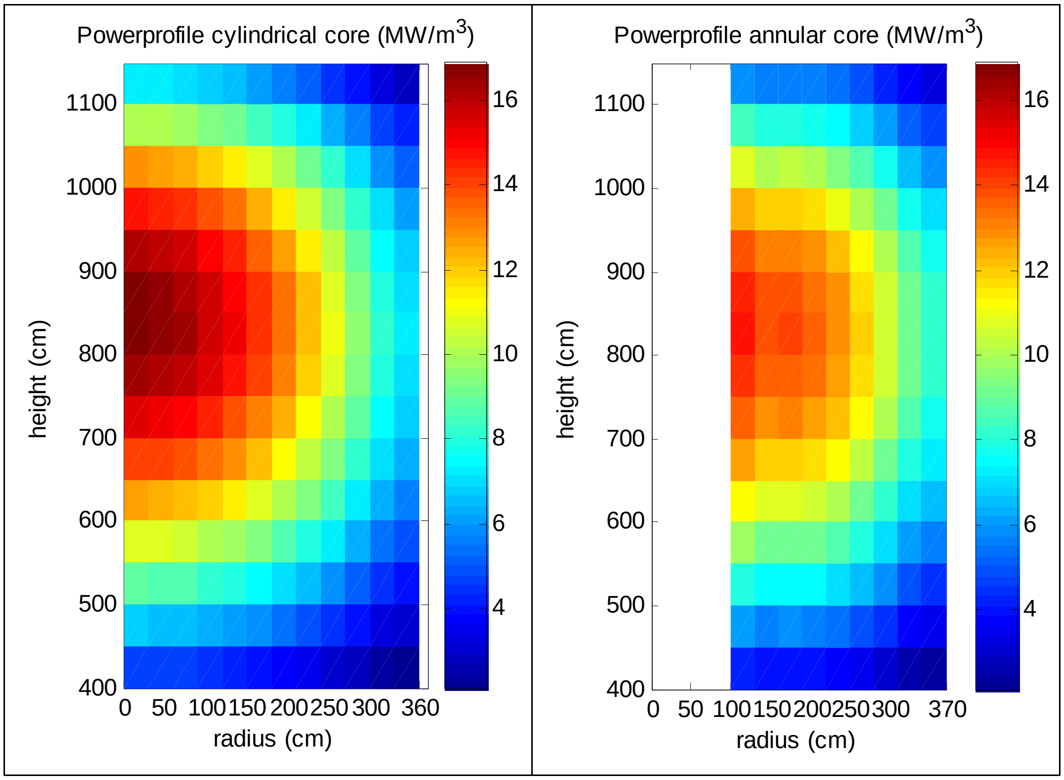
To examine the behavior of the LSPBR during normal operation, steady state calculations were performed with a coupled neutronics and thermo-hydraulics code system. For the first the 3-D neutron transport code EVENT [5] was used, while for the second a modified version of the well-known THERMIX code [6] was used. Temperature dependent cross sections were generated with the SCALE code system [7].

Table 4: Results of steady state calculations for the annular and the cylindrical core.

Description	**Annular core**	**Cylindrical core**
Core height (m)	7.5	7.5
Core outer diameter (m)	3.60	3.70
Core annulus (m)	n. a.	1.0
Total Core Volume (m^3)	305.36	299.0
Power level (MW(t))	2500	2500
Average power density $\overline{P}$ (MW(t)/m^3)	8.36	8.19
Maximum power density P_{max} (MW(t)/m^3)	14.7	16.8
Peak factor ($P_{max}/\overline{P}$)	1.75	2.05
Average velocity of salt in the pebble bed (m/s)	0.37	0.36
Coolant inlet temperature (°C)	900	900
Coolant outlet temperature (°C)	1000	1000
Maximum coolant temperature(°C)	1028	1051
Maximum fuel (pebble centre) temperature (°C)	1152	1190

The steady state solution is found by transferring the power distribution from EVENT to THERMIX, and returning the temperature distribution to EVENT. In Tab.4 the steady state results are summarized and Fig. 3 shows the steady state power density profiles in the two core geometries.

Figure 3: Power density profiles of the cylindrical core (left) and the annular core (right).

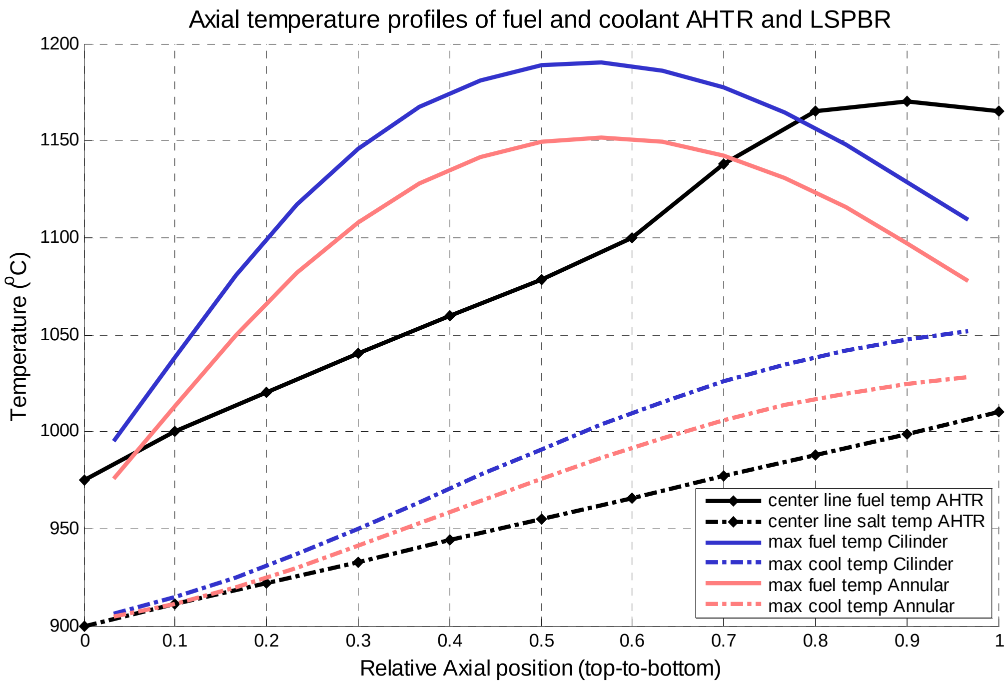


The power profiles have their maximum in the center of the core (especially in the cylindrical core). Because of the small volume of this zone, the high power density does not contribute much to the total heat produced. Clearly the peak factor is larger in the cylindrical core. In the annular core, the flatter power profile leads to lower maximum temperatures, which is a clear benefit for the annular core geometry.

Fig. 4 shows the maximum fuel temperature (at the center of the pebbles) and the maximum coolant temperature in the LSPBR compared with the fuel centerline temperature and the coolant temperature in the hot channel of the prismatic AHTR design [1]. The maximum fuel temperature in the AHTR is about 1180 °C, while the maximum temperature in the cylindrical LSPBR is around 1190°C and the maximum temperature in the annular LSPBR around 1150°C. From these results it is concluded that the annular core has the best ratio of the maximum fuel and coolant outlet temperatures.

The steady state calculations on the LSPBR were performed with a homogenous core with additional poison to reach a k-effective of 1 at 2500 MW. During operation the core will continuously be refueled. Fresh fuel is added at the top of the core while (partially) burned fuel is unloaded at the bottom. This will move the maximum in the power profile to the top of the core (the cooler region) and therefore also the maximum temperature difference between the coolant and the maximum fuel temperature. There are several options to modify power profiles, during startup dummy pebbles (graphite only) can be used to flatten the power profile.

Figure 4: A comparison between the axial profiles of the maximum fuel temperatures and the maximum coolant temperature of the 2400 MW AHTR [1] and the 2500 MW LSPBR (annular & cylindrical).



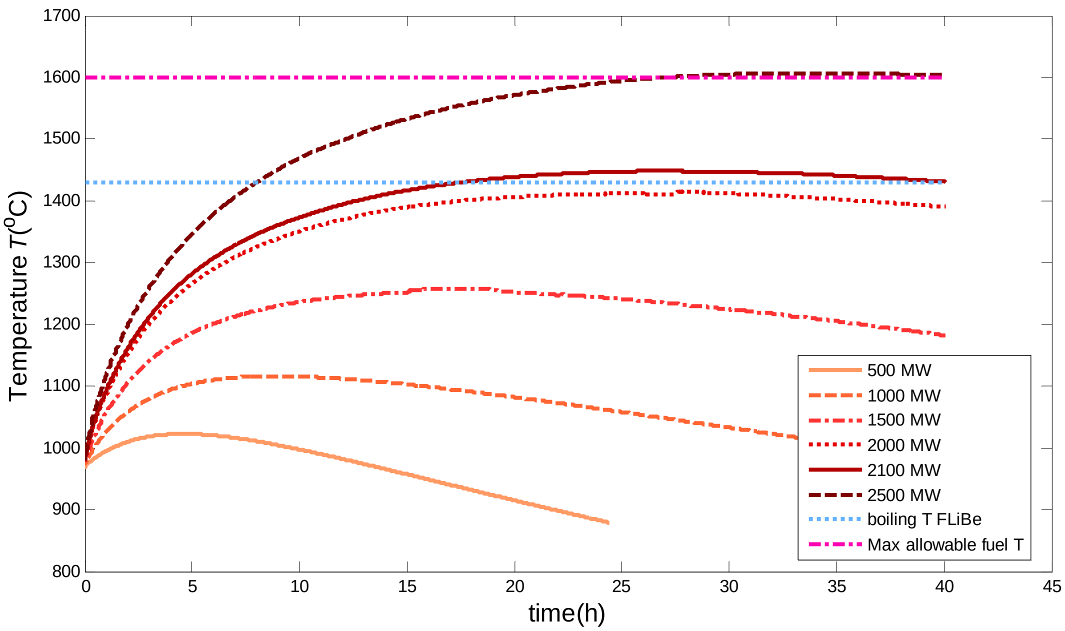
3.2 Decay Heat Removal Calculations

In a Loss of Forced Cooling (LOFC) accident, the decay heat cannot be removed by the coolant and the secondary cooling system. Instead it should be removed from the core by natural convection, conduction and thermal radiation. The maximum power that can be produced in the LSPBR is limited by the temperatures that are reached during a LOFC accident.

To examine the temperature distribution in the LSPBR during a LOFC accident with scram, the code HEAT, originally written for fluidized beds in chemical applications, was applied [8]. With HEAT time dependent natural circulation problems in a packed bed can be solved. Because of geometry limitations, this analysis is limited to the cylindrical core, which is considered the least favorable geometry for decay heat removal.

Two cases were investigated. The first is a pebble bed with coolant surrounded by a graphite reflector, while the second has an additional 7.5 m high salt plenum on top of the pebble bed. Various initial power levels were used in the simulations to derive the maximum power possible without exceeding the limits on fuel temperature and coolant temperature. All simulations were run for 40 hours of real time. In Fig. 5, we show the maximum fuel temperature as a function of time with the initial power level as a parameter. The thermal transients show an increase in core temperature during the first few hours after which it gradually cools down.

Figure 5: The maximum fuel temperature as a function of time with the initial power as a parameter, geometry *without* an additional salt plenum.

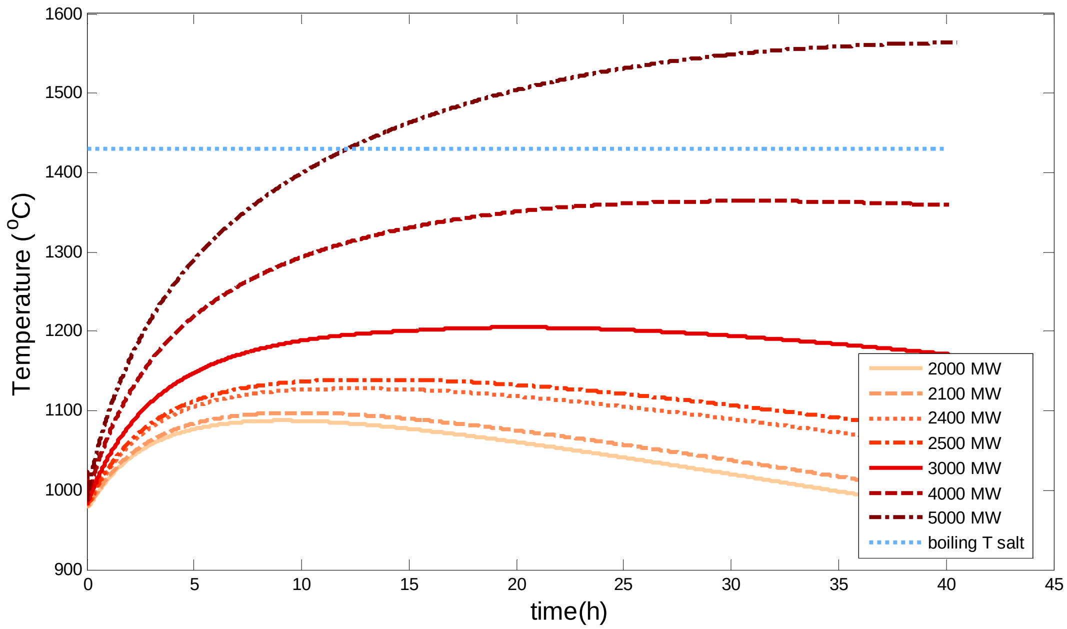


At first the heat transfer from the coolant to the reflector is insufficient to compensate for the decay power produced inside the core. The salt and core are heated and a natural convection flow is induced inside the core. Because of the thermal inertia of the salt the heating of the core will take several hours. When the coolant flow induced by natural convection increases, the convective heat transfer to the reflector wall increases until it exceeds the decay heat power produced in the fuel. Then, the coolant and the fuel will gradually cool.

There are two temperature limits that need to be considered: the maximum of 1600 ^{0}C for TRISO coated fuel particles and the temperature at which the salt coolant starts to boil (for FLIBE, this is at 1430 ^{0}C). Because the latter effect could not be modeled in the HEAT code, the lowest temperature limit is chosen to be restrictive. This means that for the geometry without a salt plenum on top of the core, the maximum power is 2000 MWth.

For the geometry with a 7.5 m high additional salt plenum on top of the core, the total volume of salt is larger by a factor of 3.5. So much more decay heat can be stored without exceeding the limits on the coolant and fuel temperatures. Furthermore, the outer surface of the reactor core is enlarged with a factor of 1.7, which enhances the heat transfer from the salt to the graphite reflector considerably. In Fig. 6 the maximum fuel temperature is shown as a function of time with the initial power as a parameter ranging from 2000 to 5000 MWth.

Figure 6: The maximum fuel temperature as a function of time with the initial power as a parameter, geometry *with* an additional salt plenum on top of the core.



Only in the 5000 MWth case the maximum fuel temperature exceeds the boiling temperature of FliBe (1430 °C). The highest permissible power in the LSPBR with a 7.5 high salt plenum is about 4000 MWth. The maximum coolant temperature reached in the transient is well below the boiling point of FLIBE. This result is comparable to that of the University of California at Berkeley for a 4000 MWth core, which yielded a peak core temperature of 1325 °C as reported in [1].

4. Conclusions

From the liquid salt coolants considered in this paper, the best choice for the LSPBR is LiF-BeF_2 (FLIBE). It has the highest moderating ratio, the largest k_∞ values, a negative voiding reactivity coefficient and the strongest total temperature coefficient.

An investigation of the core dimensions of the LSPBR was made. The size of a pebble bed is not restricted by its pressure drop. If a pebble bed height of 7.5 m is chosen with a pebble bed volume of 300 m^3 the pressure drop will be less then 1 bar.

From the reactor physics and thermal dynamics calculations, it is found that the power density is largest in the center of the core. Because of the lower fuel temperatures in the annular geometry, this is the preferred core shape for the Liquid Salt Pebble Bed Reactor. Compared to the AHTR the annular LSPBR has lower maximum fuel temperatures

An investigation was made of the decay heat removal capability of the cylindrical reactor core by passive means. The maximum allowable nominal power is 2000 MWth without salt plenum and 4000 MWth with a 7.5 m high salt plenum on top of the core.

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