Paper ID APEN-MIT-2022_3708
Applied Energy Symposium: MIT A+B
July 5-8, 2022 • Cambridge, USA

In-Core Printed Circuit Heat Exchange in Molten Salt Reactors

Kraig Farrar
Department of Nuclear Engineering
Texas A&M University
College Station, TX, USA
kraigsf@tamu,edu

Mark Kimber
Department of Nuclear Engineering
Texas A&M University
College Station, TX, USA
mark.kimber@tamu.edu

Abstract**—** Printed circuit heat exchange has been found beneficial in various chemical applications to allow for high rates of reaction per unit volume of reactor space. This is especially true where large amounts of heat exchange are necessary to provide either energy input to the reaction or remove heat produced from an exothermic reaction. Given that fission is a highly exothermic chemical reaction, the same concept may be applied to a fluid phase fission reaction like in a molten salt reactor. Calculations performed both with the NTU-efficiency method as well as in RELAP5-3D suggest an order of magnitude increase in power density is possible relative to a base case thermal spectrum, graphite moderated, molten salt reactor core. Along with the benefit of increased power density, other benefits are identified: elimination of hot leg/cold leg corrosion and deposition mechanisms, nearly flat axial temperature profile, having a maximum axial temperature gradient of 6.5 °C or less in the core at full power, elimination of the primary heat exchanger from the fuel loop, since primary heat exchange occurs in-core; minimal reduction in delayed neutron fraction due to a lower ex-core salt fraction, and facilitation of chemical separations of radionuclides due to smaller fuel salt volume and higher radionuclide concentration. Increasing the rate of heat transfer in the core with a novel heat exchange design drastically improves the output of a small footprint reactor, allowing for the benefits of small modular manufacturing while exceeding the thermal and electrical output of traditional large scale nuclear construction projects on a volumetric basis.

I. Introduction

Several next generation nuclear reactors are proposed under the Generation IV International Forum. These reactor designs include helium cooled reactors, sodium and lead cooled fast reactors, as well as molten salt reactors. The primary goal of the Gen IV forum is to present paths to improvements on safety, cost, efficiency, and sustainability [1]. Molten Salt Reactors (MSR) are among the Gen IV design concepts and provides a unique advantage of liquid fuel. The use of liquid fuels provides novel options for heat transfer configurations.

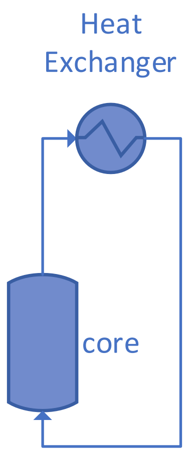

Figure 1 diagram of a basic primary heat exchange loop for an MSR

A common MSR heat transfer configuration in design concepts involves a primary fuel loop in which fuel travels between the active core, where fission occurs, and the primary heat exchanger, which is outside the core [4]. In this case, heat is produced directly in the primary fluid and transferred to a secondary fluid outside the core. This is as opposed to a conventional solid fueled reactor where heat must be transferred from the fuel to the primary coolant fluid and then generally to a secondary coolant fluid outside the core.

In this analysis, we intend to show the advantage of performing the primary heat transfer of an MSR within the core rather than in an ex-core heat exchanger. This means that a secondary fluid will flow directly through the core, which will be constructed as a printed circuit heat exchanger. Alternating layers of core structural material will be filled with primary fuel fluid and secondary coolant fluid respectively. In our case both fluids will be considered to have the properties of a 2/3 lithium fluoride, 1/3 beryllium fluoride eutectic commonly known as FLiBe among MSR designers [4].

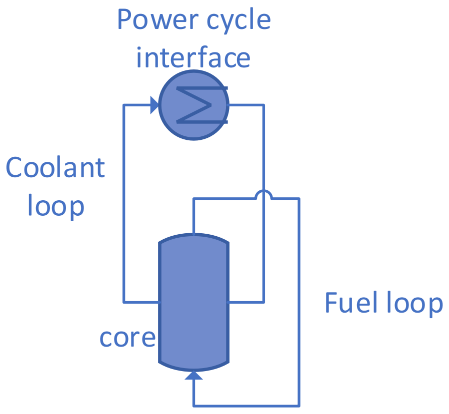

Figure 2 Diagram of proposed core flow configuration

A thermal MSR design modeled after the Molten Salt Reactor Experiment (MSRE), performed at Oak Ridge National Laboratory would use graphite as a core moderator and for that reason, graphite will be used for core moderation and core structure in this analysis as well [4]. This means that heat is transferred from fuel fluid, across a graphite wall to the next fluid layer, which is the secondary coolant fluid.

The proposed core configuration in figure 2 will provide several advantages over the more common design shown in figure 1. First it is intended to provide a significant increase in reactor power density with respect to both core volume and overall salt volume. Power density is improved by several mechanisms: 1) Printed circuit heat exchangers have high heat exchange surface area to volume ratios, allowing for more heat exchange in equivalent volumes. 2) By configuring the active core and the heat exchanger as the same volume, heat generation occurs within the fuel along the axial profile as it is cooled, allowing it to maintain a nearly flat axial temperature profile. 3) The high thermal conductivity of the graphite moderator and small distance between fuel and coolant minimize heat transfer resistance across the walls between the fuel and coolant fluids.

In a reactor where coolant is expensive and often isotopically enriched power density is important. Higher power density with respect to salt volume also facilitates online fission product separation efficiency by creating higher concentrations of fission products. Also beneficial to reactor performance is the creation of a flat axial temperature profile and elimination of a temperature gradient between the inlet and outlet of the reactor core. This means that solubility differences between the inlet and outlet of the core due to temperature cannot act as a mechanism for corrosion in the hot leg and deposition/fouling in the cold leg and the heat exchanger.

An additional benefit to this configuration is limiting the amount of delayed neutron precursors that decay outside the core. This is because the ex-core salt fraction is relatively small in this design, allowing the delayed neutron fraction in the core to remain relatively high even at large flow rates.

As power density is a key optimization metric for this analysis, data published by IAEA is shown in figure 3 as a reference for comparison to results.

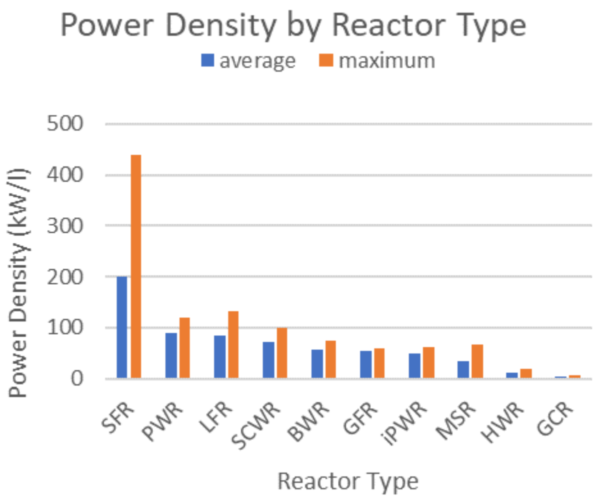

Figure 3 Data on power density of existing reactor designs

The highest power densities come from sodium fast reactors at over 400 MW/m^3 while conventional PWR designs such as the AP-1000 seem to commonly be just over 100 MW/m^3. An average MSR power density of 34 MW/m^3 was reported.

II. Methodology

An NTU-effectiveness calculation [5] and a RELAP5-3D model are used together as verification of calculations [6]. For each set of calculations assumptions are matched as closely as possible apart from the Nusselt correlation, which is limited to a select list in RELAP5-3D from which the Gnielinski correlation is chosen, while a Nusselt correlation specific to an S-fin printed circuit heat exchanger is used for the NTU calculation [2]. Mass flow rates are matched in each set of calculations based on calculated pressure drops, so that the RELAP5-3D simulations are performed at identical flow rates to the NTU calculations.

Table 1 flow rates used for calculations/simulations

Pressure Drop (bar)	**Conditions**	
	Fuel Flow Rate (kg/s)	***Coolant Flow Rate (kg/s)***
1.0	993	924
2.0	1507	1476
2.5	1724	1673
3.75	2201	2103
5.0	2617	2478
8.5	3603	3354
9.5	3852	3587

For the purpose of these calculations a one-meter-cubed volume is assumed for the printed circuit heat exchange core. The flow area is made up of 123,457 equivalent tubes for each salt, with the effective inner diameter of each being 0.00163 m. This makes a volume fraction of 25.762% for coolant, 25.762% for fuel and 48.476% for the structural graphite. This geometric configuration is a neutronically plausible size, though likely under moderated depending on fuel concentrations. Fluid properties for LiF-BeF_2 (67-33 mol%) are used for both fuel and coolant [7].

III. Results

Data was produced based on matched flow rates within a printed circuit heat exchange core by both NTU-effectiveness method and RELAP5-3D simulations. Both were found to be largely in agreement within 10%. RELAP5-3D data shows consistently lower heat exchange rates than NTU method calculations, which is expected due to the use of the more favorable S-fin Nusselt correlation used in the NTU calculations, as compared to the slightly less favorable Gnielinski correlation, that is representative of channel flow, used by RELAP5-3D.

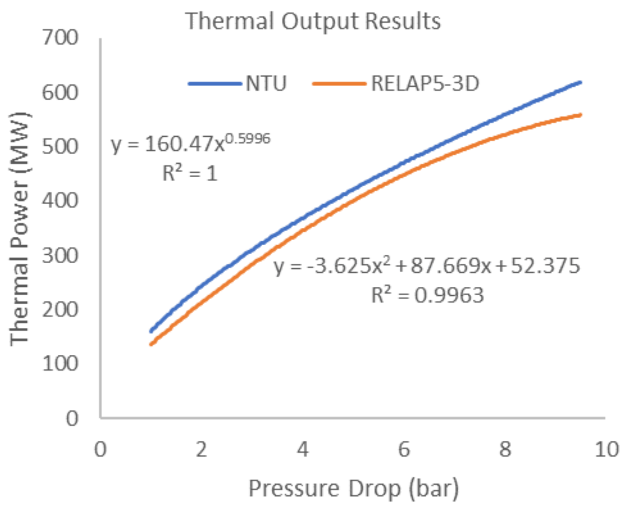

Figure 4 Thermal power produced by PCHE core designs

Thermal power outputs were found to vary between 160 and 617 MWth for the NTU calculations and between 123 and 564 MWth for RELAP5-3D simulations. These results compare with the highest power densities of sodium fast reactor designs (440 MWth), suggesting that it is possible for molten salt reactors to be among the highest power density designs to date.

Table 2 Thermal power output for printed circuit heat exchange core designs

Pressure Drop (bar)	Conditions	
	NTU thermal output (MW)	***RELAP5-3D thermal output (MW)***
1.0	160	123
2.0	244	224
2.5	278	259
3.75	355	333
5.0	422	390
8.5	578	530
9.5	617	564

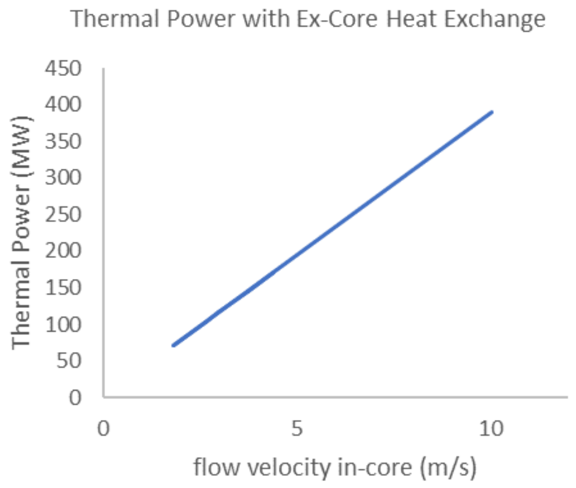

Figure 5 Expected core power output at equivalent flow rates with ex-core heat exchange

A direct comparison is made between the power output of the printed circuit heat exchanger core and a loop-style MSR with ex-core heat exchange. The velocity of flow at each data point from the PCHE core calculations was used to calculate the amount of heat that would be carried out of the core by an equivalent loop-style MSR. This results in a range of 70-390 MWth of heat transfer. On the high end of the flow rate range the PCHE core produces 1.59 times the power of the loop-style reactor, while at the low end of the flow rate range the PCHE produces 2.27x as much power.

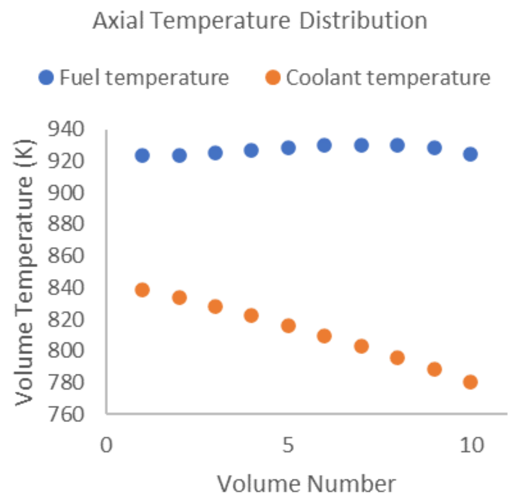

Figure 6 The axial power distribution on each side of the PCHE core

Figure 6 shows a volume matched temperature distribution of a counterflow PCHE core. The fuel can be seen to enter at core volume one and exit at ten while the coolant enters at volume ten and exits at one. The fuel temperature distribution shows that the exit and entrance temperatures are equal with a slight peak at volume six that is less than 7 °C above the entry and exit temperatures. This allows a larger heat transfer rate since, due to generation of heat within the core, the temperature on the fuel side does not drop to approach the temperature of the coolant. This constant temperature across the axial length of the fuel in

Table 3 Axial fuel temperature gradient for several RELAP5-3D simulations

Thermal Power (MW)	Maximum axial ΔT (°C)
123	4.6
224	5.7
259	6.1
333	6.4
390	6.5
530	6.5
564	6.5

the core allows for a larger temperature gradient between fuel and coolant, allowing for increased heat transfer.

IV. CONCLUSION

From the calculations presented the benefits achieved by using printed circuit heat exchange in the core are substantial. Generally, a power output increase of nearly two times that of ex-core heat exchange was found on average over the range measured. This is in addition to the benefits of producing a negligible axial temperature gradient and eliminating the driving force of hot leg/cold leg corrosion.

Further research into the technological limitations of this concept is required before development work can take place. The lifespan of graphite as a moderator may be insufficient for the increased power density of the proposed design. Alternate moderator materials such as silicon carbide may be worth investigating to resolve the short-lived nature of graphite within high neutron flux. Core structure manufacturability is another question outside the scope of this initial work. Whether graphite or other substitutable materials can be appropriately layered to produce a printed circuit heat exchanger is an outstanding question not answered here.

If a ceramic core material such as graphite is used, it would likely be desirable to interface the ceramic core with metal piping in the loop. This will likely create challenges around the substantial difference in thermal expansion coefficients of the two materials. Development of appropriate interface techniques may be necessary for this core concept to be practicable.

The possibility of a flat axial temperature gradient is discussed here, however, appropriate optimization of core channels may also allow the radial temperature gradient to be minimized if desired. Channel flow optimization constitutes a potentially fruitful area of research to improve the performance of a PCHE core design.

ACKNOWLEDGMENT

REFERENCES

[1] Locatelli, Giorgio; Mancini, Mauro; Todeschini, Nicola (2013-10-01). "Generation IV nuclear reactors: Current status and future prospects". Energy Policy. 61: 1503–1520, https://www.sciencedirect.com/science/article/pii/S0301421513006083?via%3Dihub

[2] Xiaodong Sun, Mark Anderson, In Hun Kim, and Richard Christensen, Xiaoqin Zhang, Ian Jantz "Compact heat exchanger design and testing for advanced reactors and advanced power cycles," Final Report UM/THL-18-06, US Department of Energy, https://www.osti.gov/servlets/purl/1437159.

[3] Su-Jong Yoon, Piyush Sabharwall, Eung-Soo Kim "Analytical study on thermal and mechanical design of printed circuit heat exchanger," INL/EXT-13-30047, US Department of Energy, https://inldigitallibrary.inl.gov/sites/sti/sti/5901289.pdf.

[4] Massimiliano Fratoni , Dan Shen, Germina Ilas, Jeffrey Powers "Molten Salt Reactor Experiment benchmark evaluation (Project 16-10240)," https://www.osti.gov/servlets/purl/1617123

[5] F. P. Incropera, D. P. Dewitt, T. L. Bergman, A. S. Lavine "Fundamentals of heat and mass transfer," 6th ed.. Hoboken, NJ; John Wiley, 2007

[6] *RELAP5-3D*. Idaho Falls, ID: Idaho National Laboratory, 2015.

[7] Manohar S. Sohal, Matthias A. Ebner, Piyush Sabharwall, Phil Sharpe "Engineering database of liquid salt thermophysical and thermochemical properties," US Department of Energy, June 2013