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Thermal hydraulic design of a liquid salt-cooled flexible conversion ratio fast reactor

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ABSTRACT

A 2400 MWth liquid-salt cooled flexible conversion ratio reactor was designed, utilizing the ternary chloride salt NaCl–KCl–$MgCl_2$ (30–20–50%) as coolant. The reference design uses a wire-wrapped, hexagonal lattice core, and is able to achieve a core power density of 130 kW/l with a core pressure drop of 700 kPa and a maximum cladding temperature under 650 °C. Four kidney-shaped conventional tube-in-shell heat exchangers are used to connect the primary system to a 545 °C supercritical CO_2 power conversion system. The core, intermediate heat exchangers, and reactor coolant pumps fit in a vessel approximately 10 m in diameter and less than 20 m high. Lithium expansion modules (LEMs) were used to reconcile conflicting thermal hydraulic and reactor physics requirements in the liquid salt core. Use of LEMs allowed the design of a very favorable reactivity response which greatly benefits transient mitigation. A reactor vessel auxiliary cooling system (RVACS) and four redundant passive secondary auxiliary cooling systems (PSACSs) are used to provide passive heat removal, and are able to successfully mitigate both the unprotected station blackout transient as well as protected transients in which a scram occurs. Additionally, it was determined that the power conversion system can be used to mitigate both a loss of flow accident and an unprotected transient overpower.

1. Introduction and main challenges

The goal of this work is the thermal hydraulic design and analysis of a flexible conversion ratio (FCR) reactor using liquid salt as coolant, as part of a larger project comparing different FCR reactor designs (Todreas et al., 2008, 2009). An FCR reactor is designed to be compatible with cores operating at conversion ratios approaching unity (CR = 1) and zero (CR = 0), to allow flexibility in meeting future fuel cycle demands. Details of the CR = 1 and CR = 0 core designs used in this project, including core layouts, are given in an accompanying reactor physics paper (Shwageraus and Hejzlar, 2009).

Use of liquid salt as a coolant in fast reactor systems offers a number of valuable advantages: liquid salts are optically transparent, have very high boiling points and heat capacities, and many are stable under irradiation and compatible with reactor materials. However, to realize these advantages, several challenges pertaining to liquid salt coolants need to be addressed. Liquid salts have a high viscosity; the selected salt NaCl–KCl–$MgCl_2$ (30–20–50%) has a viscosity about a factor of 10 greater than liquid sodium's in the temperature range of interest. High viscosity reduces flow Reynolds numbers which substantially deteriorates friction factors and heat transfer coefficients. Liquid salts also have much lower thermal conductivities than liquid metals, which also reduces heat transfer effectiveness. Liquid salts have high melting points (396 °C for the reference salt vs. 98 °C for sodium) which make it more challenging to design for systems using materials available in the near term. Finally, liquid salts have high thermal expansion coefficients and moderating power, which lead to high coolant temperature coefficients, making passive safety more difficult to achieve.

Two important design decisions were driven by these challenges: the decision to use a chloride salt and the introduction of lithium expansion modules (LEMs) into the design. As described in the flexible conversion ratio fast reactor overview paper (Todreas et al., 2009), much of the salt selection process was driven by the need to minimize the effect of these challenges. Chloride salts in general have lower viscosities and coolant temperature coefficients than fluoride salts, making them better suited for this design. Even using a chloride salt, meeting passive safety goals required a core coolant fraction too small to allow an acceptable power density. To increase the coolant fraction and improve core thermal hydraulics, LEMs were added to offset the coolant temperature coefficient and make passive safety easier to accomplish. LEMs are reservoirs of liquid lithium above the core connected to capillaries extending into the core (Kambe and Uotani, 1998). An increase in coolant outlet temperature causes lithium to thermally expand into the capillaries, reducing reactivity as neutrons are absorbed in the lithium. LEMs are able to passively introduce a strong negative reactivity

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feedback, making it much easier to achieve reactivity coefficients compatible with passive safety.

In addition to the above challenges intrinsic to liquid salt coolants, several state-of-knowledge challenges exist which make it difficult to design a liquid salt-cooled reactor. First, coolant properties for liquid salts are not known with the same detail and accuracy as for liquid metal coolants, with just a single reference existing for some salt properties and zero references for others. Second, the low Reynolds numbers and high Prandtl numbers encountered in salt reactor analysis have not been well analyzed in the context of heat transfer in a wire-wrapped core. These state-of-knowledge challenges were overcome by using conservative property estimates and correlations where needed. Assumed salt properties are given in Section 2 of this paper. Pressure drop through the wire-wrapped core is calculated using the Cheng–Todreas correlation (Cheng and Todreas, 1986). For heat transfer in the wire-wrapped core, the Gnielinski correlation is used, which is judged to be conservative because it does not include the heat transfer enhancement caused by wire wrap.

2. Properties of selected salt

The salt selection section of the flexible conversion ratio fast reactor overview (Todreas et al., 2009) describes how the reference salt, NaCl–KCl–$MgCl_2$ (30–20–50%, mol%) was chosen. The assumed properties for NaCl–KCl–$MgCl_2$ are given in Table 1, with summaries of the methods used to obtain them.

Melting point, density, and viscosity are all given in a 1960 BNL report (BNL-627) on fused chloride salts. Because density and viscosity are relatively straightforward to measure, the values given can be used with reasonable certainty.

Heat capacity is estimated using a mole fraction average, using the constituent values recommend in Janz's Molten Salts Handbook (1967): 22 W/mol-K for $MgCl_2$, 16 W/mol-K for NaCl and KCl, respectively. A simple mole fraction average is used because non-ideal behavior may be complex and there is insufficient data to predict such behavior. The value obtained is slightly less than that given by the Dulong–Petit prediction, which gives a heat capacity of 8 W/mol-K per atom.

Thermal conductivity is the property with the most uncertainty, largely because there is almost no thermal conductivity data on $MgCl_2$ or its mixtures. Only one 1974 paper by Polyakov and Gildebrandt was found to measure conductivities of $MgCl_2$ salts, however the thermal conductivities it quotes for KCl, a commonly measured salt, are anomalously high. Several approaches were taken to produce a range of estimates for thermal conductivity. First, one can use the approach taken by Williams and Toth (2006b) to estimate the thermal conductivities of NaCl–$MgCl_2$ and KCl–$MgCl_2$. Williams estimated the thermal conductivity of $MgCl_2$ based on its formula weight and took a mole fraction average of this value with the thermal conductivities of NaCl and KCl. The value of thermal conductivity obtained in this way for KCl–$MgCl_2$ (50–50) can be used as a conservative estimate for the thermal conductivity of NaCl–KCl–$MgCl_2$ (30–20–50) because there is a clear trend of increasing thermal conductivity with decreasing formula weight. The value of thermal conductivity obtained using this method is 0.39 W/m-K, and is the one adopted by this study, mainly because it is consistent with the thermal conductivity values given for the other chloride salts.

Other methods to estimate the thermal conductivity of NaCl–KCl–$MgCl_2$ incorporate the data given in Polyakov and Gildebrandt (1974). This is done by multiplying all the Polyakov data by a constant such that its KCl thermal conductivity values agree with those of reliable modern measurements. Doing this, one obtains a thermal conductivity for KCl–$MgCl_2$ (50–50) of about 0.25 W/m-K, which may be again taken as a conservative value for the ternary. Alternately, one can use the scaled value for KCl–$MgCl_2$ (20–80) of 0.17 W/m-K, and average it with the known conductivities of NaCl and KCl to produce a value for the desired ternary composition. Doing this yields a thermal conductivity of around 0.28 W/m-K.

Short of performing a measurement, there appears to be no reliable method to obtain thermal conductivities for salts containing $MgCl_2$ at this time. Williams' method relies on an estimate based on formula weight, while methods using the Polyakov data rely on older data and an untested scaling method. Similar concerns can be raised for the other properties: viscosity and density are based on a single 1960 reference, and the mole fraction average used to estimate heat capacity is similar to the Dulong–Petit prediction, which has an uncertainty of around 20% (Williams et al., 2006a). Because of the central position of salt properties to the following analyses, present-day measurements to confirm these values would be an economical way to reduce uncertainty.

To quantify the significance of these property uncertainties, sensitivity studies were performed to determine the maximum power density achievable for different values of density, viscosity, thermal conductivity, and heat capacity. Each property was varied from 50 to 200% of the value assumed in this report, and the reference core design reanalyzed. Results are given in Fig. 1.

The dashed horizontal line denotes the power density that allows the target power rating of 2400 MWt to be achieved for the reference geometry. Using the assumed property values yields a power density above this line because the reference design has a maximum cladding temperature slightly below the 650 °C limit, allowing some margin for the power to be increased beyond

Table 1
Assumed NaCl–KCl–$MgCl_2$ (30–20–50) physical properties.

Property	Value	Method of obtaining
Melting point (°C)	396	Measured value from BNL report[a]
Density (kg/m^3)	$2260 - 0.778 \times T$ (°C)	Measured value from BNL report[a]
Thermal expansion coefficient (vol%/K)	0.043	Measured value from BNL report[a]
Dynamic viscosity (cP)	$\exp(3040/T\,(\mathrm{K}) - 2.96)$	Measured value from BNL report[a]
Thermal conductivity (W/m-K)	0.39	Mole fraction average for KCl–$MgCl_2$ (50–50)
Heat capacity (cal/g K)	0.24	Mole fraction average

[a] Raseman et al. (1960).

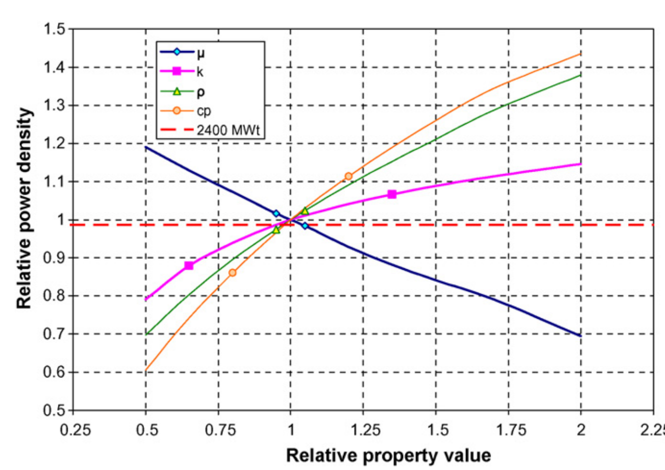

Fig. 1. Power density vs. NaCl–KCl–$MgCl_2$ property values.