Selecting Optimal Heat Transfer Chloride Salt for Molten Salt Fast Reactor

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1. Introduction

To meet the increasing global demand for energy, nuclear power plants have been widely used. As the technology advances, the next generation nuclear reactors are receiving attention and being researched. Among the next generation reactors, the Molten Salt Reactor (MSR) is continuously being researched, due to its high efficiency, sustainability, and safety. In 1964, Oak Ridge National Laboratory (ORNL) conducted various experiments in Molten Salt Reactor Experiment (MSRE), shown in Figure 1 [1]. In MSRE, fluoride-based salts were used. On the other hand, the chloride-based salts are preferred for the Molten Salt Fast Reactors (MSFR), because chloride-based salts have lower melting points, and neutron moderation and absorption.

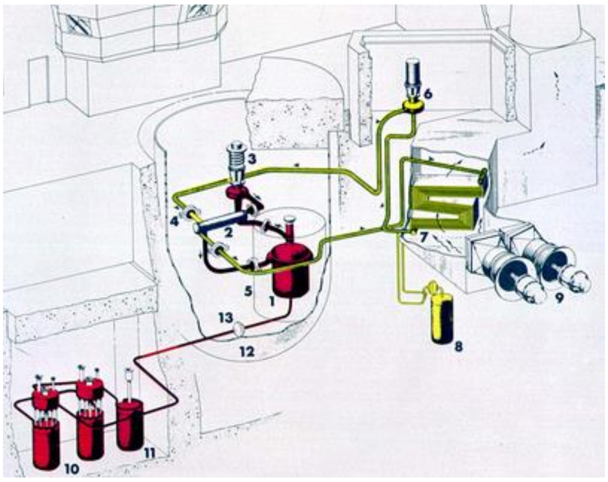

Figure 1. Overview of MSRE

One of the critical components of an MSFR is the heat transfer salt, which not only transfers heat from the reactor side to the power conversion system, but also serves as the coolant for the fuel salt. In this paper, the selection of an optimal heat transfer chloride salt for the MSFR is presented in the perspective of melting point, volumetric heat capacity, kinematic viscosity and thermal diffusivity. Based on these criteria, several candidate chloride salts will be evaluated.

2. Methods and Results

2.1 Chloride Salt Candidates

One of the most serious problems with the MSR is the corrosion of the structural alloys. According to Sridharan, the chloride salt would not be reduced by the common alloying elements, which means that there should be no corrosion in the structural alloys if they are in contact with pure chloride salts. Thus, the corrosion in MSFR is dominantly driven by the presence of H_2O, OH^-, and O_2 [2]. Hence, it is assumed that the MSFR maintains very high purity level during operation.

Sridharan also stated that the alkali chlorides and alkaline earth chlorides are preferred than the transition metal chlorides [2]. Thus, NaCl-$MgCl_2$, KCl-$MgCl_2$, and NaCl-KCl-$ZnCl_2$ are compared in this study.

2.2 Thermodynamic Properties of the chloride salts

In this study, the melting point, volumetric heat capacity, kinematic viscosity and thermal diffusivity will be compared to select optimal heat transfer chloride salts. If the melting point is low, the operating temperature can be lowered to prevent the solidification of the heat transfer salt. The volumetric heat capacity is the amount of energy that can be stored in a unit volume of the salt. Thus, the higher the volumetric heat capacity is, more amount of heat can be stored and released by the salt. The kinematic viscosity is the ratio of the dynamic viscosity to the density of the salt, and measures the internal resistance of the salt to flow under the influence of gravity, which suggests that the salts with low kinematic viscosity values are beneficial to be used as the heat transfer salt. Finally, the thermal diffusivity measures the ability to move heat through the salt. The salts with higher thermal diffusivity values can transfer heat more quickly, which is desirable for the heat transfer salt. The equations to calculate volumetric heat capacity, kinematic viscosity and thermal diffusivity are given in equations (1)-(3), respectively.

$$c_{vol} = \rho \times C_p \quad (1)$$

$$\nu = \frac{\mu}{\rho} \quad (2)$$

$$\alpha = \frac{\kappa}{c_{vol}} \quad (3)$$

Based on the definitions of each thermodynamic properties, the chloride salt with low melting point and low kinematic viscosity, and high volumetric heat capacity and high thermal diffusivity is the optimal chloride salt as the heat transfer salt in an MSFR. To evaluate each value, the basic thermodynamic properties, such as density and heat capacity, of the candidate salts can be found in references [3-6]

2.3 Result

Based on the basic thermodynamic properties as functions of temperature, the volumetric heat capacity, kinematic viscosity and thermal diffusivity are shown in Figures 2-4, respectively.

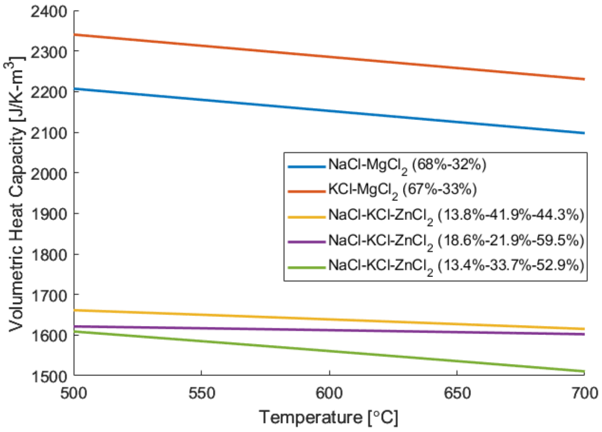

Figure 2. Volumetric heat capacity of candidate salts

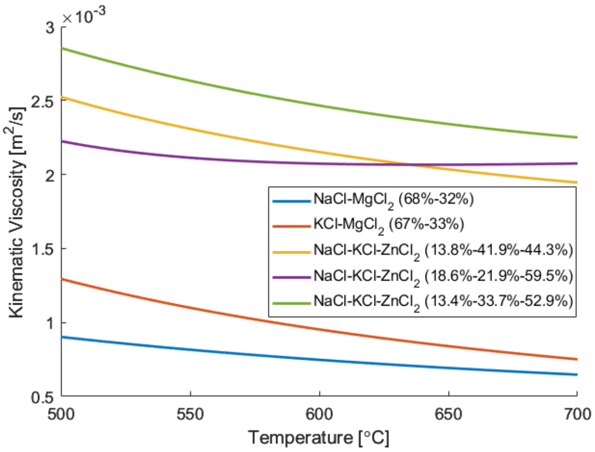

Figure 3. Kinematic viscosity of candidate salts

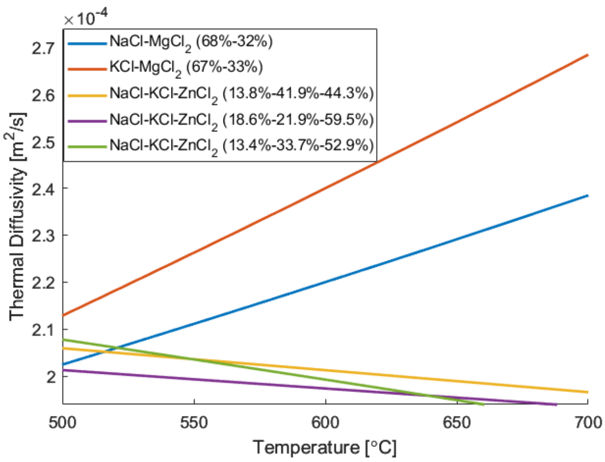

Figure 4. Thermal diffusivity of candidate salts

The core outlet temperature of MSRE was about 663°C (1225°F). Therefore, the operating temperature range of the heat transfer salt is assumed to be between 600°C and 650°C. At such temperature range, NaCl-KCl-$ZnCl_2$ with different compositions have lower volumetric heat capacity and thermal diffusivity, and higher kinematic viscosity, which is the exact opposite of the ideal heat transfer salt characteristic. This result is in accordance with the statement made by Sridharan that alkali chlorides and alkaline earth chlorides are thermodynamically preferred than the transition metal chlorides. The NaCl-$MgCl_2$ has the lowest kinematic viscosity among all of the candidate salts. However, the volumetric heat capacity and thermal diffusivity at the operating temperature range are lower than the KCl-$MgCl_2$. Table 1 indicates the rank of the candidate salts, where the lower rank means the better heat transfer salt.

Table 1. Rank of the candidate chloride salt

Salt	T_{melt}	C_{vol}	ν	α	Sum
NaCl-$MgCl_2$	3	2	1	2	8
KCl-$MgCl_2$	2	1	2	1	6
NaCl-KCl-$ZnCl_2$	1	3	3	3	10

Based on this thermodynamic property analysis, KCl-$MgCl_2$ is the optimal heat transfer salt for an MSFR. However, there are many crucial factors, including pumping work and heat exchanger size, when selecting the optimal heat transfer salt for the MSFR. As a further work, the sizes of the heat exchangers and the pumping work for each candidate salt will be compared for the selection of the optimal heat transfer salt.

3. Summary & Further work

In this study, the selection of the optimal heat transfer chloride salt for the MSFR is discussed in perspective of thermodynamic property analysis. By referencing the MSRE operating conditions, the operating temperature range of the heat transfer chloride salts are assumed to be between 600°C and 650°C. At such temperature range, the volumetric heat capacity, kinematic viscosity and thermal diffusivity were compared. Among all the candidates, KCl-$MgCl_2$ is the optimal heat transfer chloride salt for MSFR in terms of thermal-hydraulic performance. In future, the pumping work and the heat exchanger size of each chloride salt will be compared to better select the optimal heat transfer chloride salt for the MSFR application.

NOMENCLATURE

Symbol [Unit]	Definition
T_{melt} [°C]	Melting Temperature
C_{vol}[J K^{-1}m^{-3}]	Volumetric Heat Capacity
ν[m^2 s^{-1}]	Kinematic Viscosity
α[m^2 s^{-1}]	Thermal Diffusivity
ρ [kg m^{-3}]	Density
C_p [J kg^{-1} K^{-1}]	Heat Capacity
μ [kg m^{-1}s^{-1}]	Dynamic Viscosity
κ [W m^{-1} K^{-1}]	Thermal Conductivity

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