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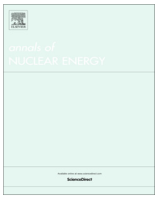

Review

Fluoride salt coolant properties for nuclear reactor applications: A review

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ABSTRACT

Fluoride salts are crucial to achieving the benefits of Fluoride-salt-cooled High-temperature Reactors (FHRs). Intensive studies and modeling are being performed in different countries aimed at FHR technology development. Better understanding of liquid fluoride salt coolant properties and their uncertainties are needed for design and analysis of nuclear facilities. The main objective of the present study is to perform a literature survey of the experimental data, numerical studies, reports, and other review compilations for the main thermophysical properties of liquid fluoride salts. The review recommends density, heat capacity, thermal conductivity, and viscosity properties for potential primary coolants LiF-BeF$_2$ (flibe) and NaF-ZrF$_4$ (nafzirf) and secondary coolant LiF-NaF-KF (flinak). It is found that there is a dearth of experimental data. Thus recommended property uncertainties are included, which range from 2 to 20%, complete with a discussion on the recommended definition of the uncertainties. The recommended properties and their uncertainties provide a reference point for incorporating uncertainty in modeling to understand its impacts and for code benchmarking and validation.

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1. Introduction

One of the critical issues for the Fluoride-salt-cooled High-temperature Reactor (FHR) is to acquire comprehensive knowledge of the fluoride salt coolant properties and their uncertainties in order to ensure reactor designs perform as expected. The use of liquid fluoride salt as a coolant for the FHR is crucial to achieving the benefits of the design. Fluoride salts have high melting temperatures at low pressure in the range of 400–600 °C allowing for high-temperature low-pressure operation. At these high temperatures, efficiency of converting heat to electricity is improved with the ability to use an open-air-Brayton combined-cycle plant similar to that used in natural-gas fired power plants. The boiling point of these liquids is very large, on the order of 500 °C above peak coolant temperatures, allowing for large margins (Forsberg et al., 2013). Unlike water, which has extensive steam tables for its properties, the thermophysical properties of salts are not well known. As a result, determination of the fluoride salt coolant properties and their uncertainties would be necessary for design and analysis for nuclear applications like the FHR. Hence, it is essential to summarize the coolant property research to date to present a comprehensive picture of research on fluoride salt coolant properties. Additionally, having reference coolant properties and associated uncertainties allows for incorporating uncertainty in modeling to understand its impacts and for performing code benchmarking and validation without introducing another source of uncertainty from selection of coolant properties.

The first work studying salt coolants for nuclear reactors comes from Oak Ridge National Laboratory (ORNL), specifically the Aircraft Nuclear Propulsion (ANP) project in the 1950s and early 1960s and the Molten Salt Reactor Experiment (MSRE) project in the 1960s and 1970s. During the 1970s and 1980s, interest in salt coolants suited for nuclear applications waned. However, in the 2000s, a resurgence of interest in using fluoride salts as nuclear coolants yielded assessments of candidate coolant thermophysical properties. Several reviews or summaries of the existing literature emerged. First, Williams et al. (2006) assessed molten salt performance, which included determining properties for molten salts, for the Advanced High Temperature Reactor and coolant loop between the Next Generation Nuclear Plant and the Nuclear Hydrogen Initiative hydrogen-production plant (Williams, 2006; Williams et al., 2006). Benes and Konings (2009) present properties for fluoride salts for molten salt reactors including flibe and flinak (Benes and Konings, 2009). Holcomb and Cetiner (2010) look at the technologies involved in liquid salt heat transport including an assessment of heat transfer loop performance which includes an overview of salt properties (Holcomb and Cetiner, 2010). Serrano-Lopez et al. (2013) review a wide range of molten salts for energy applications including flibe and flinak (Serrano-Lopez et al., 2013). Sohal et al. (2010) also review molten salts for energy applications including properties of flibe and flinak (Sohal et al., 2010). Lastly, Yoder (2014) reviews heat transfer data for liquid salts including flinak and compares existing heat transfer correlations (Yoder, 2014). A handful of studies presented updates, and in recent years, a couple molecular dynamics simulations have looked at molten salts.

This paper reviews the experimental and theoretical property data for candidate fluoride salt coolants for the FHR to provide an easy reference point for recommended coolant properties and associated uncertainties for use in nuclear application analyses. The review traces coolant properties to experimental data when available and importantly emphasizes including property uncertainties estimated to be at the 95% confidence level, which is an important consideration for thermal-hydraulic licensing analysis (Romatoski, 2017).

2. Determination of candidate coolants

The salts currently under consideration for the FHR include LiF-BeF_2 (flibe) and NaF-ZrF_4 (nafzirf) as potential primary loop coolants and LiF-NaF-KF (flinak) as a secondary loop coolant. Flibe is the primary candidate for the primary loop coolant. It has the lowest neutron cross section, is chemically stable with low corrosion rates in high-nickel alloy systems, and is weakly radioactive with the primary activation product tritium resulting in very low radiation levels in the primary loop. Flibe does have some disadvantages, which include toxicity of beryllium and the need to enrich lithium to at least 99.995% Li-7 to maintain a low nuclear cross section (Forsberg et al., 2013). For neutronic design analysis, the baseline salt used is nafzirf because it has less attractive neutronic and thermophysical properties. The benefits of nafzirf over flibe include no direct tritium production and lower cost. By designing a reactor to operate using nafzirf, it is assumed that the reactor will operate better using flibe as the coolant. Thus, one can consider the coolants flibe and nafzirf to be bounding primary salt coolants for reactor design (Richard, 2016). For the secondary loop, the neutronic properties are not a concern. Ignoring any salts with beryllium, flinak has the best figures of merit for turbulent forced convection and for turbulent and laminar natural convection (Williams, 2006). Thus, flinak is the leading candidate due to its low melting point, its high heat capacity, and its chemical stability at high temperatures.

3. Investigation of coolant properties

3.1. LiF-BeF_2 (Flibe)

The preferred FHR primary coolant choice and primary candidate for a commercial FHR is peritectic LiF-BeF_2 (flibe), with a 2 to 1 ratio (66–34 mol%) of LiF to BeF_2. The primary coolant operating temperature range for the FHR is approximately 600-700 °C (873–973 K). The melting temperature is 459 °C, and it boils at over 1430 °C (Kato et al., 1983; Davis, 2005; Williams et al., 2006; Benes and Konings, 2009; Samuel, 2009; Holcomb and Cetiner, 2010; Serrano-Lopez et al., 2013; Dewan, 2013).

3.1.1. Density

The literature available on density is more prolific, and typically has a smaller uncertainty than other properties. Most density correlations are based on three sets of experimental data from Blanke et al. (1956), Cantor (1973), and Janz et al. (1974), which are plotted in Fig. 1 as data points. Several correlations for the density of flibe have been proposed and are enumerated in Table 1. Each correlation is plotted in Fig. 1 where any data markers only at the end points of correlation lines correspond to the temperature range limits and are not experimental data points. The majority of the data converge to the experimental data presented by Cantor (1973) and Janz et al. (1974), with their reported density correlation converted to units of kg/m^3 as a function of temperature in Kelvin of $\rho = 2413 - 0.488 * T[K]$. The best report of uncertainty that includes more than just precision is 2% from Cantor (1968).

3.1.2. Heat capacity

The experimental data reported for heat capacity is summarized in Table 2 along with heat capacity data reported by others reviewing the literature. Review of listed data suggests that a temperature independent heat capacity of 2386 ± 3% J/kg-K for the liquid temperature range envelopes all the data surveyed.

3.1.3. Thermal conductivity

Thermal conductivity measurements typically have the greatest error in heat transfer analysis because the fluid property is difficult