ANL/CFCT-24/23

Property Measurements of LiF-NaF-KF Molten Salts Doped with Surrogate Fission Products

Chemical and Fuel Cycle Technologies Division

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September 16, 2024

ACKNOWLEDGEMENTS

This report was produced under the auspices of the US DOE Advanced Reactor Technology Program Molten Salt Reactor Campaign. Issuance of this report meets milestone M3AT-24AN0705012. The authors gratefully acknowledge efforts by Dr. Sara Thomas and Mr. Joshua Jackson for preparation of salts. Compositional analyses of salt samples provided by Ms. Kristin DeAngeles, Ms. Susan Lopykinski, Dr. Seema Naik, and Ms. Yifen Tsai (Argonne Analytical Chemistry Laboratory) are gratefully acknowledged. This work was conducted at Argonne National Laboratory and supported by the U.S. Department of Energy, Office of Nuclear Energy, under Contract DE-AC02-06CH11357.

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1. Introduction

Measurements of molten salt properties including transition temperatures, phase behavior, heat capacity, density, volumetric thermal expansion, surface tension, viscosity, thermal diffusivity, thermal conductivity, and vapor pressure are being performed at Argonne. The properties of several fuel and coolant salts including eutectic LiF-NaF-KF (FLiNaK) have been measured [1–3]. These properties are suitable for use in evaluating reactor performance during startup and early operating conditions.

Reactor operation will result in the accumulation of fission products in the fuel salt of a molten salt reactor (MSR). The increased fission product concentrations affect the physical and chemical properties of the salt and operation of the reactor. Previous work performed at Argonne evaluated the effects of fission product dopants on the melting behavior, heat capacity, and thermal diffusivity of eutectic NaCl-UCl_3 and FLiNaK [4]. Properties of FLiNaK are commonly used to represent those of MSR salts, and work summarized in this report was performed to measure the effects of surrogate fission products on the density and viscosity of FLiNaK.

Thermophysical property measurements were made using two salts that had been prepared previously by doping eutectic mixtures of FLiNaK with surrogate fission products for use in spill experiments performed at Argonne [5]. Samples of the same salts were used for thermal measurements [4]. The densities of those two salts were measured by using the Archimedes method and the viscosities were measured by using the rotating cylinder method. Measurements were made at temperatures spanning the range of 500–900 °C, which is the expected operating range of MSRs. Measured properties were compared to previous measurements made with eutectic FLiNaK without fission product dopants [2]. Differences between property values measured for the doped and non-doped salts were compared with the precision of the method to determine the significance of the effect of fission product generation on the salt properties.

2. Salt Preparation and Analysis

Two previously prepared fission product-doped salt mixtures were used in property measurements. Eutectic mixtures of FLiNaK were doped with ZrF_4, Mo, NdF_3, CeF_3, CsF, CsI, SrF_2, Ru, and Na_2Te to represent low- and high-burnup fluoride-containing thermal spectrum fuel salts. Those salt mixtures are referred to as FLiNaK-L and FLiNaK-H, respectively.

2.1 FLiNaK without Fission Product Dopants

Property values measured for the doped FLiNaK salts were compared to values that were measured previously for eutectic FLiNaK as part of an interlaboratory study of thermal property measurements as part of the DOE Molten Salt Reactor Campaign Round Robin Project [4]. That salt had been prepared at Oak Ridge National Laboratory and shipped to laboratories for property measurements. The salt received at Argonne was unpackaged and handled within an ultra-high purity argon atmosphere glovebox maintained with <10 ppm O_2 and <5 ppm H_2O.

As part of the Round Robin Project, the concentrations of major components in the FLiNaK salt were measured by using inductively coupled plasma-optical emission spectrometry (ICP-OES) and concentrations of trace metals were determined by using inductively coupled plasma-mass spectrometry (ICP-MS). The ICP-OES measurements were performed by using a PerkinElmer® Optima™ 8300DV ICP optical emission spectrometer, and ICP-MS measurements were performed by using a PerkinElmer® NexION® 2000 ICP mass spectrometer. Both instruments were calibrated with standards prepared from NIST-traceable solutions. The composition of three samples of FLiNaK were analyzed.

The concentrations of major components were calculated by using measured cation concentrations of FLiNaK samples. Averages and one standard deviation (1 s) of the salt composition based on analyses of three samples of FLiNaK are reported in Table 1.

Table 1. Composition of major components in FLiNaK without fission product dopants calculated from measured cation concentrations, in wt % [2]

Sample	LiF	KF	NaF
1	30.4	57.5	12.0
2	30.6	57.7	11.7
3	30.3	57.8	11.9
Average	30.4	57.7	11.9
1 s	0.1	0.3	0.2

The measured concentrations of trace elements in the FLiNaK samples are reported in Table 2. The ICP-MS method is typically accurate to within 10% of measured values. However, the need to dissolve salt samples prior to analysis adds uncertainty due to the limited solubilities of some constituents and potential volatilization of others. In cases where analytes were not detected, the limit of detection is reported. The averages and one standard deviation of concentrations measured in replicate samples are reported in Table 2. Detectable amounts of Ca, Rb, Be, Cr, Mn, and Ni were measured. Calcium contamination was likely present in one or more of the reagent salts.

Table 2. Concentrations of trace elements in FLiNaK, in ppm [2]

Sample	Be	Mn	Ca	Cr	Fe	Ni	Rb	Cs
1	19.7	3.48	150	5.01	<1.37	8.73	15.0	<0.10
2	11.9	3.66	300	3.35	<2.75	7.55	15.1	<0.03
3	9.87	3.74	227	3.64	<1.73	8.07	15.4	<0.03
Average	14.0	3.6	230	4.0	-	8.1	15.2	-
1 s	5.0	0.1	80	0.9	-	0.6	0.2	-

2.2 FLiNaK with Fission Product Dopants

The FLiNaK-L and FLiNaK-H salt mixtures were prepared previously at Argonne National Laboratory in an argon atmosphere glovebox in which oxygen and moisture concentrations were maintained below 10 ppm and 5 ppm, respectively [5]. The purities of reagents used for doped salt preparation were higher than 99.9% except for KF, which was higher than 99% purity. All reagents were dried at 300 °C for four hours and at 700 °C for eight hours to remove volatile contaminants. A eutectic mixture of FLiNaK was prepared in three separate batches in which dried reagents were weighed directly into cleaned nickel crucibles, mechanically mixed and then heated at 700 °C for at least eight hours. The prepared batches were then ground, combined into a single mixture, and fused again in a cleaned nickel crucible at 700 °C for eight hours. The FLiNaK was then allowed to cool and ground for use as a base salt.

Known amounts of surrogate fission product dopants representing fuel salts generated during low burnup and high burnup conditions were added to aliquots of the eutectic FLiNaK base salt. The FLiNaK-L and FLiNaK-H salt mixtures were fused in cleaned graphite crucibles at 700 °C for at least 16 hours. Doped salts were used in a series of spill accident experiments in which charges of salt were heated in cleaned graphite crucibles at temperatures in the range of 650–850 °C for at least 16 hours and then poured onto a stainless steel catch pan to simulate processes expected in a salt spill scenario [5]. Following the salt spill experiments, the doped salts were recovered and stored in containers within a glovebox. The recovered salts were used for thermophysical property measurements.

The concentrations of major cations (Li, Na, and K) and minor components (i.e., trace metals and surrogate fission products) in FLiNaK-L and FLiNaK-H were measured after salt spill testing by using ICP-OES and ICP-MS, respectively [5]. Three samples of each salt mixture were prepared for compositional analyses. The concentrations of major and minor constituents were measured by using a PerkinElmer NexION 2000 ICP mass spectrometer. A known amount of each salt sample was dissolved in a mixture of deionized water, HNO_3, and HCl and heated overnight at 140 °C. Small black particles were observed in several solutions after overnight dissolution; the particles were not analyzed but are probably metallic ruthenium that had not dissolved into the salt during production. Separate solutions were prepared for use in measuring iodine concentrations. Samples of each salt were mixed with deionized water and boric acid and were stirred occasionally over several days prior to iodine concentration measurements. The concentrations of major components in samples of FLiNaK-L and FLiNaK-H calculated from cation concentrations are reported in Tables 3 and 4, respectively. The averages and 1s values of concentrations measured in three samples are also reported.

Concentrations of metals and iodine measured in samples of FLiNaK-L and FLiNaK-H are reported in Tables 5 and 6, respectively. The averages and 1s values of concentrations measured in three samples are included. Concentration measurements performed by ICP-MS are typically accurate to within 10% of measured values. However, the measured values are also affected by uncertainties in the salt dissolution and solution preparation steps. The concentrations of analytes may be impacted by the preparation of salt samples by dissolution in acid due to incomplete dissolution or volatilization of certain species. In cases where the analytes were not detected, the limit of detection is reported.

The concentrations of trace elements in samples of FLiNaK-L and FLiNaK-H mixtures are shown in Tables 7 and 8, respectively. The limit of detection is reported in cases where impurities were not detected. The averages and 1s values of concentrations measured in three samples are also reported. Detectable amounts of Cr and Ni were likely introduced during grinding, salt synthesis, or contacting the steel catch pan in the salt spill experiments. These are not expected to affect the density or viscosity properties of the salts. The total amounts of contaminants in the FLiNaK-L and FLiNaK-H mixtures are much lower than the total amount of contaminants in the non-doped FLiNaK.

Table 3. Composition of major components in FLiNaK-L, in wt % [5]

Sample No.	LiF	KF	NaF
1	26.1	54.8	10.9
2	26.7	57.1	11.3
3	29.6	66.0	12.6
Average	27.5	59.3	11.6
1 s	1.9	5.9	0.9

Table 4. Composition of major components in FLiNaK-H, in wt % [5]

Sample No.	LiF	KF	NaF
1	25.9	53.3	10.5
2	26.0	53.8	10.6
3	26.4	54.1	10.8
Average	26.1	53.7	10.7
1 s	0.2	0.4	0.1

Table 5. Concentrations of fission product surrogates in FLiNaK-L, in ppm [5]

Sample No.	Sr*	Zr	Mo	Te	Cs	Ce	Nd	I
1	<1.53	987	237	127	1640	1550	1610	188
2	<1.21	1110	379	128	1700	1680	1720	156
3	<0.88	1190	435	146	2120	1710	2090	154
Average	—	1010	350	134	1820	1650	1810	166
1 s	—	103	102	10	262	85	252	19

*< indicates the concentration was below the reported detection limit.

Table 6. Concentrations of fission product surrogates in FLiNaK-H, in ppm [5]

Sample No.	Sr	Zr	Mo	Te	Cs	Ce	Nd	I
1	3.68	4460	963	268	7800	5960	6750	714
2	3.62	4160	664	284	7570	3340	4630	695
3	3.80	4560	943	280	8350	3120	4400	672
Average	3.7	4390	857	277	7910	4140	5260	694
1 s	0.1	208	168	8	400	1580	1300	21

Table 7. Concentrations of trace elements in FLiNaK-L, in ppm [5]

Sample No.	Be*	B*	Mg*	Al*	Si*	Ca*	Cr	Fe*	Ni	Cu*
1	<0.6	<11.0	<13.8	<33.4	<1290	<52.4	19.0	<89.8	<4.5	<1.6
2	<0.5	<8.7	<10.9	<26.5	<1160	<41.5	26.4	<150	18.2	<2.7
3	<0.3	<5.8	<7.2	<17.4	<401	<205	17.2	<46.8	17.0	<1.8
Average	—	—	—	—	—	—	20.8	—	17.6	—
1 s	—	—	—	—	—	—	4.9	—	—	—

*< indicates the concentration was below the reported detection limit.

Table 8. Concentrations of trace elements in FLiNaK-H, in ppm [5]

Sample No.	Be*	B*	Mg*	Al*	Si*	Ca*	Cr	Fe*	Ni	Cu*
1	<1.5	<6.7	<8.4	<20.4	<470	<32.0	13.7	<64.1	8.5	<1.1
2	<1.3	<6.0	<7.5	<18.3	<421	<28.7	14.4	<49.1	5.4	<1.4
3	<1.3	<5.7	<7.1	<17.2	<397	<27.1	18.2	<88.9	8.8	<1.7
Average	—	—	—	—	—	—	15.4	—	7.6	—
1 s	—	—	—	—	—	—	2.4	—	1.9	—

*< indicates the concentration was below the reported detection limit.

3. Density

3.1 Method

The Archimedes method was used to measure the densities of FLiNaK-L and FLiNaK-H salts. The method is based on the fact that the buoyant force on an object is equal to the weight of the liquid it displaces. The same method and apparatus had been used to measure the density of molten FLiNaK without dopants. In this method, the density of the molten salt is determined by comparing the mass of a solid bob of known volume measured in a gas space with the mass measured when the bob is fully immersed in the molten salt. The liquid density ρ(T) is calculated by using Equation 1, where Δm is the difference in the mass of the bob measured in gas and liquid, V is the volume of the bob, α is the thermal expansion of the bob material, in this case tungsten (4.4×10^{-6} K^{-1}) [6], and T is the absolute temperature of the salt.

$$\rho(T) = \frac{\Delta m(T)}{V(1+\alpha T)^3} \tag{1}$$

The densitometer assembly consists of a cylindrical bob and support wire suspended from a balance on a scissor lift above a furnace. The densitometer is housed within an inert atmosphere radiological glovebox that is maintained at <10 ppm oxygen and <5 ppm water. Salts were contained within nickel crucibles that were fabricated at Argonne. Cylindrical tungsten bobs (Midwest Tungsten Service, Willowbrook, IL) and wire (McMaster-Carr) were used for density measurements. Crucibles and bobs were cleaned with methanol wipes and then heated in a furnace at 700 °C for at least four hours to remove any moisture or other contaminants. Salt mixtures were crushed and appropriate amounts of salt were loaded into the crucible and placed into the furnace. The volume of each bob was calculated by using the measured mass and density of tungsten at room temperature, which is 19.3 g cm^{-3} [7]. The diameters of the support wires were measured by using digital calipers. The wire was then attached to the bob and suspended from a balance above the crucible.

A calibrated balance accurate to ±0.001 g was used to perform mass measurements of the tungsten bob and wire within the furnace. The balance was adjusted so that the hook used to suspend the bob and wire set was axially aligned with the center of crucible. The balance was then leveled by using the bubble level on the instrument. The mass of the suspended bob and wire set was first measured at room temperature while suspended above the furnace with the heat shield in place. The salt was then heated to the target temperature above the melting point and allowed to stabilize for at least 30 minutes to ensure complete melting of the salt. The scissor lift was then lowered until the top of the bob was immersed to a depth of at least 1 cm below the surface of the molten salt. The system was left for at least 30 minutes to stabilize at the target temperature. The level of the balance was checked again and adjusted as needed. Ten mass readings were recorded at each temperature during a two-minute period. The furnace controller maintained a salt temperature that was stable to within 1 °C during the measurements. The furnace setting was then adjusted to the next target temperature and the system allowed to stabilize. Mass measurements of the immersed bob were performed at 500, 550, 600, 650, 700, 800, and 900 °C.

Measurements were made using two bob and wire sets. Bobs with equal diameters but different lengths had volumes of approximately 1.25 and 2.00 cm^3, respectively. Equal lengths of wire were used with diameters of 0.2 and 0.1 mm respectively. The appropriateness of accounting for the effect of surface tension on the measurements by using Equation 2 was assessed, where measurements made with different bob and wire sets are indicated by subscripts 1 and 2. The equality in this equation is based on the density of the salt being independent of the bob and wire set used to perform measurements. The interaction between the salt and wire is represented as the product of the surface tension of the salt and diameter of the wire divided by the rate of acceleration due to gravity, 9.81 m s^2, as given in Equation 2 [8–9].

$$\frac{\Delta m_1(T) + \frac{\pi D_1 \sigma(T)}{g}}{V_1(1+\alpha T)^3} = \frac{\Delta m_2(T) + \frac{\pi D_2 \sigma(T)}{g}}{V_2(1+\alpha T)^3} \tag{2}$$

Heavier bobs were paired with the thinner wire (0.1 mm) to deemphasize the contribution of surface tension and lighter bobs were paired with the thicker wire (0.2 mm) to emphasize the effect of surface tension relative to the difference in measured masses. The contributions of the surface tension terms were either negative or not significant within the measurement uncertainty. The surface tension term was deemed to be inappropriate for these measurements and was not used in the density calculation. Instead, Equation 1 was used. The effect of bob geometry and wire diameter on the density measurement is the focus of active research.

3.2 Density of FLiNaK-L and FLiNaK-H

The densities of FLiNaK-L and FLiNaK-H salts calculated by using Equation 1 are shown in Figure 1. The results of previous measurements of FLiNaK without dopants performed by using two bob and wire sets with wires of different diameter and bobs of the same volume are included for comparison [2]. Negative temperature dependance is observed for all measurement sets. Density measurements with FLiNaK-H were repeated due to the relatively large difference between measurements made using the first two bob and wire sets. The repeated measurements (FLiNaK-H 3 and FLiNaK-H 4) closely match the initial measurements (FLiNaK-H 1 and FLiNaK-H 2). The greater differences in measurements of FLiNaK-L and FLiNaK-H made with different bob and wire sets compared to measurements with FLiNaK indicates there are effects of the bob geometry that must be quantified and taken into account. The measured densities of FLiNaK-L and FLiNaK-H are higher than those measured for FLiNaK at all temperatures and more significantly affected. Averages for measurements of FLiNaK, FLiNaK-L and FLiNaK-H are reported in Tables 9–11. Average densities of FLiNaK-H are higher than those for FLiNaK-L. These differences are greater than the measurement uncertainty typical for pure salts (±0.01 g cm^{-3}), which takes the precision of the balance, calipers, and thermocouple into account. The presence of fission products at both low and high concentrations impacts the density of FLiNaK and the sensitivity of the measurement. Measured values used to calculate densities are provided in Appendix A. Other factors that could affect the density measurement include interfacial effects between the molten salt and wire such as wetting. These data, and data collected for other salts with other paired sets of bobs and wires, indicate the need to further investigate the effects of bob geometry, wire diameter, and interfacial properties on measured density to accurately differentiate effects of fission products and impurity contents.

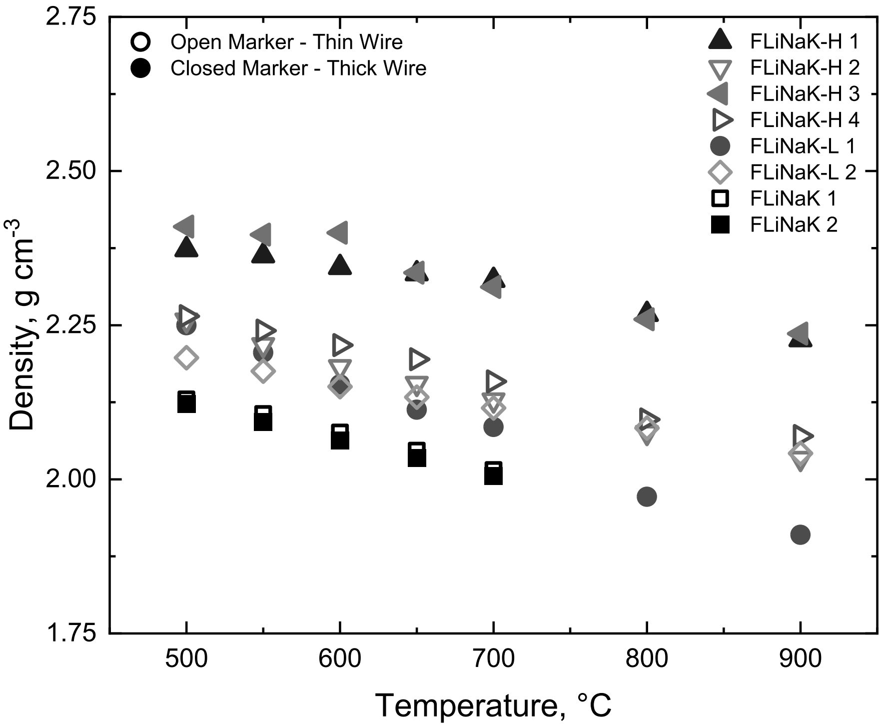


Figure 1. Densities of FLiNaK, FLiNaK-L, and FLiNaK-H salts measured at different temperatures with different bob and wire sets.

Table 9. Measured densities of FLiNaK at different temperatures [2]

Measurement Number	Temperature, °C				
	500	550	600	650	700
1 – Thick Wire, Large Bob	2.12	2.09	2.06	2.03	2.01
2 – Thin Wire, Large Bob	2.13	2.11	2.08	2.05	2.01
Average	2.13	2.10	2.07	2.04	2.01

Table 10. Measured densities of FLiNaK-L at different temperatures

Measurement Number	Temperature, °C						
	500	550	600	650	700	800	900
1 – Thick Wire, Small Bob	2.25	2.21	2.15	2.11	2.08	1.97	1.91
2 – Thin Wire, Large Bob	2.20	2.18	2.15	2.13	2.12	2.08	2.04
Average	2.22	2.19	2.15	2.12	2.10	2.03	1.98

Table 11. Measured densities of FLiNaK-H at different temperatures

Measurement Number	Temperature, °C						
	500	550	600	650	700	800	900
1 – Thick Wire, Small Bob	2.37	2.36	2.34	2.33	2.32	2.27	2.23
2 – Thin Wire, Large Bob	2.26	2.22	2.18	2.16	2.13	2.08	2.03
3 – Thick Wire, Small Bob	2.41	2.40	2.40	2.34	2.31	2.26	2.24
4 – Thin Wire, Large Bob	2.26	2.24	2.22	2.20	2.16	2.10	2.07
Average	2.33	2.30	2.29	2.25	2.23	2.18	2.14

4. Viscosity

4.1 Method

The rotating cylinder method was used to measure the viscosities of FLiNaK-L, and FLiNaK-H for comparison with previously measured viscosities of FLiNaK. In this method, a nickel spindle is immersed within the molten salt and rotated at a known velocity to measure the resistance of the thin layer of salt between the spindle and the inner wall of a cylindrical nickel crucible to flow. The torque required to maintain a targeted spindle velocity is measured by the viscometer. The viscosity μ is calculated by using Equation 3, which is appropriate under laminar flow conditions, where M is the measured torque, R_c is the inner radius of the crucible, R_b is the radius of the spindle, L is the spindle length, and ω is the imposed rotational velocity.

$$\mu = \frac{M(R_c^2 - R_b^2)}{4\pi R_c^2 R_b^2 L\omega} \tag{3}$$

The spindles and crucibles were fabricated at Argonne to provide exact tolerance of dimensions. They were cleaned before use with methanol wipes, and dried in a furnace within the glovebox at 700 °C for at least four hours. The inner diameters of the crucibles were dimensioned by using a digital bore gauge. The diameters and lengths of the spindles were measured by using digital calipers.

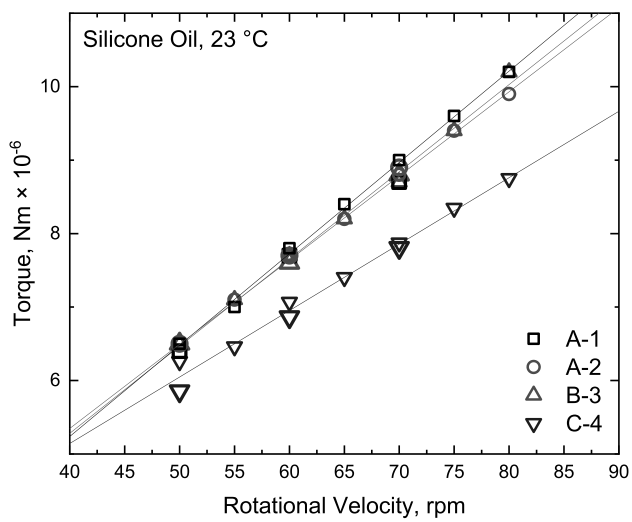
Viscosity measurements were performed by using a DV2T-LV viscometer (AMETEK Brookfield, Middleborough, MA) mounted on a height-adjustable stand and a Kerr ElectroMelt furnace housed within an inert atmosphere radiological glovebox. A known amount of salt was loaded into the crucible and placed in the furnace. The horizontal levels of both the furnace and the viscometer were checked by using bubble levels. The spindle was then suspended from the viscometer and axially aligned with the crucible.

The salt was heated in the furnace to a target temperature above the melting point and allowed to equilibrate for at least thirty minutes. The viscometer was then lowered until the spindle was completely immersed in the molten salt and left stationary for an additional 30 minutes to heat the spindle to the salt temperature. The spindle depth was adjusted such that the top of the spindle was approximately 5 mm below the surface of the salt. Measurements were performed at seven different rotational velocities. The order of the rotational velocities at which measurements were performed in each set was random to avoid any systematic effects due to regular incremental increases or decreases in velocity. Measurements at three of the seven velocities were repeated to check for consistency. The consistency of the measured torque values indicates measurements are repeatable. The generation of turbulent flow occurs above critical velocities in rotating Couette flow and is a well-studied occurrence [10]. Equation 3 is not applicable to responses measured under turbulent flow. Combinations of crucible and spindle geometries and rotational velocities were used to ensure the viscosities reported herein were not affected by turbulence. Measurements demonstrating the detectable and avoidable effect of turbulent flow on measured torque are reported in Appendix B.

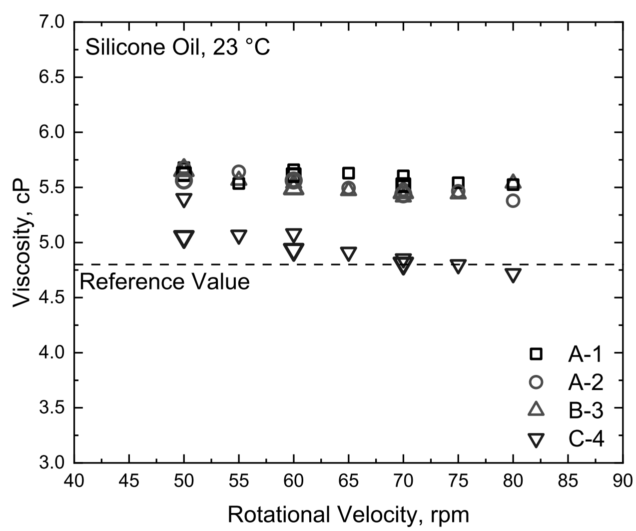
4.2 Measurement Conditions and Instrument Calibration

The responses of the viscometers used to make measurements with FLiNaK-L and FLiNaK-H were checked before use by performing measurements of a silicone reference oil (Cannon Instrument Co., State College, PA) at room temperature. The use of silicone oil is appropriate because the viscosity at room temperature is within the range of values that have been measured for molten FLiNaK at 500–900 °C. Known amounts of oil were loaded into the crucible and a series of measurements performed at rotational velocities in the range of 50–80 rpm, including repeated measurements at 50, 60, and 70 rpm. Viscosities were calculated by using each measured torque value and averages were then calculated for each data series.

The measured torque and viscosity values for silicone oil are shown in Figure 2. Repeated measurements within each data set are plotted with larger markers for distinguishability. Letter designations used in the legend entries indicate which of three viscometers (labeled A, B, and C) was used to perform each measurement. The numbers in the legend refer to series of oil measurements that were performed prior to two measurements with FLiNaK (1 and 2) and prior to measurements with FLiNaK-L (3) and FLiNaK-H (4). The measured torque in each series increases linearly with increasing rotational velocity, as seen in Figure 2a. That the torque is linearly proportional to the rotational velocity consistent with Equation 3 indicates laminar flow conditions were achieved at all velocities. The dashed line in Figure 2b represents the reference value of 4.8 cP for the silicone oil. That the measured viscosities are higher than the reference value is attributed to the wear of the instrument bearings (which differ slightly between viscometer heads) and gyration of the coupling rod. Both are unavoidable instrumental effects necessary for measuring salt viscosities at high temperatures using solid spindles with high mass and long coupling rods to avoid heating the viscometer head. Measurements of the silicone oil are being used to monitor and quantify the effects of instrumental sensitivity, precision, and bias on the calculated viscosity. The torque values, viscosities, and associated spindle and crucible dimensions used in silicone reference oil measurements are tabulated in Appendix B.



(a)



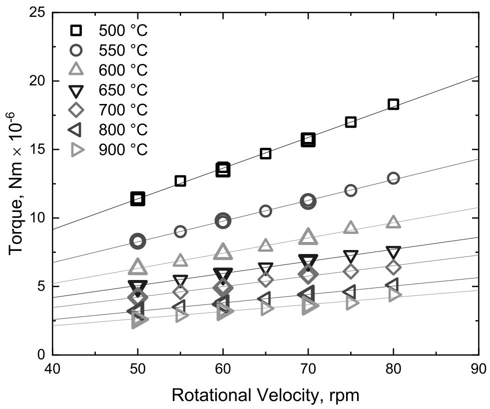
(b)

Figure 2. Measured torque (a) and calculated viscosity (b) of silicone reference oil used to calibrate the response of viscometers used in salt measurements.

4.3 Viscosity of FLiNaK with and without Fission Product Dopants

The measured torque values of FLiNaK, FLiNaK-L, and FLiNaK-H are reported in Figure 3 for the range of rotational velocities generating non-turbulent flows. Larger markers are used to distinguish replicate measurements. The calculated viscosities of FLiNaK, FLiNaK-L, and FLiNaK-H are reported in Figure 4, where larger markers are used to distinguish replicate measurements. Horizontal lines mark the average of viscosity values calculated for the set of velocities at each temperature. Viscosities are independent of velocity.

Average viscosities calculated for measurements at each temperature for FLiNaK, FLiNaK-L, and FLiNaK-H are shown in Figure 5. The viscosity values for each salt decrease with increasing temperature. Average viscosities of FLiNaK-L and FLiNaK-H are higher than those measured for pure FLiNaK at 500–700 °C. However, measurements with silicone oil indicate the effects of bearing wear and gyration can be on the order of 1 cP, which is similar to the difference in viscosities measured for the three salts. These data are being used to quantify measurement uncertainties and identify controllable aspects of the instrumental and measurement method uncertainties to be addressed in an ASTM standard test method. The torque values, viscosities, and associated spindle and crucible dimensions used in salt measurements are reported in Appendix B.



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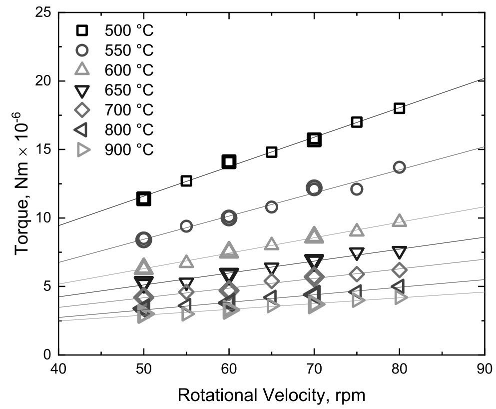

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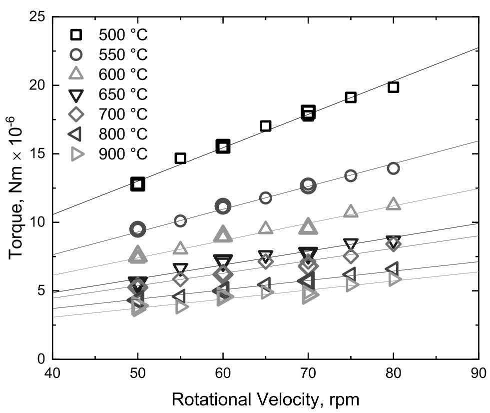

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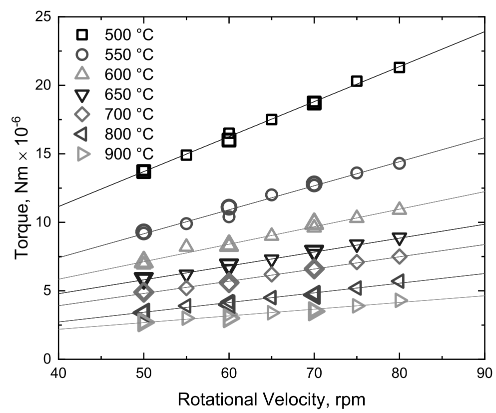

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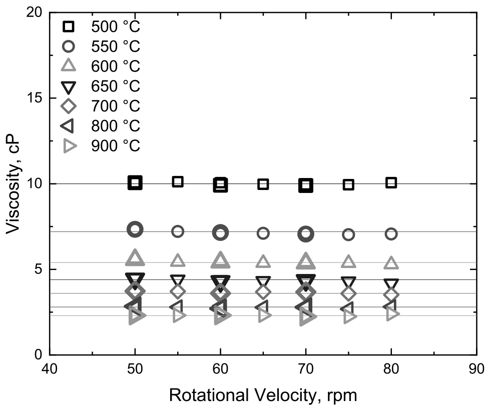
Figure 3. Measured torques for FLiNaK 1 (a), FLiNaK 2 (b), FLiNaK-L (c), and FLiNaK-H (d) at different rotational velocities and temperatures.



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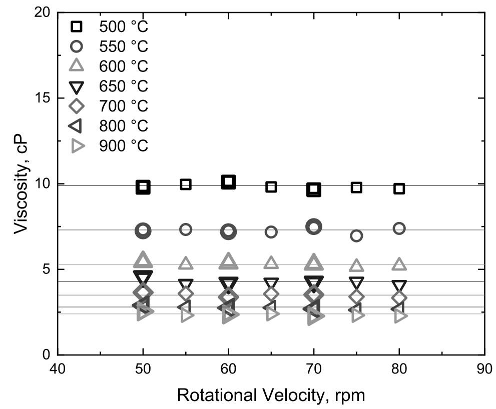

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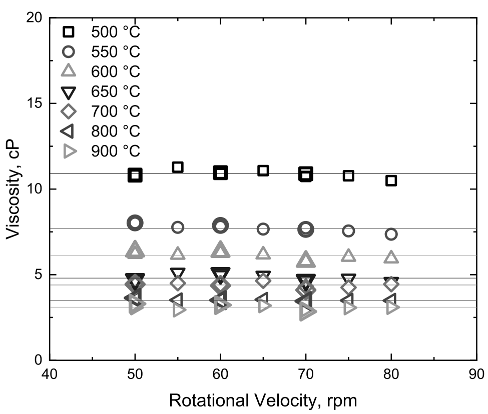

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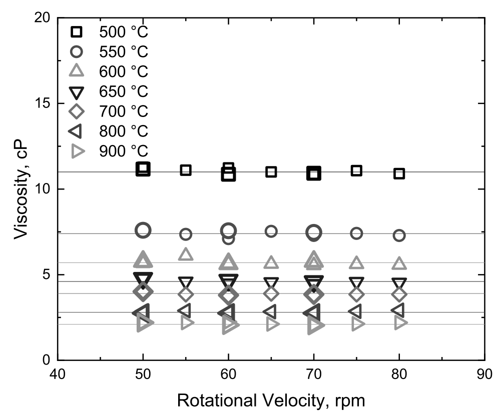

(d)

Figure 4. Calculated viscosities of FLiNaK 1 (a), FLiNaK 2 (b), FLiNaK-L (c), and FLiNaK-H (d) at different rotational velocities and temperatures.

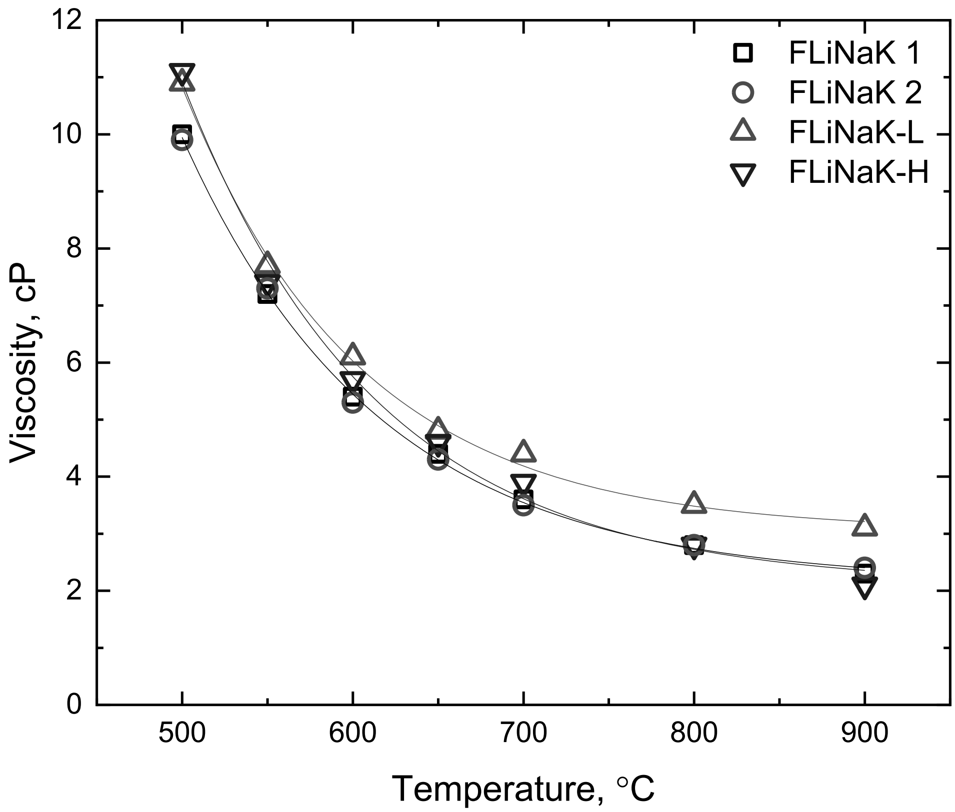

Figure 5. Averages of measured viscosities of FLiNaK, FLiNaK-L, and FLiNaK-H at different temperatures.

5. Conclusion

The densities of FLiNaK salt mixtures with and without surrogate fission products were measured by using the Archimedes method and viscosity was measured by using the rotating cylinder method. Average densities of FLiNaK-L and FLiNaK-H are higher than those measured for pure FLiNaK and average FLiNaK-H density measurements are higher than those for FLiNaK-L. However, the measurements indicated an effect of the dimensions of the bob and wire that is not currently quantified or taken into account in the density calculation. The impacts of bob geometry and wire dimensions on the salt density measured using the Archimedes method is an active area of research. Average viscosities of FLiNaK-L and FLiNaK-H mixtures are higher than those measured for pure FLiNaK up to 700 °C. The impact of fission products at low concentrations on the density and viscosity of FLiNaK are similar to the uncertainty in both measurements.

All sources of uncertainty must also be taken into account. Controllable aspects of the instrumental and measurement method uncertainties using a rotational viscometer are being addressed in an ASTM standard test method. Data presented herein and other experimental values are being used to identify and quantify uncertainties in density and viscosity measurements. This is necessary for all property measurements to distinguish the effects of the salt composition (e.g., the presence of undissolved solids) and environmental factors from instrumental measurement uncertainties.

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Appendix A: Density Calculations

The bob and wire measurements used in density calculations are reported in Table A.1. The wire and bob diameters were measured by using digital calipers and bob and wire masses were measured by using a balance. The volumes of Bob 1 and Bob 2 were determined by dividing the mass of the bob measured in the gas space at room temperature by the density of tungsten at 20 ºC (19.3 g cm^{-3}) [7]. The masses of each bob and wire set measured while immersed in FLiNaK-L and FLiNaK-H at different temperatures are reported in A.2–A.3 and A.4–A.7, respectively. Values for Δm were calculated by subtracting the mass of the submerged bob and wire measured at each temperature from the bob and wire masses measured in the gas space at room temperature.

Table A.1. Bob and wire masses, bob volumes, and wire diameters in the gas space at room temperature

Salt Mixture-Measurement Number	Bob and Wire Mass, g	Bob Volume, cm^3	Wire Diameter, mm
FLiNaK-L - 1	25.859	1.255	0.2
FLiNaK-L - 2	40.276	2.061	0.1
FLiNaK-H - 1	26.128	1.256	0.2
FLiNaK-H - 2	40.253	2.059	0.1
FLiNaK-H - 3	25.937	1.196	0.2
FLiNaK-H - 4	40.118	2.007	0.1

Table A.2. Measured immersed masses of bob and wire set 1 used in FLiNaK-L density measurements

Measurement Number	Temperature, °C						
	500	550	600	650	700	800	900
1	23.020	23.068	23.134	23.183	23.226	23.359	23.020
2	23.017	23.069	23.133	23.180	23.214	23.358	23.017
3	23.011	23.068	23.137	23.190	23.219	23.359	23.011
4	23.016	23.070	23.136	23.185	23.213	23.354	23.016
5	23.012	23.067	23.133	23.183	23.212	23.360	23.012
6	23.020	23.065	23.134	23.184	23.219	23.356	23.020
7	23.024	23.083	23.133	23.184	23.220	23.358	23.024
8	23.005	23.071	23.136	23.182	23.230	23.360	23.005
9	23.013	23.077	23.129	23.181	23.209	23.358	23.013
10	23.028	23.069	23.134	23.190	23.216	23.358	23.028
Average	23.017	23.071	23.134	23.184	23.218	23.358	23.017

Table A.3. Measured immersed masses of bob and wire set 2 used in FLiNaK-L density measurements

Measurement Number	Temperature, °C						
	500	550	600	650	700	800	900
1	35.720	35.762	35.811	35.834	35.881	35.938	35.720
2	35.720	35.768	35.809	35.840	35.877	35.940	35.720
3	35.717	35.761	35.811	35.843	35.878	35.941	35.717
4	35.722	35.761	35.811	35.844	35.874	35.936	35.722
5	35.719	35.760	35.802	35.844	35.873	35.937	35.719
6	35.723	35.760	35.815	35.850	35.873	35.935	35.723
7	35.717	35.752	35.803	35.845	35.876	35.938	35.717
8	35.719	35.759	35.812	35.843	35.875	35.937	35.719
9	35.715	35.760	35.814	35.843	35.881	35.937	35.715
10	35.719	35.767	35.816	35.841	35.873	35.940	35.719
Average	35.719	35.761	35.810	35.843	35.876	35.938	35.719

Table A.4. Measured immersed masses of bob and wire set 1 used in FLiNaK-H density measurements

Measurement Number	Temperature, °C						
	500	550	600	650	700	800	900
1	23.130	23.140	23.164	23.175	23.186	23.248	23.300
2	23.130	23.141	23.162	23.175	23.185	23.251	23.298
3	23.130	23.142	23.161	23.174	23.184	23.250	23.299
4	23.130	23.141	23.161	23.172	23.186	23.250	23.298
5	23.129	23.140	23.162	23.171	23.186	23.250	23.299
6	23.129	23.139	23.162	23.172	23.184	23.250	23.300
7	23.130	23.139	23.161	23.171	23.184	23.250	23.299
8	23.130	23.140	23.163	23.173	23.184	23.254	23.299
9	23.130	23.140	23.163	23.173	23.184	23.253	23.299
10	23.130	23.140	23.163	23.176	23.183	23.253	23.300
Average	23.130	23.140	23.162	23.173	23.185	23.251	23.299

Table A.5. Measured immersed masses of bob and wire set 2 used in FLiNaK-H density measurements

Measurement Number	Temperature, °C						
	500	550	600	650	700	800	900
1	35.574	35.653	35.720	35.782	35.832	35.933	36.014
2	35.573	35.653	35.729	35.780	35.832	35.933	36.016
3	35.574	35.653	35.727	35.777	35.830	35.933	36.019
4	35.573	35.652	35.727	35.778	35.831	35.934	36.018
5	35.575	35.653	35.727	35.779	35.831	35.934	36.014
6	35.575	35.653	35.727	35.777	35.832	35.934	36.016
7	35.576	35.654	35.727	35.778	35.832	35.935	36.016
8	35.573	35.656	35.722	35.778	35.830	35.937	36.017
9	35.575	35.657	35.721	35.779	35.830	35.936	36.017
10	35.575	35.656	35.724	35.778	35.831	35.936	36.018
Average	35.574	35.654	35.725	35.779	35.831	35.935	36.017

Table A.6. Measured immersed masses of bob and wire set 3 used in FLiNaK-H density measurements

Measurement Number	Temperature, °C						
	500	550	600	650	700	800	900
1	23.042	23.050	23.046	23.121	23.147	23.210	23.231
2	23.039	23.052	23.047	23.124	23.147	23.210	23.232
3	23.036	23.051	23.046	23.123	23.144	23.211	23.234
4	23.035	23.053	23.046	23.122	23.145	23.209	23.233
5	23.035	23.051	23.044	23.120	23.150	23.205	23.231
6	23.035	23.050	23.042	23.124	23.149	23.204	23.231
7	23.038	23.048	23.047	23.120	23.148	23.205	23.233
8	23.037	23.050	23.044	23.118	23.146	23.206	23.231
9	23.035	23.050	23.044	23.121	23.147	23.205	23.230
10	23.038	23.051	23.044	23.119	23.151	23.205	23.230
Average	23.037	23.051	23.045	23.121	23.147	23.207	23.232

Table A.7. Measured immersed masses of bob and wire set 4 used in FLiNaK-H density measurements

Measurement Number	Temperature, °C						
	500	550	600	650	700	800	900
1	35.545	35.589	35.631	35.675	35.748	35.864	35.912
2	35.546	35.589	35.631	35.677	35.752	35.866	35.915
3	35.544	35.590	35.636	35.678	35.748	35.862	35.915
4	35.546	35.590	35.639	35.677	35.744	35.867	35.919
5	35.542	35.589	35.637	35.676	35.748	35.863	35.917
6	35.544	35.588	35.630	35.672	35.746	35.869	35.915
7	35.544	35.589	35.632	35.680	35.745	35.869	35.913
8	35.543	35.588	35.631	35.677	35.743	35.867	35.909
9	35.544	35.589	35.634	35.681	35.747	35.869	35.914
10	35.545	35.586	35.632	35.674	35.745	35.861	35.917
Average	35.544	35.589	35.633	35.677	35.747	35.866	35.915

Appendix B: Viscosity Calculations

The diameters and lengths of the spindles and crucibles used in viscosity measurements of silicone reference oil and FLiNaK salts are reported in Tables B.1–B.6. The diameters and lengths of the spindles were measured by using digital calipers and the inner diameters of the crucibles were measured by using a digital bore gauge. The radii of the spindle and crucible were calculated from the average diameters.

Table B.1. Crucible and spindle dimensions used in silicone oil measurements 1 and 2

Measurement Number	Spindle Diameter, mm	Spindle Length, mm	Crucible Inner Diameter, mm
1	19.01	49.99	22.07
2	19.00	49.98	22.06
3	19.00	49.98	22.06
4	19.00	49.98	22.06
5	19.01	–	22.05
6	19.00	–	22.05
Average	19.00	49.98	22.06

Table B.2. Crucible and spindle dimensions used in silicone oil measurements 3 and 4

Measurement Number	Spindle Diameter, mm	Spindle Length, mm	Crucible Inner Diameter, mm
1	19.02	49.98	22.07
2	19.01	50.01	22.09
3	19.01	49.98	22.03
4	19.02	49.99	22.03
5	19.01	–	22.06
6	19.01	–	22.09
Average	19.01	49.99	22.06

Table B.3. Crucible and spindle dimensions used for viscosity calculations of FLiNaK-1

Measurement Number	Spindle Diameter, mm	Spindle Length, mm	Crucible Inner Diameter, mm
1	18.97	49.99	22.03
2	18.96	49.99	22.04
3	18.96	49.99	22.04
4	18.96	49.98	22.04
5	18.97	–	22.04
6	18.96	–	22.04
Average	18.96	49.99	22.04

Table B.4. Crucible and spindle dimensions used for viscosity calculations of FLiNaK-2

Measurement Number	Spindle Diameter, mm	Spindle Length, mm	Crucible Inner Diameter, mm
1	19.01	50.01	22.05
2	19.01	50.02	22.05
3	19.01	50.02	22.03
4	19.01	50.02	22.04
5	19.02	–	22.03
6	19.02	–	22.04
Average	19.01	50.02	22.04

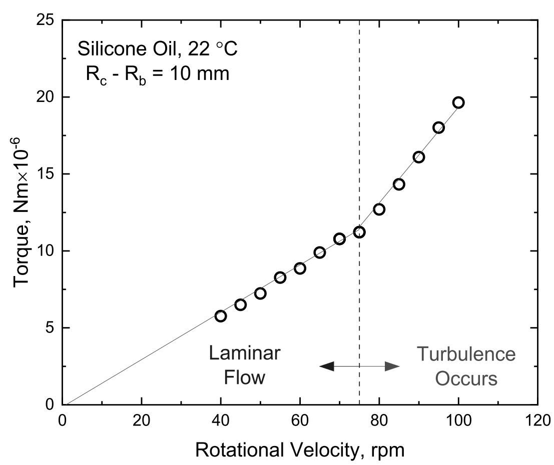
Table B.5. Crucible and spindle dimensions used for viscosity calculations of FLiNaK-L

Measurement Number	Spindle Diameter, mm	Spindle Length, mm	Crucible Inner Diameter, mm
1	19.01	50.01	21.97
2	19.01	50.00	21.99
3	19.01	49.99	21.89
4	19.01	50.01	21.93
5	19.00	–	22.00
6	19.01	–	22.04
Average	19.01	50.00	21.97

Table B.6. Crucible and spindle dimensions used for viscosity calculations of FLiNaK-H

Measurement Number	Spindle Diameter, mm	Spindle Length, mm	Crucible Inner Diameter, mm
1	19.07	50.01	21.95
2	19.07	50.01	21.95
3	19.07	49.99	21.93
4	19.08	50.01	21.93
5	19.07	–	21.93
6	19.08	–	21.94
Average	19.07	50.01	21.94

The effect of crucible and spindle geometry on the rotational flow behavior at different speeds was investigated by performing two series of torque measurements on silicone oil at room temperature in cylindrical crucibles with different inner diameters. The same spindle was used in both series of measurements to create annular regions with different widths. Torque measurements are shown in Figure B.1. The use of high rotational velocities can induce turbulence in wide annular regions, which is manifest as a sharp increase in measured torque. Measurements over a similar range of velocities with a thinner annular region did not show a sharp increase in torque, indicating laminar flow was maintained over the entire range of velocities at which measurements were performed.



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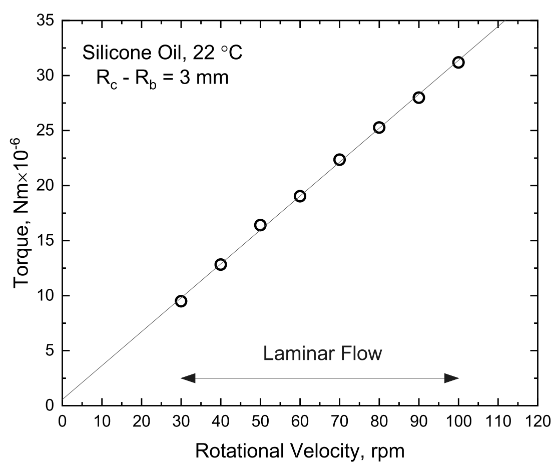
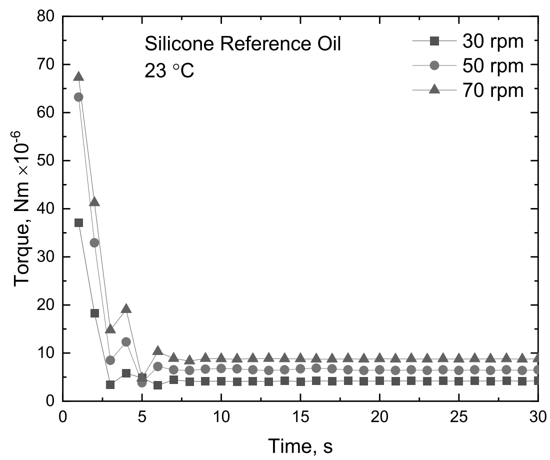


(b)

Figure B.1. Torque measurements of silicone oil performed in different sized crucibles.

Measurements were performed in a silicone reference oil (Cannon Instrument Co., State College, PA) and FLiNaK-L to determine the time required for the rotational flow to fully develop. Torque measurements performed in oil at room temperature and FLiNaK-L at 500 °C are shown in Figures B.1 and B.2, respectively. Measurements indicate that torque values in both fluids stabilize in less than 10 seconds. Based on these findings, torque measurements of reference oil and molten salt were collected 15 seconds after initiating rotation and at 15-second intervals over a two-minute period for a total of eight measurements at each rotational velocity.



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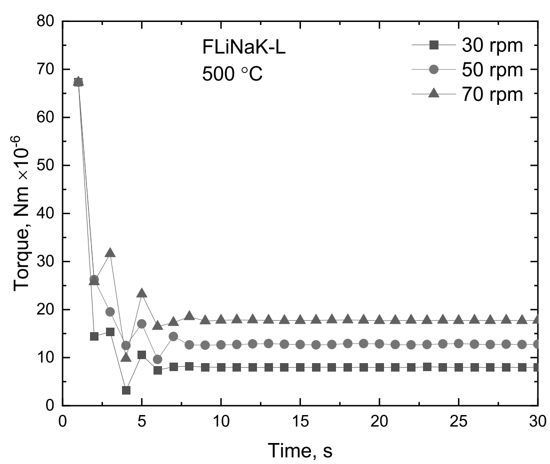

(b)

Figure B.2. Torque values measured over time at three different rotational velocities for silicone reference oil at room temperature (a) and FLiNaK-L at 500 °C (b).

The response of the viscometer was checked prior to measurements of FLiNaK-1, FLiNaK-2, FLiNaK-L and FLiNaK-H (measurements 1, 2, 3, and 4, respectively) by performing measurements on a silicone reference oil over a range of 50–80 rpm. The measured torque and calculated viscosities of silicone reference oil are reported in Tables B.7–B.10.

Table B.7. Torque values and calculated viscosities for silicone reference oil measurement 1

Rotational Velocity, rpm	% Max	Torque, Nm × 10^{-6}	Viscosity, cP
60	11.6	7.8	5.7
55	10.4	7.0	5.5
80	15.1	10.2	5.5
70	13.4	9.0	5.6
50	9.7	6.5	5.7
75	14.2	9.6	5.5
65	12.5	8.4	5.6
70	13.2	7.8	5.7
60	11.5	7.0	5.5
50	9.6	10.2	5.5
		Average	5.6
		Reference	4.8
		Difference	0.8

Table B.8. Torque values and calculated viscosities for silicone reference oil measurement 2

Rotational Velocity, rpm	% Max Torque	Torque, Nm × 10^{-6}	Viscosity, cP
60	11.4	7.7	5.6
55	10.6	7.1	5.6
80	14.7	9.9	5.4
70	13.1	8.8	5.5
50	9.7	6.5	5.7
75	14.0	9.4	5.5
65	12.2	8.2	5.5
70	13.0	8.7	5.4
60	11.4	7.7	5.6
50	9.5	6.4	5.6
		Average	5.5
		Reference	4.8
		Difference	0.7

Table B.9. Torque values and calculated viscosities for silicone reference oil measurement 3

Rotational Velocity, rpm	% Max	Torque, Nm × 10^{-6}	Viscosity, cP
60	11.4	7.7	5.5
55	10.5	7.1	5.6
80	15.2	10.2	5.5
70	13.0	8.7	5.4
50	9.7	6.5	5.7
75	14.0	9.4	5.4
65	12.2	8.2	5.5
70	13.1	8.8	5.5
60	11.3	7.6	5.5
50	9.7	6.5	5.7
		Average	5.5
		Reference	4.8
		Difference	0.7

Table B.10. Torque values and calculated viscosities for silicone reference oil measurement 4

Rotational Velocity, rpm	% Max	Torque, Nm × 10^{-6}	Viscosity, cP
60	10.5	7.1	5.1
55	9.6	6.5	5.1
80	13.0	8.8	4.7
70	11.7	7.9	4.9
50	9.3	6.3	5.4
75	12.4	8.4	4.8
65	11.0	7.4	4.9
70	11.6	7.8	4.8
60	10.2	6.9	4.9
50	8.7	5.9	5.1
		Average	5.0
		Reference	4.8
		Difference	0.2

Measurements of FLiNaK salts with and without fission product dopants were performed at 500, 550, 600, 650, 700, 800, and 900 °C. The torque values measured at each temperature for FLiNaK-1, FLiNaK-2, FLiNaK-L and FLiNaK-H are listed in Tables B.11–B.14, respectively. Data were collected over a range of rotational velocities from 50 to 80 rpm. Results were provided by the instrument as percent maximum torque and torque values were calculated using a maximum torque value of 6.73×10^{-5} Nm (per Brookfield DV2T Operating Manual M13-167-B0614, p. 5). Torque measurements and geometric quantities were used to calculate the viscosity of each salt mixture by using Equation 3. Calculated viscosities are reported in Tables B.15–B.18.

Table B.11. Torque measurements of FLiNaK 1 salt, in Nm $\times 10^{-6}$

Rotational Velocity[a], rpm	Temperature, °C													
	500		550		600		650		700		800		900	
	% Max	Torque	% Max	Torque	% Max	Torque	% Max	Torque	% Max	Torque	% Max	Torque	% Max	Torque
60	20.4	13.7	14.4	9.7	11.1	7.5	8.9	6.0	7.4	5.0	5.8	3.9	4.9	3.3
55	18.8	12.7	13.4	9.0	10.1	6.8	8.2	5.5	6.9	4.6	5.2	3.5	4.3	2.9
80	27.2	18.3	19.1	12.9	14.3	9.6	11.3	7.6	9.5	6.4	7.6	5.1	6.5	4.4
70	23.5	15.8	16.8	11.3	12.8	8.6	10.2	6.9	8.6	5.8	6.7	4.5	5.4	3.6
50	17.0	11.4	12.4	8.3	9.5	6.4	7.6	5.1	6.3	4.2	4.7	3.2	4.0	2.7
75	25.2	17.0	17.8	12	13.6	9.2	10.9	7.3	9.1	6.1	6.8	4.6	5.7	3.8
65	21.9	14.7	15.6	10.5	11.8	7.9	9.5	6.4	8.1	5.5	6.1	4.1	5.1	3.4
70	23.4	15.7	16.7	11.2	12.7	8.5	10.3	6.9	8.7	5.9	6.6	4.4	5.3	3.6
60	20.1	13.5	14.5	9.8	11.0	7.4	8.7	5.9	7.3	4.9	5.5	3.7	4.7	3.2
50	17.0	11.4	12.4	8.3	9.4	6.3	7.5	5.0	6.3	4.2	4.8	3.2	3.9	2.6

[a]Listed in order of measurement.

Table B.12. Torque measurements of FLiNaK 2 salt, in Nm × 10^{-6}

Rotational Velocity[a], rpm	Temperature, °C													
	500		550		600		650		700		800		900	
	% Max	Torque	% Max	Torque	% Max	Torque	% Max	Torque	% Max	Torque	% Max	Torque	% Max	Torque
60	21.0	14.1	15.0	10.1	11.3	7.6	8.7	5.9	7.0	4.7	5.6	3.8	5.0	3.4
55	18.9	12.7	13.9	9.4	10.0	6.7	7.9	5.3	6.8	4.6	5.3	3.6	4.4	3.0
80	26.8	18.0	20.4	13.7	14.4	9.7	11.3	7.6	9.2	6.2	7.4	5.0	6.3	4.2
70	23.5	15.8	18.0	12.1	12.8	8.6	10.3	6.9	8.5	5.7	6.5	4.4	5.5	3.7
50	17.0	11.4	12.6	8.5	9.4	6.3	7.8	5.2	6.3	4.2	4.8	3.2	4.3	2.9
75	25.3	17.0	18.0	12.1	13.3	9.0	11.1	7.5	8.8	5.9	6.8	4.6	6.0	4.0
65	22.0	14.8	16.1	10.8	11.9	8.0	9.5	6.4	8.0	5.4	6.2	4.2	5.4	3.6
70	23.3	15.7	18.1	12.2	12.8	8.6	10.3	6.9	8.5	5.7	6.5	4.4	5.5	3.7
60	20.9	14.1	14.9	10.0	11.1	7.5	8.7	5.9	7.0	4.7	5.7	3.8	4.9	3.3
50	16.9	11.4	12.5	8.4	9.4	6.3	7.9	5.3	6.3	4.2	5.0	3.4	4.4	3.0

[a]Listed in order of measurement.

Table B.13. Torque measurements of FLiNaK-L salt, in Nm × 10^{-6}

Rotational Velocity[a], rpm	Temperature, °C													
	500		550		600		650		700		800		900	
	% Max	Torque	% Max	Torque	% Max	Torque	% Max	Torque	% Max	Torque	% Max	Torque	% Max	Torque
60	23.0	15.5	16.5	11.1	13.2	8.9	10.5	7.1	9.3	6.3	7.6	5.1	6.8	4.6
55	21.8	14.7	15.0	10.1	11.9	8.0	9.9	6.7	8.7	5.9	6.8	4.6	5.7	3.8
80	29.5	19.9	20.7	13.9	16.7	11.2	12.9	8.7	12.5	8.4	9.8	6.6	8.7	5.9
70	26.4	17.8	19.0	12.8	14.2	9.6	11.5	7.7	10.6	7.1	8.5	5.7	7.3	4.9
50	19.0	12.8	14.1	9.5	10.9	7.3	8.3	5.6	7.8	5.2	6.3	4.2	5.4	3.6
75	28.4	19.1	19.9	13.4	15.9	10.7	12.6	8.5	11.2	7.5	9.2	6.2	8.1	5.5
65	25.3	17.0	17.5	11.8	14.1	9.5	11.3	7.6	10.6	7.1	8.1	5.5	7.3	4.9
70	26.8	18.0	18.8	12.7	14.2	9.6	11.5	7.7	10.1	6.8	8.5	5.7	7.0	4.7
60	23.1	15.5	16.6	11.2	13.4	9.0	10.7	7.2	9.2	6.2	7.4	5.0	6.8	4.6
50	19.0	12.8	14.1	9.5	11.2	7.5	8.3	5.6	7.8	5.2	6.4	4.3	5.8	3.9

[a]Listed in order of measurement.

Table B.14. Torque measurements of FLiNaK-H salt, in Nm × 10^{-6}

Rotational Velocity[a], rpm	Temperature, °C													
	500		550		600		650		700		800		900	
	% Max	Torque	% Max	Torque	% Max	Torque	% Max	Torque	% Max	Torque	% Max	Torque	% Max	Torque
60	24.5	16.5	15.5	10.4	12.3	8.3	9.8	6.6	8.2	5.5	6.2	4.2	4.9	3.3
55	22.2	14.9	14.7	9.9	12.2	8.2	9.2	6.2	7.7	5.2	5.8	3.9	4.4	3.0
80	31.7	21.3	21.2	14.3	16.2	10.9	13.2	8.9	11.2	7.5	8.5	5.7	6.4	4.3
70	28.0	18.8	18.8	12.7	14.3	9.6	11.5	7.7	9.8	6.6	7.2	4.8	5.3	3.6
50	20.5	13.8	13.7	9.2	10.3	6.9	8.7	5.9	7.3	4.9	5.2	3.5	4.0	2.7
75	30.2	20.3	20.2	13.6	15.3	10.3	12.5	8.4	10.5	7.1	7.8	5.2	5.8	3.9
65	26.0	17.5	17.8	12.0	13.3	9.0	10.8	7.3	9.2	6.2	6.7	4.5	5.0	3.4
70	27.8	18.7	19.0	12.8	14.7	9.9	11.7	7.9	9.8	6.6	7.0	4.7	5.2	3.5
60	23.7	16.0	16.5	11.1	12.3	8.3	10.2	6.9	8.3	5.6	6.0	4.0	4.5	3.0
50	20.3	13.7	13.8	9.3	10.5	7.1	8.7	5.9	7.3	4.9	5.0	3.4	4.0	2.7

[a]Listed in order of measurement.

Table B.15. Calculated viscosities of FLiNaK 1, in cP

Rotational Velocity, rpm	Temperature, °C						
	500	550	600	650	700	800	900
60	10.1	7.1	5.5	4.4	3.6	2.9	2.4
55	10.1	7.2	5.4	4.4	3.7	2.8	2.3
80	10.1	7.1	5.3	4.2	3.5	2.8	2.4
70	9.9	7.1	5.4	4.3	3.6	2.8	2.3
50	10.1	7.3	5.6	4.5	3.7	2.8	2.4
75	9.9	7.0	5.4	4.3	3.6	2.7	2.2
65	10.0	7.1	5.4	4.3	3.7	2.8	2.3
70	9.9	7.1	5.4	4.4	3.7	2.8	2.2
60	9.9	7.2	5.4	4.3	3.6	2.7	2.3
50	10.1	7.3	5.6	4.4	3.7	2.8	2.3
Average	10.0	7.2	5.4	4.4	3.6	2.8	2.3

Table B.16. Calculated viscosities of FLiNaK 2, in cP

Rotational Velocity, rpm	Temperature, °C						
	500	550	600	650	700	800	900
60	10.1	7.2	5.5	4.2	3.4	2.7	2.4
55	10.0	7.3	5.3	4.2	3.6	2.8	2.3
80	9.7	7.4	5.2	4.1	3.3	2.7	2.3
70	9.7	7.5	5.3	4.3	3.5	2.7	2.3
50	9.9	7.3	5.4	4.5	3.7	2.8	2.5
75	9.8	7.0	5.1	4.3	3.4	2.6	2.3
65	9.8	7.2	5.3	4.2	3.6	2.8	2.4
70	9.6	7.5	5.3	4.3	3.5	2.7	2.3
60	10.1	7.2	5.4	4.2	3.4	2.8	2.4
50	9.8	7.2	5.4	4.6	3.7	2.9	2.6
Average	9.9	7.3	5.3	4.3	3.5	2.8	2.4

Table B.17. Calculated viscosities of FLiNaK-L, in cP

Rotational Velocity, rpm	Temperature, °C						
	500	550	600	650	700	800	900
60	10.9	7.8	6.3	5.0	4.4	3.6	3.2
55	11.3	7.8	6.2	5.1	4.5	3.5	2.9
80	10.5	7.4	5.9	4.6	4.4	3.5	3.1
70	10.7	7.7	5.8	4.7	4.3	3.5	3.0
50	10.8	8.0	6.2	4.7	4.4	3.6	3.1
75	10.8	7.5	6.0	4.8	4.2	3.5	3.1
65	11.1	7.7	6.2	4.9	4.6	3.5	3.2
70	10.9	7.6	5.8	4.7	4.1	3.5	2.8
60	11.0	7.9	6.4	5.1	4.4	3.5	3.2
50	10.8	8.0	6.4	4.7	4.4	3.6	3.3
Average	10.9	7.7	6.1	4.8	4.4	3.5	3.1

Table B.18. Calculated viscosities of FLiNaK-H, in cP

Rotational Velocity, rpm	Temperature, °C						
	500	550	600	650	700	800	900
60	11.2	7.1	5.6	4.5	3.8	2.8	2.2
55	11.1	7.4	6.1	4.6	3.9	2.9	2.2
80	10.9	7.3	5.6	4.5	3.9	2.9	2.2
70	10.9	7.3	5.5	4.5	3.8	2.8	2.1
50	11.3	7.5	5.7	4.8	4.0	2.9	2.2
75	11.1	7.4	5.6	4.6	3.9	2.9	2.1
65	11.0	7.5	5.6	4.6	3.9	2.8	2.1
70	10.9	7.5	5.8	4.6	3.9	2.8	2.0
60	10.9	7.6	5.6	4.7	3.8	2.8	2.1
50	11.2	7.6	5.8	4.8	4.0	2.8	2.2
Average	11.1	7.4	5.7	4.6	3.9	2.8	2.1

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