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Molten Salt Spectroscopy for Quantification of Radiative Absorption in Novel Metal Chloride-Enhanced Thermal Storage Media

This study describes the development and characterization of novel high-temperature thermal storage media, based on inclusion of transition metal chlorides in the potassium–sodium chloride eutectic system, (K–Na)Cl (melting temperature of 657 °C, latent heat of 278 J/g). At the melting temperature of (K–Na)Cl, infrared (IR) radiation can play a major role in the overall heat transfer process—90% of spectral blackbody radiation falls in the range of 2–13 μm. The authors propose inclusion of small amounts (less than 0.2 wt.%) of IR-active transition metal chlorides to increase radiative absorption and thereby enhance heat transfer rates. A new IR-reflectance apparatus was developed to allow for determination of the spectral absorption coefficient of the newly formulated phase-change materials (PCMs) in the molten state. The apparatus consisted of an alumina crucible coated at the bottom with a reflective (platinum) or absorptive (graphite) surface, a heated ceramic crucible-holder, and a combination of zinc sulfide (ZnS) and zinc selenide (ZnSe) windows for containment of the salt and allowance of inert purge gas flow. Using this apparatus, IR spectra were obtained for various transition metal chloride additives in (K–Na)Cl and improved IR activity, and radiative transfer properties were quantified. Further, thermophysical properties relevant to thermal energy storage (i.e., melting temperature and latent heat) are measured for the pure and additive-enhanced thermal storage media. [DOI: 10.1115/1.4029934]

Keywords: molten salt, thermal energy storage, PCM, spectroscopy, radiative heat transfer

Introduction

Molten inorganic salts hold a great deal of promise as high-temperature heat transfer fluids and thermal storage media in renewable energy applications, and they have found use in nuclear and solar thermal power [1,2]. In solar energy conversion, the most widespread use has been made of the nitrate salts—namely, the eutectic of potassium nitrate (KNO₃) and sodium nitrate (NaNO₃), commonly known as “solar salt.” This nitrate eutectic has been used in a variety of parabolic trough—and central receiver—type solar thermal facilities as the storage medium in a two-tank thermal energy storage configuration [2,3].

The next generation of solar thermal plants will likely need higher melting materials for their thermal storage systems. Receivers for use in the solar power tower arrangement have reached temperatures as high as 750, 812, and even 950 °C [4–6]. At these elevated temperatures, salts such as sodium chloride (NaCl), potassium chloride (KCl), and the eutectic (minimum melting) mixture of the two salts [(K–Na)Cl] present themselves as nearly ideal storage media candidates, owing to comparatively low cost, high heats of fusion, and melting temperatures in the range of interest (for NaCl, 800.7 °C, for KCl, 770.9 °C, and for the eutectic, 657 °C; see Table 1) [7–11]. It is likely that, as central receivers in the power tower arrangement achieve higher

operating temperatures, materials such as these may be used as heat transfer fluids (e.g., in a dual tank storage system) or as PCMs. The latter provide the potential for increased energy storage density for limited ranges of operating temperatures owing to characteristically high heats of fusion, and moreover they are desirable due to their consistent energy delivery at design temperature [12].

These salts, however, are typically hampered by relatively low thermal conductivity (less than 1 W/m K in the molten state) [13]. To that end, many conductivity enhancement strategies have been explored. These include addition of greater conductivity materials, either as low concentration dispersed additives or in greater amounts as components of salt-based composites [14,15]. Much work has also been done in the design of the containment—e.g., use of heat pipes or curved slabs to improve conduction and/or convection [16,17].

This study explores a novel heat transfer enhancement strategy for the storage material itself. At the higher temperatures, where these salts would be applied as storage media (>500 °C), radiation becomes a significant mode of heat transfer. It is proposed that inclusion of small amounts of IR-absorptive additives in highly IR-transmissive salts (e.g., alkali metal halides) will allow for greater radiative heat transfer, thereby compensating for characteristically low thermal conductivity.

Determining the degree of improvement requires measurement of the absorption coefficient in the spectral range of interest. Unfortunately, traditional spectroscopic methods are ill-suited for work with molten salts: Direct transmittance measurements overestimate absorption if they do not capture backscattering, and many window materials are prone to corrosive attack by these

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Table 1 Thermophysical properties of eutectic salt and constituent salts

Salt	mol. % (KCl:NaCl)	T_m (°C)	ΔH_{fus} (J/g)	C_p (J/g K)		Density (g/ml)	
				$T = 600^\circ\text{C}$	$T = 700^\circ\text{C}$	$T = 600^\circ\text{C}$	$T = 700^\circ\text{C}$
KCl [7]	100:0	770.9	353		0.858		1.98
NaCl [7]	0:100	800.7	482		1.04		2.16
(K–Na)Cl [8]	50.02:49.98	656.74	306	0.945	1.08	2.08	1.58
[9]	48.5:51.5	657	278	—	—	—	—
[10]	50:50	661	273 ± 8	—	—	—	—
[11]	50:50	658	—	—	—	—	1.58

molten salts [18]. Another strategy to employ would be attenuated total reflectance spectroscopy [19]; but, here again, owing to the close contact between the reflecting prism and liquid, material compatibility renders this method impractical. The authors therefore developed a new IR-reflectance apparatus (Fig. 1) to allow for determination of the spectral absorption coefficient of the newly formulated storage media in the molten state. The apparatus consisted of an alumina crucible coated alternately at the bottom with a reflective (platinum) or absorptive (graphite) surface, a ceramic heating element housing the crucible, and a combination of zinc sulfide (ZnS) and zinc selenide (ZnSe) windows for containment of the salt and allowance of inert purge gas flow, respectively.

This paper specifically addresses the eutectic mixture of potassium and sodium chloride, (K–Na)Cl. Both KCl and NaCl are highly transmissive in the spectral region of 2.0–13.0 micrometers (μm), and it is worth noting that at the melting point of the eutectic (657°C), nearly 90% of spectral blackbody emissive power falls within this region, as given by the Planck distribution [20]. Various transition metal chlorides of known solubility in KCl and/or NaCl were investigated as potential absorptive additives, including cuprous chloride (CuCl), cobaltous chloride (CoCl₂), ferrous chloride (FeCl₂), and nickelous chloride (NiCl₂). Using the reflectance apparatus, IR spectra were obtained for these additives at less than 0.2 weight percent (wt.%) concentration in (K–Na)Cl and improved IR absorption, and radiative transfer properties were demonstrated. Using these spectra, estimations of the absorption coefficient of the additives in the pure salt were

calculated. Further, thermophysical properties relevant to thermal energy storage (i.e., melting temperature and latent heat of fusion) were measured via differential thermal analysis (DTA) for the pure and additive-enhanced PCMs.

Background

A general treatment of the absorptive properties of inorganic salts is given in Modest’s description of the Lorentz model, shown to adequately capture the absorption behavior of ionic crystals [21]. This model predicts that such materials should have one or more absorption bands in the mid- to far-IR (*Reststrahlen* absorption) and several absorption bands near the ultraviolet (electronic excitation)—between these absorptive (opaque) regions, ionic crystals are generally transparent. A discussion of the quantum-mechanical considerations behind absorption and emission of photons in these systems is beyond the scope of this paper; for detailed discussions of this topic the reader is referred elsewhere [22–24].

In speaking of the absorptive properties of these materials and those of KCl and NaCl in particular, it is worthwhile to note the expansive reference work of Touloukian and DeWitt, which collects the radiative properties (reflectance, transmittance, emittance, etc.) of various nonmetallic solids [25]. According to data compiled in this reference, KCl is highly transmissive (transmittance greater than 90%) in the spectral region of 0.4–15.0 μm , for crystals 10–12 mm thick; analogously, NaCl is highly transmissive in the region of 0.4–13.0 μm , for crystals 2.8–6.5 mm thick. Other halides are similarly transmissive over much of the IR including calcium fluoride, which has also been proposed for thermal energy storage applications [26]. It bears mentioning that these measurements were made at or near room temperature; the near- to mid-IR absorption of such crystalline solids, especially if appreciable concentrations of lattice defects or dopants are present within the crystal, can be expected to rise significantly with temperature [21]. (Further information on the radiative properties of materials can be found in other references [27,28], as well as in various textbooks [20,21,29].)

Of course, the high transmissivity of either KCl or NaCl does not guarantee that the mixture of the two will be itself transmissive; indeed, at room temperature, one will notice that the solidified (K–Na)Cl salt is quite opaque to visible radiation, as the cooling solid will self-diffuse to form closely packed lamellae of alternately high concentration KCl and high concentration NaCl phases. Importantly, though, the salt regains its high transmissivity as it heated to elevated temperatures with a consolute point at approximately 500°C [30]. At this point, the salt becomes a homogeneous solid solution which is transparent to visible radiation.

The (K–Na)Cl eutectic has been studied extensively, and a review of pertinent literature yields the properties data relevant to our study here. A collection of these data is compiled in Table 1 with properties of the pure component salts included for reference. The first entry of the table for the eutectic salt was obtained from the thermophysical properties software FACTSAGE [8]; the second entry presents calculated values obtained from analytical formulations of the system’s thermodynamic mixing properties [9]. The

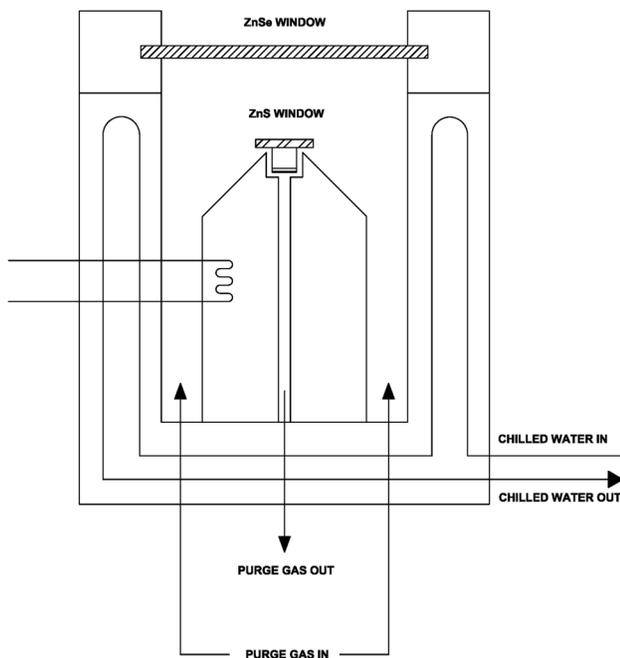


Fig. 1 Molten salt reflectance cell

remaining entries are experimental data. It can be observed there is significant variability in the data. It is hoped that thermophysical properties data collected for this current study will serve to clarify the validity of some of these values. For the purposes of this study, the molar composition of the eutectic was taken as 50.02:49.98 KCl:NaCl and the density of the molten salt was taken as 1.58 g/ml. More detailed discussion of the various studies performed and their assertions concerning the composition and melting point of the (K–Na)Cl eutectic salt can be found in the referenced literature [9,30].

The additives for potential radiative absorption enhancement have been chosen on the basis of two criteria:

- (1) Potential for IR absorption
- (2) Solubility in the molten salt

With regard to the first criterion, previous work has shown the potential for transition metal oxides—namely, Co_3O_4 and CuO —to increase radiative absorption in the ultraviolet, visible, and near-IR regions of the electromagnetic spectrum [31]. Further, studies into the middle and far-IR show broadband absorption for such transition metal oxides [32]. While these materials are no doubt promising for IR absorption, there is an attendant complication to the use of insoluble additives: maintenance of their suspension in the salt. For PCMs especially, which would likely be sequestered in a containment of some kind (e.g., capsule), continuous agitation may be difficult, and such additives may aggregate and settle.

As such, the second criterion, molten salt solubility, was examined critically during the selection process. It was determined that the four additives ultimately selected— CuCl , CoCl_2 , FeCl_2 , and NiCl_2 —were each miscible in KCl and NaCl as binary solutions; indeed, in the case of FeCl_2 , there is strong suggestion that it would form a solid state compound with KCl (double salt), K_2FeCl_4 , which would allow for improved distribution in both the solid and liquid states [33].

To describe the method for determination of absorbance from reflection-absorption spectroscopy, it is worthwhile to discuss the mathematical basis of the analysis. For a single layer of homogeneous molten salt, as one would expect of the chloride systems considered here, the net radiation method gives the following equation for overall reflectance, R , of the layer [34]:

$$R = \frac{\rho_1 + \rho_2(1 - 2\rho_1)\tau^2}{1 - \rho_1\rho_2\tau^2} \quad (1)$$

Also, the transmissivity, τ , of the layer will depend on the path-length and the absorption coefficient, κ , as follows [35]:

$$\tau = e^{-\kappa\delta/\cos\theta_i} \quad (2)$$

Here, δ is the film thickness and θ_i is the angle of incidence of the radiation. For the situation under consideration here, we can reasonably specify the thickness of the layer (using a specific mass and known density) and the angle of incidence (set by the geometry of the reflectance apparatus). Thus, for any single reflectance measurement, there are three unknown quantities:

- (1) The reflectivity at the surface of the salt (i.e., nitrogen–salt interface), ρ_1 .
- (2) The reflectivity at the salt–substrate interface, ρ_2 .
- (3) The absorption coefficient, κ .

In our case, the reflectivity of the salt–substrate interface is measured separately: The reflective substrate (platinum) is measured relative to a silvered mirror. The absorptive substrate (graphite) is taken to have reflectivity of zero. Hence, from measurement of the reflectance of the salt over graphite, we obtain ρ_1 ; given this value and the known value of ρ_2 , measurement of the reflectance of the salt over the platinum value yields the transmissivity of the salt layer. Given the transmissivity of the pure salt and that

of the additive–salt system, the absorption coefficient, κ , of the additive in the pure salt can be calculated directly.

All IR spectra were obtained using a Jasco FTIR-6300 Fourier-transform infrared spectrometer. In this system, a high-intensity ceramic source was used in conjunction with a mercury cadmium telluride detector, effectively limiting the observable spectral range to 7800–650 cm^{-1} (although the range into the far-IR is further limited by the window materials and the salts themselves).

The heated sample chamber was provided by Pike Technologies of Madison, WI. Designed for diffuse reflectance applications, the chamber consists of a heated ceramic sample holder to be used in conjunction with porous alumina crucibles. The heater is capable of reaching 900 °C, and the chamber is cooled by chilled water pumped at a rate of approximately 50 ml/min. The cooling water keeps most of the sample chamber at approximately room temperature, so that, for instance, during emission measurements, background radiation interference is minimized. Using a suitable window (in this case, ZnSe), inert gas purge can be passed through the chamber, with the pores of the alumina crucibles allowing the purge gas to pass directly through the (diffuse) powdered sample.

For work with regular reflectance of molten salts, some additional features were introduced to the sample holder. First, porous alumina pans would not allow for liquid samples; therefore, solid alumina pans were used. However, these pans provide a hindrance to the flow of the inert purge gas. The pans were therefore scored across the bottom in a cross-hatch manner. These grooves allowed purge gas to flow around the sample and beneath the pan to the purge outlet.

Methodology

Important study of the reflectance and optical properties of molten nitrates [36], chlorides [37], and carbonates [38] was undertaken by Makino et al., and a thorough description of their apparatus has been given in Ref. [36]. The basic strategy of this paper's measurement of radiative properties is similar: Regular reflection is measured of molten salt over a reflecting background. However, our study adds the step of performing a separate measurement over black background to elucidate the absorption coefficient.

It was found that for high vapor pressure salts (notably, metal halides), evaporated salt would condense upon and outermost ZnSe window and severely degrade it. Therefore, a second additional feature was introduced: A salt containment window to be placed directly over the sample crucible such that significant amounts of salt vapor would not be allowed to escape. A variety of materials were tested for this purpose; their properties have been presented elsewhere, and these data are presented in Table 2 [39]. KCl, NaCl, potassium bromide (KBr), and calcium fluoride (CaF_2) are all promising as window materials, but they are prone to ion exchange with the evolved salt vapors tested here. Hence, they would only serve for one use. (It is possible that these materials could be used as pressed powders, significantly reducing the cost of the window material; the authors are currently exploring this option.) Also, ZnSe, too, showed a high susceptibility to attack by the salts and also by the high temperatures alone. ZnS

Table 2 Window materials considered for molten salt study

Window material	Transmissive range (cm^{-1}) [39]	Transmissive range (μm)
CaF_2	25,000–800	0.40–12.5
KBr	40,000–200	0.25–50
KCl	47,600–300	0.210–33
NaCl	47,600–400	0.210–25
ZnS	10,000–700	1.0–14
ZnSe	22,200–500	0.45–20

alone showed the desired resistance to degradation upon multiple uses. While the transmissive range of ZnS crystals is smaller than some of the other materials, it should cover the spectral range relevant here—namely, 2.0–13.0 μm , in which 90% of blackbody emissive power at 657 °C is captured. (CaF₂, on the other hand, would cut off this range on longer wavelength side.) A schematic of the dual-window reflectance cell is shown in Fig. 1.

To determine the reflectivity of the platinum backing, it was insufficient to make a simple regular reflectance measurement at room temperature. Rather, the emissivity of the backing was measured against a blackbody radiator with both sources heated to 680 °C. Upon measuring the spectral emissivity, the spectral reflectivity for the opaque surface is easily obtained via the well-known Kirchhoff relations

$$\rho_\lambda = 1 - \varepsilon_\lambda \quad (3)$$

It should be emphasized that the relation above is accurate for spectral quantities—e.g., owing to spectral variability of radiative properties, the same relation does not apply to total reflectivity and emissivity. Also, strictly speaking, this yields the normal incidence spectral reflectivity; due to the relatively small angles of incidence considered here, no correction shall be applied for any directional variation in the following analyses. The blackbody reference used was an IR-563/301 manufactured by Infrared Systems Development Corporation of Winter Park, FL.

DTA measurements were performed using a TA Instruments SDT-Q600 TGA/DSC. A three-point calibration of the instrument was performed using high purity tin, zinc, and sodium fluoride as calibrants. The cell constant (latent heat) was calibrated using high purity zinc. Samples were placed in platinum pans to prevent the creeping of salt samples during melting and solidification. In each case, samples were melted twice; the second run (after formation of the binary/ternary system) was used to obtain thermophysical properties. Multiple samples for each material were tested, and averaged values were obtained. All measurements were made under argon purge flow at a heating rate of 10 °C/min.

A novel method was applied to prepare samples for study. Given the potential for the additives to solid solutions or double salts with bulk NaCl and/or KCl, the following strategy was employed:

- (1) Additives were mixed at a concentration of 0.4 wt.% in agate mortar with spectroscopic-grade NaCl in a glovebox under inert gas.
- (2) The mixtures were heated to approximately 250 °C for 24 hr in the glovebox to encourage formation of solid solutions.
- (3) The heated mixtures were then mixed in agate mortar with the required quantity of KCl (99.997% purity, metals basis) [8]. The resultant mixtures were approximately 0.18 wt.% additive.
- (4) Throughout the following analyses they were kept in a vacuum desiccator or drying oven kept at 110 °C.

These moisture control steps were important, since three of the four additives considered (excepting CuCl) are known to be very hygroscopic. The concentrations of the salt systems studied are shown in Table 3.

Table 3 Additive concentrations in pure (K–Na)Cl

Additive	wt. %	mol. %
CoCl ₂	0.176	0.0986
CuCl	0.176	0.125
FeCl ₂	0.176	0.101
NiCl ₂	0.176	0.0988

Results and Discussion

The measured reflectance of the platinum substrate is shown in Fig. 2. The reflectivity is comparatively high, and so will serve the purpose of providing a reflective background to the semitransparent molten salts.

Next, the salts' spectra were measured. Upon heating, it was observed that the characteristic spectra of the loose powder samples changed dramatically upon melting, thus making it a simple matter to determine when to collect the spectra. That said, the general procedure involved heating the sample/background to approximately 680 °C, which ensures the melting would take place rapidly. Spectra were collected as soon as the melt had occurred, which could be verified by visual examination of the sample.

In Fig. 3(a), the spectra obtained for the pure eutectic salt are presented—namely, the reflectance of the overall system (R), the reflectivity of the salt–nitrogen interface (ρ_1), and the calculated transmissivity (τ) from the net radiation method [34]. (The reflectivity of the platinum substrate, ρ_2 , is illustrated in Fig. 2.) Similar spectra are obtained for each of the salt–additive systems, and these are depicted in Fig. 3(b).

Given the transmissivity of the salt systems, it is possible to make an estimation of the absorption coefficient of the additive materials in the pure eutectic salt. For these calculations, the density of the salt is assumed unchanged upon addition of the small concentration (~0.18 wt.%) of additive—i.e., the film thickness, δ , is assumed to be constant in each case. The angle of incidence for the geometry considered here is approximately 30.6 deg. The calculated absorption coefficients for each additive–salt system are presented in Fig. 4. Note that these measurements show absorption relative to the pure fused eutectic salt (e.g., see Fig. 3(a)), which itself was found to have a transmissivity of approximately 0.9.

The spectra obtained agree qualitatively with expected behavior: The pure eutectic appears mostly transparent. Inclusion of the additives results in a marked decrease in the measured reflectance, especially in the case of FeCl₂. From the calculated absorption coefficients, it is clear that the additives increase IR absorption, and therefore they are promising candidates for heat transfer enhancing additives. One exception is the case of NiCl₂ at wavelengths greater than 12 μm . Here, the absorption coefficient is approximately zero, and it is likely that the additive has no effect on the absorption of the pure eutectic in this region. It is also prudent to note here that the FeCl₂ measurement was complicated by the formations of oxides, which likely exaggerated the degree of attenuation in this case. This was the only sample that displayed any evidence of oxide formation—it is possible that the other additives are less prone to this issue, although it may simply have been an error of the experimental apparatus (e.g., greater infiltration of oxygen or moisture into the reflection cell). Further

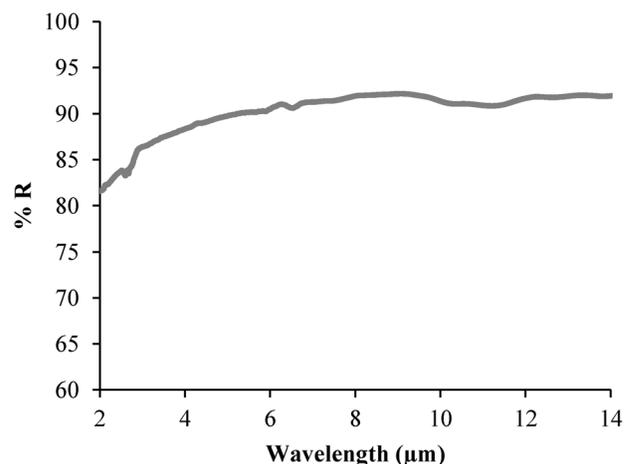


Fig. 2 Measured reflectivity of platinum substrate

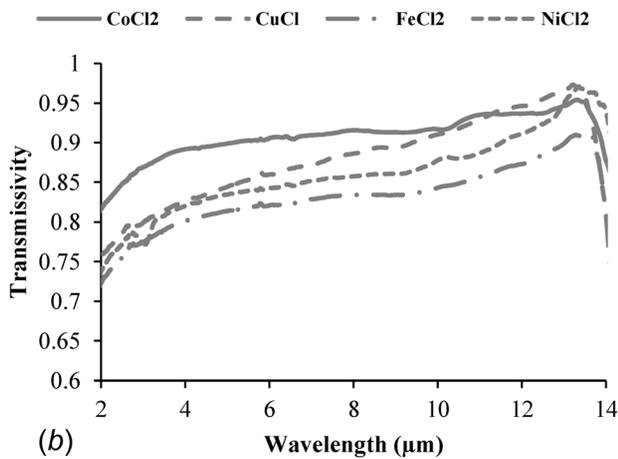
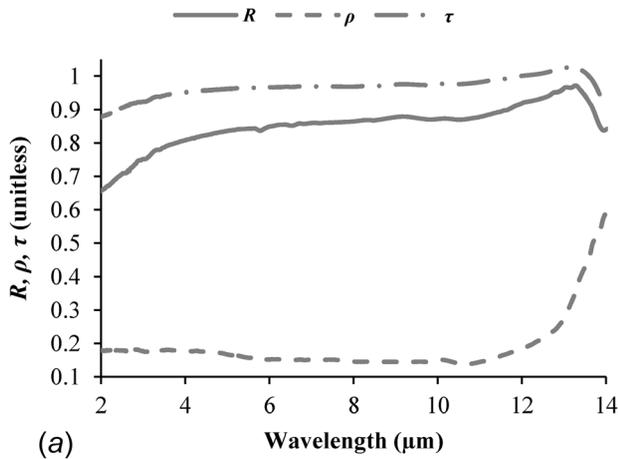


Fig. 3 Spectra for transmissivity determination of pure (K-Na)Cl (a) and calculated transmissivity for the additive-salt systems (b)

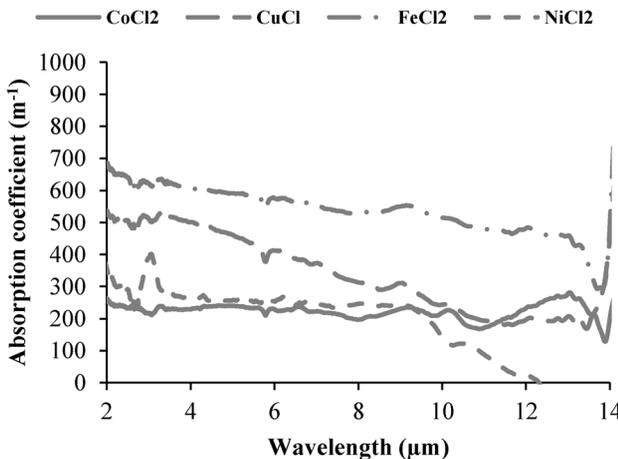


Fig. 4 Absorption coefficients of additives in (K-Na)Cl

measurements are planned, which will take care to void the sample chamber of oxygen/moisture prior to measurement. In any event, this behavior deserves consideration if these materials are to be employed in larger-scale thermal energy storage units. Oxidation of the material can be avoided, for instance, through atmospheric control, use of a preferential oxidizer (i.e., getter), etc.

The thermophysical properties measured by DTA are presented in Table 4. As can be seen, the heat of fusion and melting point for the pure eutectic system agree well with literature values [9]. Note that while the melting temperatures of the additive-enhanced materials are slightly lower than that of the pure salt (as one would expect by inclusion of a solute), the latent heat of fusion, of primary importance for PCM storage media, seems little impacted. Indeed, in the case of the divalent additives especially, there is an apparent increase in latent heat, although this increase lies well within the error of measurement. It is not unreasonable that latent heat would increase upon addition of small amounts of soluble additive, and this phenomenon is observed in the NaCl-KCl system. Addition of small amounts of KCl to pure NaCl increases the latent heat of fusion, most likely because the presence of the larger impurity potassium ions creates regions of stress that attract and “pin” the moving lattice vacancies required for phase change (i.e., more energy required for melting) [10]. Of course, at higher concentrations, the competing effect of weakening the lattice causes the latent heat to decrease (i.e., less energy required for melting). From the available data, though, it seems that the latent heat is approximately unchanged upon addition of the additive. The melting point, also, is little changed by addition of additives, with the highest melting point depression, approximately 1.0 °C, occurring in the CuCl-(K-Na)Cl system. In either case, the additive does not significantly impact the performance of the PCM as a thermal energy storage medium.

Conclusions/Future Work

An IR-reflectance apparatus was developed for testing the radiative absorption of novel inorganic salt thermal storage media in the molten state. The method of collection of the overall layer-substrate reflectance and the salt surface reflectivity by means of two different substrate materials (platinum and graphite) has been demonstrated. The inclusion of transition metal chloride additives shows distinct increases in absorption in the IR, with only slight impacts on melting temperature and latent heat of fusion.

Further work currently underway includes the collection of spectra from additional samples to determine the error in measurement method, as well as from different concentrations to estimate the concentration dependence of radiative absorption. Part of this study includes working with thinner windows made of pressed halide powders; as mentioned above, these materials would be good for only one use, but they may prove a good choice due to their significantly lower cost, relative to polished crystal optics. It would also be prudent to test the results obtained here with a method based on the emissivity of the substrate/salt system, as has been described by Makino [40]. Such efforts are currently underway. Also, the specific heat capacity of these systems is being measured in the solid and, if possible, molten states. It is not anticipated, however, that such small concentrations of additives will have a significant impact on this property of the salt.

Radiative transfer in thermal energy storage systems is valuable area of research, in light of the fact that radiation can play a major role in heat transfer in the next generation of high-temperature thermal energy storage. Spectroscopy, whether through transmission, reflection, or emission measurements, is a direct means of

Table 4 Measured thermophysical properties for pure salt and additive-salt systems selected literature data

Salt	T_m (°C)		ΔH_{fus} (J/g)	
	Our work	Literature [11]	Our work	Literature [10]
(K-Na)Cl	657.2 ± 0.2	658	282 ± 16	273 ± 8
+0.18 wt.% CoCl ₂	656.5 ± 1.1		290 ± 15	
+0.18 wt.% CuCl	656.2 ± 0.2		283 ± 6	
+0.18 wt.% FeCl ₂	656.8 ± 0.2		293 ± 27	
+0.18 wt.% NiCl ₂	656.5 ± 1.2		295 ± 14	

characterizing the radiative properties of materials needed in these systems. It is hoped that this paper will encourage further work in the field of radiative properties measurement in general and molten salt spectroscopy in particular.

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Nomenclature

- C_p = specific heat capacity
 (K–Na)Cl = potassium–sodium chloride eutectic salt
 R = overall reflectance
 T = temperature
 T_m = Reynolds number and similar abbreviations do not use italics
 δ = layer thickness
 ΔH_{fus} = latent heat of fusion
 ε_λ = spectral emissivity
 θ_1 = angle of incidence
 κ = absorption coefficient
 ρ_λ = spectral reflectivity
 ρ_1 = reflectivity of first interface
 ρ_2 = reflectivity of second interface
 τ = transmissivity of the layer

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