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A cost comparison of two binary eutectics

for use as PCMs in solar thermal latent heat energy storage

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As the cost of latent heat energy storage systems depend greatly on the cost of the container, a systematic method is developed to equitably compare eutectic salt mixtures with different properties. This method is applied to the binary eutectic systems "NaCl + Na_2CO_3" and "NaCl + Na_2SO_4" which are simultaneously being investigated for corrosion performance.

A previously published analytic solution for the solidification time of a phase change material (PCM) is used in conjunction with the Sunshot target of six hour charge/discharge to minimize the cost of the containment solution. This solution is valid for tube and fin or tube and shell based heat exchangers, and for the range of properties likely to be encountered when comparing salts for high temperature latent heat storage. The combined cost of the container and the salt is compared.

Theory:

An analytic equation for the melting time of a PCM in a tube and fin or tube and shell based containment is used to form the constraint for the time of the entire PCM to melt.

To determine how the melting proceeds through the heat exchanger, we discretise the length "*L*" of the tube into discrete elements with size "*Δx*." Thus for each position there is a unique time of melting. For each position, we can determine the heat flow from the HTF into the PCM:

$$\frac{d\Delta T(x)}{dx} = \frac{((R+l)^2 - R^2)\pi\rho_s\Delta H}{t_m(x)}$$

We can utilize the results from Bauer[1]† to find the time of melting ($t_m(x)$). Because the time of melting depends on the difference in temperature between the HTF and the PCM ($\Delta T(x)$), we can find the solution to the above differential equation:

$$t_m(x,0) = a \cdot e^{bx}$$

This solution is valid only for the initial time. After the first element *Δx* melts, the temperature differential between the PCM and the HTF will begin to move. We can solve for this movement to find that the time for the entire PCM to melt (*Melt*), across the length of tube is given by:

$$a = \frac{\Delta H_e \rho_e \ell^2}{2\lambda_e \Delta T_0} \cdot CF \cdot NEF$$

$$b = \frac{2((R+\ell)^2 - R^2)\lambda_e}{\ell^2 r^2 c_p^{HTF} \cdot \rho^{HTF} \cdot v^{HTF} \cdot CF \cdot NEF}$$

$$Melt(L) = a \cdot b \cdot L + a$$

These results assume that the PCM starts as a solid at the melting point, and that the contribution of the specific heat is negligible. To minimize the cost of the containment solution, the melting time is used as a constraint. In addition, Barlow's formula is used to provide a minimum tube thickness. The objective function is given by:

$$Cost = \frac{v_f \rho_f S}{\Delta H \rho_s v_s} P_f + \Big(NL\pi(R^2 - r^2) + 2Co \cdot L\pi(R+\ell)N^{0.5} + 2Co \cdot \pi N(R+\ell)^2\Big) \cdot P_m + \rho_m \frac{S}{\Delta H} P_{PCM}$$

where *S* is the total stored energy and *Co* is the corrosion allowance in the tube walls. The objective function for finless geometries is given by:

$$Cost = \big(N \cdot L\pi(R^2 - r^2) + 2Co \cdot L\pi(R+\ell)N^{0.5} + 2Co \cdot \pi N(R+\ell)^2\big) \cdot P_m + \rho_m \frac{S}{\Delta H} Price_{PCM}$$

$$t_m = NEF * CF * t_w$$

$$NEF = 0.8\left(\frac{l}{R}\right)^{1/4}\left(\frac{w_s}{l}\right)^2 \frac{v_f\lambda_f}{v_s\lambda_s} + 1$$

$$CF = \ln\left(\frac{l}{R}+1\right)\left(\frac{R}{l}+1\right)^2 - \left(\frac{1}{2}+\frac{R}{l}\right)$$

$$t_w = \frac{\Delta H_e \rho_e l^2}{2\lambda_e \Delta T}$$

$$\rho_e = v_s\rho_s + v_f\rho_f$$

$$\Delta H_e = \Delta H \frac{v_s\rho_s}{\rho_e}$$

$$\lambda_e = v_s\lambda_s + v_f\lambda_f$$

†Where ℓ is the depth of PCM, *R* is the outer radius of the tube, w_s is the half pitch of PCM, v_f is the volume fraction of fins, v_s is the volume fraction of PCM, *λ* is the thermal conductivity, *ΔH* is the latent heat, *ρ* is the density, and *ΔT* is the temperature difference between the HTF and the PCM

PCM Properties and Prices

PCM	Melting Temperature	Thermal Conductivity	Latent Heat	Density	Salt Cost
(mol%)	(°C)	(W/mK)	(kJ/kg)	(kg/m^3)	(USD/kg)
NaCl (55.3) Na_2CO_3(44.7)	632	0.599	283	1898	0.22
NaCl (53.3) Na_2SO_4(46.7)	626	0.49	266	2010	0.11

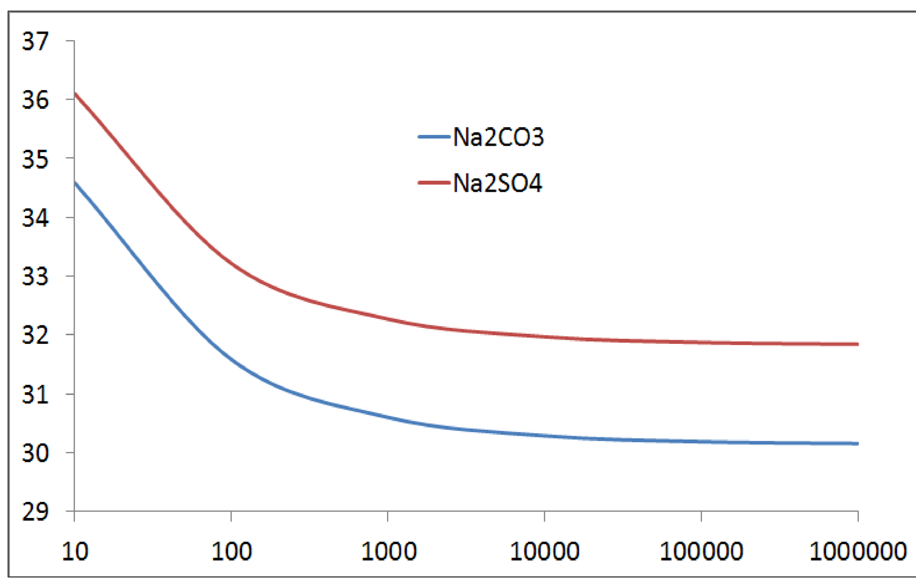

Figure 1: Cost per kWh as a function of total stored energy in the tube and shell geometry. The containment material is Inconel 601.

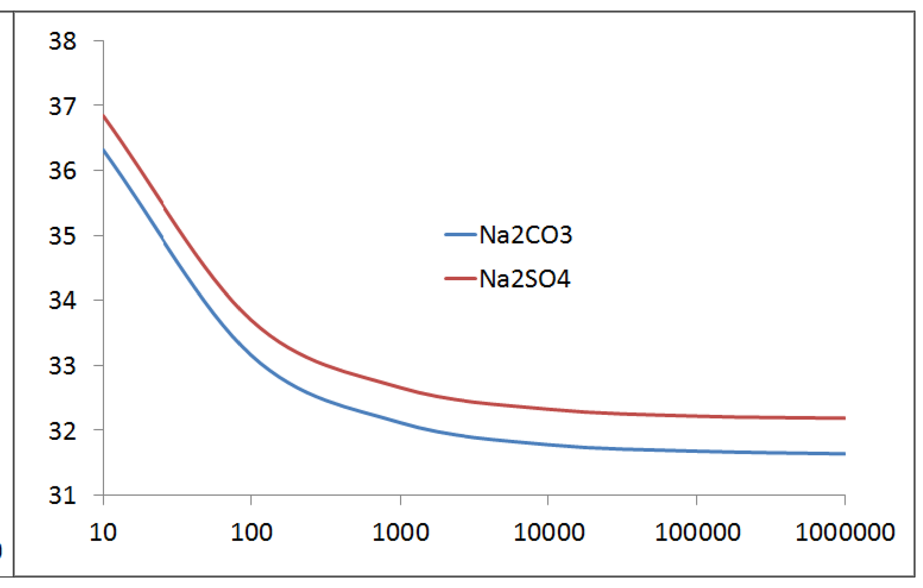

Figure 2: Cost per kWh as a function of total stored energy in the tube and fin geometry, with Inconel 601 tube and fins.

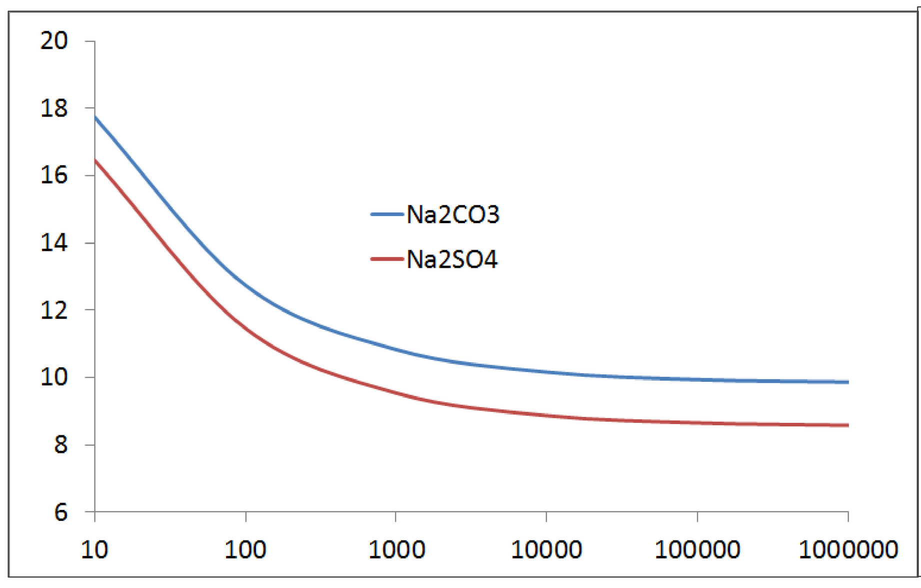

Figure 3: Cost per kWh as a function of total stored energy in the tube and fin geometry, with aluminum fins.

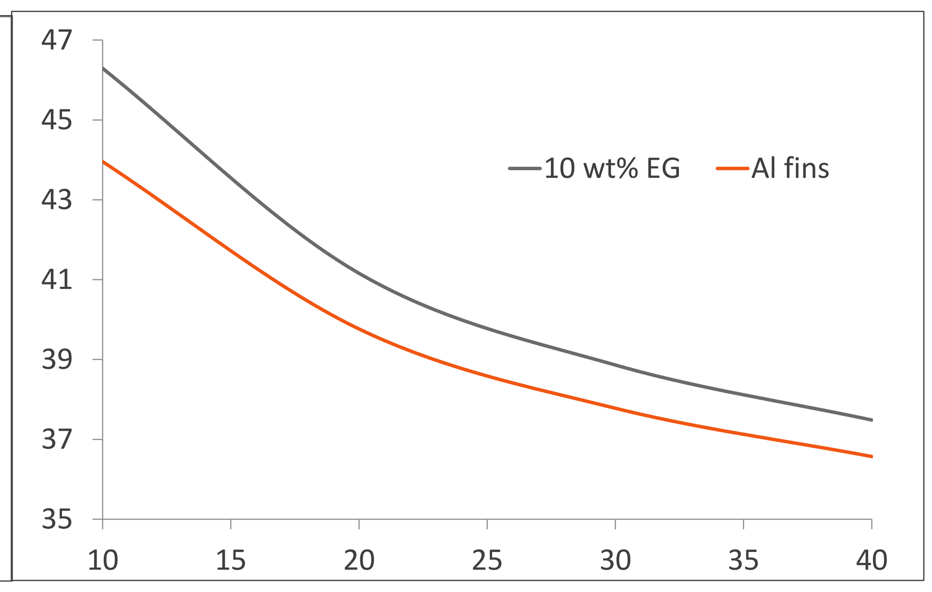

Figure 4: Cost per kWh as a function of input temperature differential for a nitrate PCM with aluminum fins or tube in shell geometry and expanded graphite (EG) thermal conductivity enhancement.

Analysis:

As shown in Fig. 1, the more expensive PCM outperforms the cheaper PCM by nearly 10%, despite having a cost twice as large. However, this difference in performance becomes negligible in the tube and fin geometry (Fig. 2) if the tube and fin share the same material. Finally, according to Fig. 3, the cheaper PCM outperforms the more expensive one when aluminum fins are utilized. This demonstrates clearly that for relatively similar energy densities, the thermal conductivity has a very large effect on the total cost.

Fig. 4 outlines the cost effectiveness of thermal conductivity enhancement. In this figure, a nitrate PCM is compared to the same PCM with the addition of expanded graphite as an agent to improve the thermal conductivity. Inconel 601 is still used as the containment material, however, the PCM without the expanded graphite is used in an aluminum fin and Inconel tube geometry. The EG PCM is used in a tube and shell geometry. The cost of the EG is assumed to be the same as the cost of the PCM. This analysis clearly shows that despite the EG increasing the thermal conductivity by 530%, aluminum fins provide superior performance for the cost. This same conclusion continues for any combination of discharge time, HTF temperature, or total storage size.

Conclusions:

The relationship between the cost and properties of the eutectic are elaborated on for two eutectic salts. For tube and shell geometries, the higher cost eutectic outperforms the lower cost eutectic. This is also true for tube and fin geometries where the tube and fin are the same material. However, with low cost enhancement of the thermal conductivity achieved via aluminum fins, the lower cost eutectic outperforms the higher cost eutectic, as expected.

Future Work:

We will expand this analytic method in order to better account for degradation and corrosion which has been informed by experimental results. In addition, a large array of possible salt combinations will be analysed to determine the most cost effective salt and containment material combination.

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REFERENCES

[1]Thomas Bauer. Approximate analytical solutions for the solidification of PCMs in tube and geometries using effective thermophysical properties. International Journal of Heat and Mass Transfer, 54(23-24),2011.

[2]Murat M Kenisarin. High-temperature phase change materials for thermal energy storage. Renewable and Sustainable Energy Reviews, 14(3):955{970, 2010.

[3]G.J. Janz. Thermodynamic and transport properties of molten salts: Correlation equations for critically evaluated density, surface tension,electrical conductance, and viscosity data. j phys chem ref data, 17,1988.

[4]G.J. Janz, C.B. Alen, N.P. Bansal, R.M. Murphy, and R.P.T. Tomkins. Physical properties data compilations relevant to energy storage ii. molten salts: Data on single and multi-component systems. NRSDSNBS 61, 1979.

[5]E.R. Van Artsdalen and I.S. Yae. Electrical conductance and density of molten salt systems: Kcl-licl, kcl-nacl and kcl-ki. j phys chem, 59:118, 1955.

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