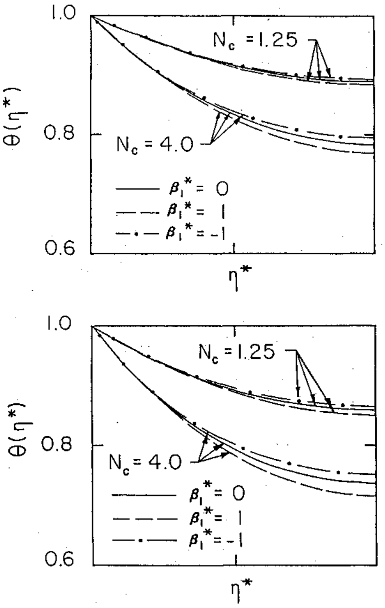

Fig. 3 Dimensionless temperature distribution in a fin when $\tau = 0.25$, $\epsilon = 0.75$, $M_{\max} = 1$: a) $\gamma = 60$ deg; b) $\gamma = 120$ deg.

temperature distribution in a fin at two distinct γ. For the sake of clarity, the constant thermal conductivity case has been omitted (this curve would lie within the envelope formed by the $+\beta_1^*$ or $-\beta_1^*$ curves). The thermal behavior depicted by this figure is in line with physical expectations (note the choice of the reference temperature when reviewing this figure). A positive β_1^* tends to lower the temperature, whereas a negative β_1^* has the opposite effect.

Conclusions

The analytic-numeric method used in this Note indicates that complex integro-differential equations of the type that appear in conductive-radiative heat transfer can be recast into a pure integral form that allows an accurate, rapid, and stable computational method to be devised.

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Thermal Conductivity Enhancement of Solid-Solid Phase-Change Materials for Thermal Storage

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Introduction

HIGH cell temperatures are seen as the primary safety problem for the Li-BCX battery, which has been used as the electrical supply source for the astronauts' space suit. The exothermic heat from the chemical reactions could raise the temperature of the lithium electrode above lithium's melting point (179°C), resulting in destruction of the battery pack and burn danger to the astronaut. Also, high temperature causes the cell efficiency to decrease.[1] This study was initiated to investigate a thermal storage system in which the batteries would be packed in solid-solid phase-change materials to ensure lower battery cell temperature.

Thermal energy storage in various materials can be categorized by systems which either depend on sensible heat accumulation or materials which undergo a primary (or latent) phase change within the temperature range of operation.[2] Those systems which depend on sensible heat typically require larger quantities of working materials, due to the relatively small heat capacity of these materials compared with the latent heat associated with phase transformation. This larger heat capacity generally results in a mass reduction that can be especially important in space-related applications.

Phase-change materials for thermal energy storage are typically salt hydrates or paraffins that absorb large amounts of heat as they melt. Certain molecular crystals undergo solid-state crystal transformations that absorb heat sufficient enough that they may also be used for practical heat storage applications. The advantages of solid-solid phase transformation are that a liquid phase need not be contained, segregation of components is less likely, and stable composites may be fabricated in which the solid-solid phase-change material is dispersed.

Pentaglycerine ($C_5H_{12}O_3$), PG, and neopentyl glycol ($C_5H_{12}O_2$), NPG, exhibit crystalline transformations that reversibly absorb large amounts of energy.[3] These compounds are of potential use in thermal energy storage components and

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systems where the fact that they remain solid throughout the temperature range of application reduces the need for containment.

Objective

The thermal conductivity values of the solid-solid phase-change materials mentioned above are low in both solid phases. Thus, while the material stores thermal energy well, it takes a long time and/or large temperature difference to get the heat to transfer into or through the phase-change materials. Methods to enhance thermal conductivity were investigated by the following approaches: 1) mixing in high thermal conductivity additives, and 2) use of a metal matrix.

Both the neopentyl glycol and pentaglycerine have a sublimation problem in vacuum conditions. At this time, it is felt that only by encapsulating these phase-change materials can this sublimation problem be avoided.

Thermal Conductivity

The thermal conductivities of the phase-change materials were measured using the heated probe technique.[4] In the heated probe method, which may be considered a variant of the line source method, the line source and temperature sensor are combined in one small diameter probe. This probe consists of a stainless steel tube, inside of which there is an axial constantan electrical resistance wire, insulated over its length and grounded to the tube at the lower end. An electrical current can be passed through this wire to provide a heat source of constant strength. The lower end of the tube is closed by a pointed plug. The resistor leads are taken out through a seal at the upper end. Within the tube and near the center of its length, the tips of the thermocouples are located. The thermocouples are connected to a cold-junction compensated data acquisition board. The thermocouple leads are also taken out through the seal at the upper end of the tube. Figure 1 diagrammatically shows the arrangement of the heater and thermocouples in the measuring circuit.

It should be noted that the reported values of solid-solid phase-change materials' thermal conductivity have not been consistent. For example, a major manufacturer of neopentyl glycol reports the thermal conductivity as 0.298 W/m-K (at 25.5°C).[5] A laboratory contracted by this same manufacturer reports the flake material neopentyl glycol thermal conductivity as around 0.11 W/m-K and the solid material around 0.10.[6] This latter value for the solid material was reported as "...contrary to our expectations and we are not sure of the reason for this." The thermal conductivity for neopentyl glycol at 25°C was found in this study to be 0.24 W/m-K (±10%).

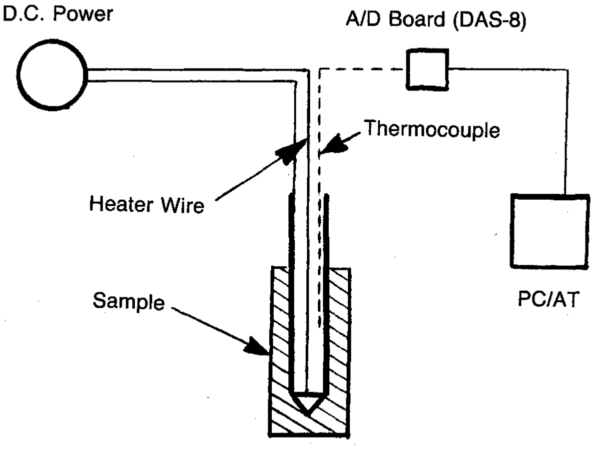

Fig. 1 Schematic of heated probe setup.

Enhancement by Mixing Approach

The results of thermal conductivity measurements on neopentyl glycol and pentaglycerine with and without additives—such as sodium sulfate decahydrate ($Na_2SO_4 10H_2O$), SSD, and magnesium chloride hexahydrate ($MgCl_2$ $6H_2O$), MCH—are summarized in the upper part of Table 1. Magnesium chloride hexahydrate and sodium sulfate decahydrate were selected as candidate additives to the solid-solid phase-change materials because of their relatively high thermal conductivities and compatibility as a storage material.

Results indicate that mixing additives with base material neopentyl glycol can increase thermal conductivity up to 2.3 times that of neopentyl glycol alone. However, for thermal conductivity enhancement by mixing, the additive approach seemed to have severe restrictions. Because of the incongruent melting behavior of these additives when mixed with the neopentyl glycol and pentaglycerine, deterioration of the isothermal phase-change characteristics of the solid-solid phase-change materials was observed.

Enhancement by Metal Matrix Approach

Previous investigations have included analyzing the effect of dispersing high conductivity particles within a low conductivity material to enhance thermal conductivity.[7] However, this approach leads to only modest increases in thermal conductivity at practical inclusion particle volume fractions. The present study approach is to use a matrix of continuously connected solid metal, which would allow high conductivity "heat transfer paths" to exist within the solid-solid phase-change material.

Aluminum foam is manufactured by directional solidification of aluminum alloy from a super-heated liquid state in an environment of inerts and vacuum. The resulting material has a reticulated structure of open dusdecahedronal-shaped cells connected by continuous solid-metal ligaments. In this study, two aluminum foam matrix densities were used which were 7% and 14% relative to the density of solid aluminum.

The aluminum foam does not undergo any chemical changes within the range of battery operation temperatures (25°C–70°C) while providing the high thermal conductivity. By entrapping solid-solid phase-change materials in the pores of this aluminum foam, these phase-change materials and aluminum foam together provide a high thermal conductivity material while leaving the phase-change characteristics unchanged. The lower part of Table 1 shows the results of thermal conductivity measurements, using the aluminum foam and neopentyl glycol combination. Notice that the composite thermal conductivity is improved by a magnitude of 30–60 times. The thermal conductivity of solid aluminum was measured using the probe, and the measured value verified that the probe use with high conductivity materials was appropriate.

Table 1 Thermal conductivity measurements

Materials	Description/ mixture	Measured conductivity, W/m-K[a]
Solid-solid PCM		
NPG	100%	0.24
PG	100%	0.36
Solid-liquid PCM		
MCH	100%	0.62
SSD	100%	0.57
Mixtures		
NPG-PG	10–90%	0.28–0.32
NPG-SSD	10–30%	0.48–0.52
NPG-MCH	10–30%	0.51–0.55
PG-SSD	10–30%	0.49–0.53
PG-MCH	10–30%	0.50–0.59
Matrix/PCM		
Aluminum-NPG	7% density	7.11
Aluminum-NPG	14% density	14.77

[a]Measurement uncertainty of ±10%.

Table 2 PCM property values[a]

Materials	Transition temperature,[1] K	Transition enthalpy,[2] KJ/Kg	Specific heat,[3] KJ/Kg-K
Solid-solid			
NPG	321	119	2.7
PG	355	139	2.8
Solid-liquid			
MCH	390	169	2.3
SSD	304	186	3.1
Mixtures (molar ratio)			
NPG-MCH (7:3)	316	87	1.5
NPG-MCH (9:1)	315	101	2.1
NPG-SSD (7:3)	362	56	0.2
NPG-SSD (9:1)	313	108	1.4
PG-MCH (7:3)	358	56	1.0
PG-MCH (9:1)	358	67	—
PG-SSD (7:3)	343	260	0.7
PG-SSD (9:1)	360	241	2.0

[a]Measurement uncertainty of 1) ±1 K; 2) ±1 KJ/Kg; 3) ±10%.

Phase-Change Property Determinations

A Perkin-Elmer differential scanning calorimeter DCS-2 was used to measure the transition temperature, enthalpies of transformation, and heat capacities of the subject phase-change materials. Thermal analysis samples consisted of carefully weighed portions of the finely powdered compounds. Mixtures were prepared by grinding together gram-size portions of the components and then extracting milligram-size samples for analysis. Table 2 shows the results of DSC measurements for phase-change characteristics of neopentyl glycol and pentaglycerine with mixing of additives.

Mixing neopentyl glycol with magnesium chloride hexahydrate lowers both enthalpy of transformation and specific heat; again, incongruent melting behavior of magnesium chloride hexahydrate deteriorates the solid-state transformation, even though transformation occurs near the neopentyl glycol phase-change transition temperature. The mix of neopentyl glycol with sodium sulfate decahydrate also lowers both the enthalpy of transformation and the specific heat by almost the same magnitude as did the mix of magnesium chloride hexahydrate. For a molar ratio of 7:3, results were largely unpredictable due to the incongruent melting behavior of the neopentyl glycol mix with sodium sulfate decahydrate. Also, the phase transformation was barely discernible with this mixture and occurred at a higher temperature.

Mixtures of pentaglycerine with magnesium chloride hexahydrate or sodium sulfate decahydrate also did not prove attractive. Similar incongruent melting behavior was observed, as with the neopentyl glycol; the phase transformation temperature was almost unchanged. Thus, the pentaglycerine mixes' phase-change occurs higher than the desired battery operation temperature range.

Sublimation Test Results

Sublimation tests on neopentyl glycol were conducted at NASA Johnson Space Center in a vacuum chamber. Sublimation of neopentyl glycol is a very serious problem at vacuum conditions (pressure $<10^{-6}$ torr). As the temperature of neopentyl glycol at vacuum conditions increased, the sublimation rate linearly increased from 300 mg/hr/g at 25°C to 800 mg/hr/g at 55°C. Several ways of eliminating this sublimation at vacuum conditions were tried, including enamel based paint and microencapsulation of the neopentyl glycol, but the coating was too porous to sustain the sublimation pressure. Macroencapsulation, using containment of the entire storage material, seems to be the most feasible approach to controlling sublimation.

Conclusion

An investigation into using solid-solid phase-change materials in space-suit battery packs for temperature control led to the aluminum foam/neopentyl glycol combination as the premiere candidate. The combination of high thermal conductivity and latent heat appears to be appropriate for maintaining battery operation at fairly low temperatures over extended time periods. The problem of neopentyl glycol sublimation at vacuum conditions appears to be best approached by sealing the entire storage material.

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Large Eddy Simulation of the Flow in a Transpired Channel

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Introduction

TRANSPIRATION (or blowing) is often used to protect the surface of a material exposed to a hot freestream: cool fluid is injected through the surface, which must be porous. Suction is used to delay boundary-layer separation in aeronautical applications. Between 1967 and 1975, many experiments were caried out on the characteristics of transpiration on boundary layers.[1-3] The effect of transpiration on the velocity field in the boundary layer was found to be significant: when fluid is injected ("blowing"), the boundary layer becomes thicker, the skin friction decreases, and turbulent fluctuations are enhanced. If suction is applied, the effect is the opposite in each instance. Turbulent boundary layers with transpiration

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