PHASE CHANGE MATERIALS (PCM) FOR THERMAL CONTROL DURING SPACECRAFT TRANSPORTATION

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Abstract: Phase Change materials (PCMs) absorb and release latent heat during their phase transition nearly at constant temperature. The latent heat storage phenomena using PCMs provides much higher storage density, with a smaller or zero temperature difference while storing and releasing of heat. PCMs have 5-14 times more heat capacity per unit volume than sensible storage materials that merits their usage as passive thermal control systems. They are effectively complemented with active thermal control systems in order to minimize their duty cycles and optimize the capacity. This paper discusses a passive thermal control system using PCMs to maintain the temperature within the limits inside the enclosures used for transportation of spacecrafts. Further, various applications of PCMs in the thermal control architecture as applied to spacecrafts are also discussed. The paper also discusses about the technologies such as Onboard power generation, Universal Spacecraft thermal control architecture and other significant spacecraft applications.

Key Words– *Phase Change Materials (PCM), Transportation, Thermal control system, Onboard Power Generation, Spacecraft applications.*

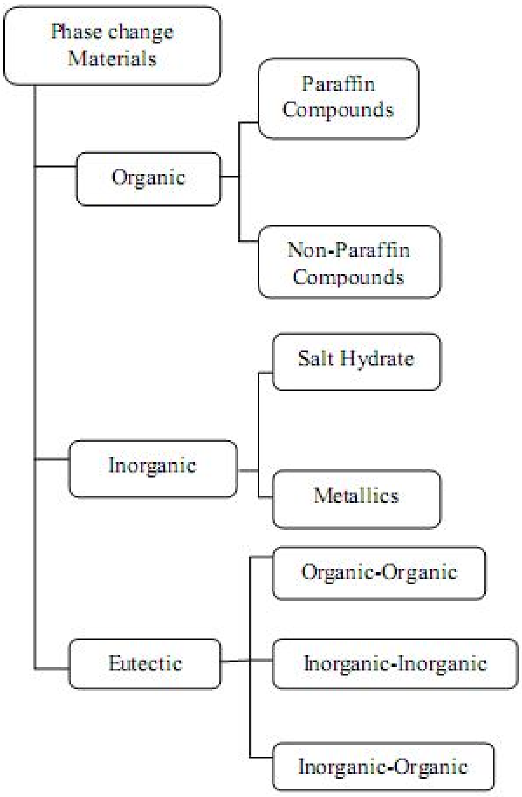
I. INTRODUCTION

Most pure substances change phase between liquid, solid or gas at some temperature and pressure. A PCM is a non- scientific expression which refers to any substance which has a single 'sharp' melting point and a sufficiently large heat of fusion that makes it of interest as a potential heat energy storage material. The latent heat per unit mass of the substance varies from substance to substance and reflects in large part, the variation in strength of the molecular bonding within the given substance at the phase change temperature. They use chemical bonds to store and release heat.

The thermal energy transfer occurs when a material changes undergoes the phase transition from a solid to a liquid or from a liquid to a solid. Initially, these solid-liquid thermal salts perform like conventional heat storage materials. When PCMs reach the temperature at which they change the phase (their melting point), they absorb large amounts of heat without getting hotter. When the ambient temperature in the space around the PCM material drops, it solidifies, releasing its stored latent heat. PCMs absorb and emit heat while maintaining a nearly constant temperature. Latent heat storage is one of the most efficient ways of storing thermal energy. Large numbers of PCMs are available that melt and solidify at a wide range of temperatures. In general, in most of the applications, PCMs are encapsulated properly for providing large heat transfer area, reduction of its reactivity with the outside environment and controlling the differences in volume of the storage materials as phase change occurs. Application of PCMs in spacecraft transportation involves calculation of heat loads such as radiative, convective and conductive heat transfer during travel, through appropriate modeling of the enclosures.

II. CLASSIFICATION & PROPERTIES OF PCM

Classification [1]:



Some of the important properties required for PCM [4] are

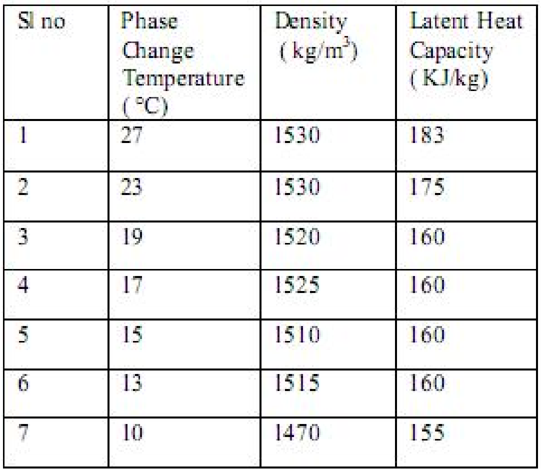
- High latent heat of fusion per unit mass, so that a lesser amount of materials stores a given amount of energy.
- High thermal conductivity so that the temperature gradient required for charging the storage material is small.
- High density, so that a smaller container volume holds the material to obtain compact encapsulation.
- A melting point in the desired operating range of temperature as per the application.
- The phase change material should be non-poisonous, non-flammable, and non-explosive.
- No chemical decomposition, so that the system life is assured.
- No corrosiveness to the encapsulation material.

Salt hydrate PCMs are more suited for the spacecraft transportation application discussed here as against Organic and Eutectic PCMs. Organic PCMs have low thermal conductivity and are flammable and hence not a candidate for the said application. Eutectic type PCMs exhibit low phase change temperatures generally in the sub zero range and further the metallic type PCMs have weight penalties.

In addition, the technical grade Salt Hydrates are inorganic type, safe, reliable, predictable, less expensive as compared to the other types of PCMs. It provides several advantages such as high thermal conductivity, high latent heat of fusion and small volume changes on melting. Based on the above, Salt Hydrates PCMs having melting point around 17°C are selected for the application.

The table below gives the properties of commercially available salt hydrates PCMs suitable for the application.

TABLE 1:



Sl no	Phase Change Temperature (°C)	Density (kg/m^3)	Latent Heat Capacity (KJ/kg)
1	27	1530	183
2	23	1530	175
3	19	1520	160
4	17	1525	160
5	15	1510	160
6	13	1515	160
7	10	1470	155

III. HEAT LOAD ESTIMATION

There is sensible heat transfer across the container wall due to the temperature difference between the inside of the container and outside ambient. This is known as fabric heat gain or loss and the heat transfer through the container wall is analyzed taking the following considerations:

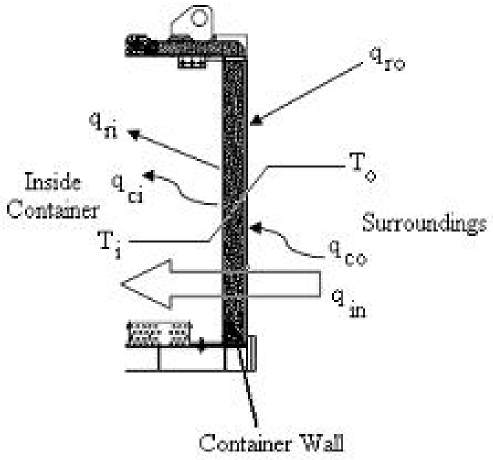


Fig 1

- Non-Homogeneous construction of container wall which includes an arrangement of Corrugation metallic sheets, Polyurethane Foam, Stainless Steel Cladding, Structural Members etc.
- Transient atmospheric conditions due to variation in solar radiation, outside temperature, wind and travel velocity, change in container orientation during shipment with respect to sun etc.
- Thermal Capacity of a container wall which introduces time lag and reduce heat transfer from ambient to inside of container.

For cooling load calculation, the conditions inside the container are assumed to be constant. However, for accurate simulation of varying outside ambient conditions, unsteady transient heat transfer analysis needs to be done. Due to the complexities involved, simplified one dimensional steady state heat transfer analysis is done for one of the Satellite Transportation Containers (STC) to obtain an initial estimate of Phase Change Material (PCM) required. For steady heat transfer across the container wall, heat transfer network considering various heat transfer resistances is shown in Fig 2.

The variables are denoted by abbreviations as per Table 2 given in the end of the paper.

The heat transfer rate per unit area of the wall qin under steady

Writing the radiative heat transfer in terms of a linearized heat transfer coefficient and combining the convective heat transfer coefficient, we can write the heat transfer rate per unit area as:

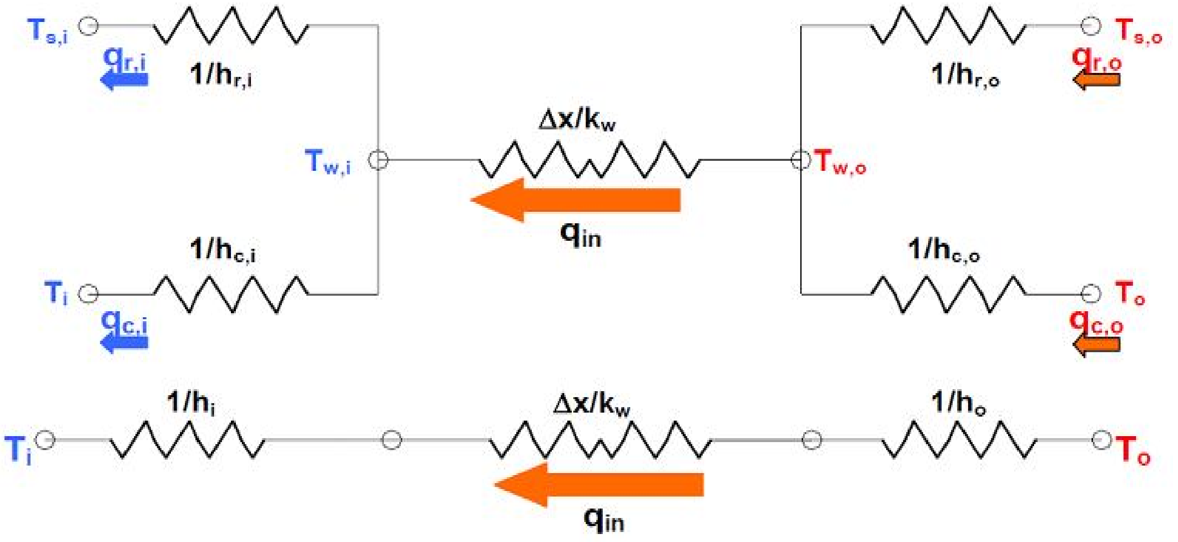


Fig 2

state is given by:

$$q_{in} = (q_{co} + q_{ro}) = (q_{ci} + q_{ri}) \quad W/m^2$$

$$q_{in} = h_o(T_o - T_{wo}) = h_i(T_{wi} - T_i) \; W/m^2$$

Eliminating the surface temperatures of the wall (Twi and Two), the steady state heat transfer rate per unit area of the wall can be written in terms of the indoor and outside air temperature and the overall heat transfer coefficient:

$$q_{in} = U(T_o - T_i) \; W/m^2$$

From heat transfer network (fig 2), the expression for overall heat transfer coefficient is given by:

$$1/U = (1/h_i + \Delta x/K_w + 1/h_o)$$

IV. CASE STUDY

Heat load was calculated for one of the existing Spacecraft Transportation Container (STC) considering the following data:

- Transportation Container Dimension: 7800 x 3000 x 3800 mm
- Container wall Insulation Thickness: 100 mm
- Thermal Conductivity of Container wall: 0.023 W/mK
- Inside Container Temperature to be maintained:
- 22±1°C
- Mean Ambient Temperature: 35 °C
- Emissivity of paint used on container: 0.8

Five walls of container were considered for heat transfer and total steady heat transfer was calculated as:

Qt = 220 Watt

Assuming steady heat transfer for continuous operation, the amount of PCM required for maintaining the temperature at 22 °C inside container can be calculated. Standard PCM with phase change temperature of 17 °C and having a Latent Heat Capacity of 160 KJ/kg is selected.

Mpcm = Heat Entering Container/Latent Heat Capacity Heat Entering Container = Qt x Cycle Time

For the above case, the mass of PCM required (Mpcm) is estimated to be around 100 kg for 24 hrs duty cycle. This is an initial estimation for PCM and a more comprehensive transient heat transfer model analysis need to be done to characterize the system for the various boundary conditions and to get more accurate results. To express the temperature gradients under various conditions, a field test to simulate the actual systems and boundaries is also planned to validate the analysis for necessary corrections and improvements on accuracies of theoretical estimation.

V. PCM IN SPACECRAFT APPLICATIONS

The application of PCM is not limited to passive thermal control for ground equipment alone. The recent research and development in PCM can be extended in novel application for spacecraft systems. In the area of heat removal and rejection, the applicable technologies for spacecraft are high thermal conductivity materials, high heat transport devices such as fixed conductance heat pipes, loop heat pipes, capillary heat pipes and low absorptivity to emissivity passive coatings [2]. The PCM is used for conserving the heat that act as a heat sink which is similar to high performance lightweight insulation, heat switches, variable emissivity coatings etc.

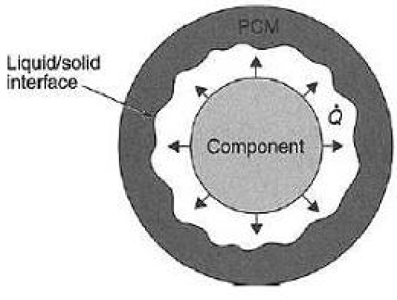


Fig 3

The simplest form of PCM thermal control for electronic components is the one that is used for short-duty cycle components in launch or reentry vehicles. Although such components are used only once, they generate large quantities of heat that must be removed, so that they will not overheat and subsequently fail. PCM laid at the vicinity to component can thermally protect such components, as seen in Fig.3. The generated heat is absorbed via latent heat of fusion by the PCM without an appreciable temperature rise of the component. This kind of system is totally passive and can be designed for high reliability.

Some of the applications of PCM in spacecraft technologies include:

- Onboard power generation using the thermal energy.
- Electronic components having cyclic operating conditions.
- Enhance efficiency of fluid-loop/radiator systems.
- Universal Spacecraft Thermal Control Architecture.
- Precise dimensional stability.
- Micro/nano satellites.

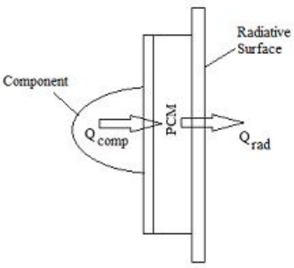


Fig 4

Onboard Power Generation [3]: With conventional photoelectric radiators, the power production ceases during the shadow portion of the orbit and energy is stored in cells or batteries for use during the OFF portion of the cycle. PCM with high melting-point can be used in conjunction With electronic power-producing systems. Radiators for collecting solar energy can be packed with PCM to store energy at melt temperature.

This stored energy can then be converted into electrical power by using the large temperature difference between radiator and deep space to drive either thermionic or thermoelectric devices. Preliminary analytical and experimental studies reported by Humphries and Griggs indicate the feasibility of this application. Electronic components having cyclic operating conditions are the ones that operate in ON or OFF cycles. The heat generated during the ON cycle, is stored in the phase change material via phase change and during the OFF cycle, the heat of fusion energy is removed via radiator, heat pipe, thermal strap or other means.

The alternate melting and freezing of the PCM enables the component to operate very nearly at isothermal condition at all the times minimize the gradients. The system is shown in Fig 4. Enhance efficiency of fluid-loop/radiator systems: The coolant fluid returning from the external radiators experienced sizable temperature variations during the course of an orbit cycle. PCMs works as a thermal capacitor for efficient operation of heat exchangers when applied to such heat exchange devices, where large temperature variations exists. PCMs are used as a passive system to mitigate these temperature variations by alternate melting and freezing, thus maintaining the fluid within allowable temperature range.

Universal Spacecraft Thermal Control Architecture [2]:

Thermal control design configurations vary significantly for each mission. A variety of spacecraft configurations are used in order to meet the needs of the individual missions. A universal flexible thermal design concept will be advantageous in terms of faster and less expensive design cycles. Cooling loop thermally integrates all the spacecraft subsystem using thermal switches and valves. The heat rejected from one subsystem is transferred to another subsystem where the heat is needed, to maintain its minimum temperature. Any excess heat generated in the spacecraft is contained in microencapsulated PCM for use in subsequent cycle within the loop. Precise dimensional stability: Missions requiring precise dimensional stability of the mechanical hardware are required to be designed with low thermal distortions. One way to maintain low thermal distortion and obtain high dimensional stability is to control the temperature precisely. PCMs can be used for maintaining the temperature apart from other methods of controlling. This approach is useful where there are difficulties for using materials with low thermal co-efficient of expansion. Micro/ nano satellites: Thermal control applications for micro/nano satellites where power levels are expected very low, can be well controlled by PCM.

VI. CONCLUSION

The basis for phase change material is the fact that these materials can absorb large amount of heat energy at constant temperature. This unique property as discussed in this paper finds multiple applications in the ground systems and spacecraft systems. The use of PCM for the passive thermal Control during spacecraft transportation provides more reliable and cost effective method of temperature control. The low temperature variations within the sealed containers result in precise humidity control too. The foregoing technique eliminates the need of complex active temperature control systems for the transportation of spacecrafts and allied hardware. Further, PCM finds its use for applications in onboard spacecraft systems. PCM material heat sinks have been recognized as an important tool in optimizing thermal control systems for space exploration vehicles and habitats with widely varying thermal loads and environment. Using appropriate PCMs in conjunction with the conventional thermal control systems, considerable optimization and improvement can be imparted to spacecraft systems design to minimize the mass of spacecraft and achieve considerable cost saving.

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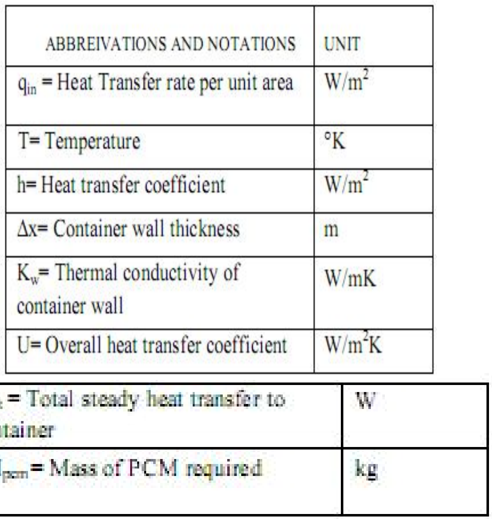
VII. ABBREIVIATIONS, NOTATIONS AND UNITS TABLE 2 :



ABBREIVATIONS AND NOTATIONS	UNIT
q_{in} = Heat Transfer rate per unit area	W/m^2
T= Temperature	°K
h= Heat transfer coefficient	W/m^2
Δx= Container wall thickness	m
K_w= Thermal conductivity of container wall	W/mK
U= Overall heat transfer coefficient	W/m^2K
Q_t = Total steady heat transfer to container	W
M_{pcm} = Mass of PCM required	kg

Subscripts Denotes:

R : Radiative
C : Convective
O : Outside Environment
I : Inside Environment
W : Container wall

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