Numerical Investigation of Thermal Energy Storage Panel Using Nanoparticle enhanced Phase-Change Material for Micro Satellites

Jelvin Tom Sebastian[1], Vinod Yeldho Baby[2]

[1]Student, Dept. of Mechanical, M A College of Engineering, Kerala, India
[2]Assistant Professor, Dept. of Mechanical Engineering, M A College of Engineering, Kerala, India

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Abstract – *Recent years have seen an increasing trend in nanosatellites, especially cubesats. A methodology that handles the thermal condition inside a cubesat that contains much-sophisticated electronic components is needed. Thermal energy storage panel with phase change material encapsulated in it is a strong candidate for maintaining the thermal condition required. This paper numerically investigates the thermal energy storage panel with nanoparticle enhanced phase change material. Silver nanostructure have increased the thermal properties of the base PCM, eicosane. Effect of nanoparticle concentration on maximum temperature of the system was studied. It was found that addition of nanoparticle allows the system to maintain a maximum temperature equal to that of the melting point of the corresponding nanoparticle enhanced phase change material.*

***Key Words*: Carbon-fiber-reinforced polymer, Composite Material, Micro/nano-satellite, Nanoparticle Phase change material, Thermal Energy Storage**

1.INTRODUCTION

Nanosatellites particularly CubeSats are budding trend for university research and various other small. The concept proves to be promising for many commercial and non-commercial applications. The less development time, smaller size and lower mass of CubeSat satellites allows designing, built, test and obtaining a cost effective satellites in order to place in orbit. Thermal analysis is one of the crucial elements during design process of spacecraft as the thermal loads in orbit can easily harm the functions of components in the system and therefore the entire system can be affected. With growing interest and rapid development in small satellite misssions, particularly Cubesats over the past few years their fields of applications have been continously extended. Following this development, the basic need for simualting and analysing the system of a CubeSat prior to its opertation in space has gained importance. This also applies for the field of thermal analysis.

In space, electronic devices are constantly bombarded with radiation, which can cause certain parts to fail or behave in unexpected ways. Engineers are finding that some devices are failing more often as nanotechnology has driven devices to be made with smaller and smaller components. While the smaller components make them lighter and faster, they also make them more susceptible to random radiation events. Similar to the conventional spacecrafts, CubeSat also need to be designed to maintain temperatures within the operational range . This is achieved by performing thermal analysis to simulate the thermal behaviour of the satellite and predict temperature distributions for varying operating conditions. The thermal condition of a micro/nano-satellite is quite different from that of a conventional large satellite because of (i) limited power resources, (ii) small heat capacity, (iii) insufficient radiator area, (iv) high-density packing of electronics, and (v) mass limitations. Thus, micro/nano-satellites are generally less thermally controllable than larger satellites. The highly sophisticated electronic components in tightly packed system require an operational environment where the temperature is maintained. To improve the thermal controllability for micro/nano-satellites, we require a new methodology and a new thermal control device that is smaller than that on conventional satellites and that needs no electrical power. This thermal control panel must have less mass, as the addition of this system shouldn't increase the total mass of satellite.

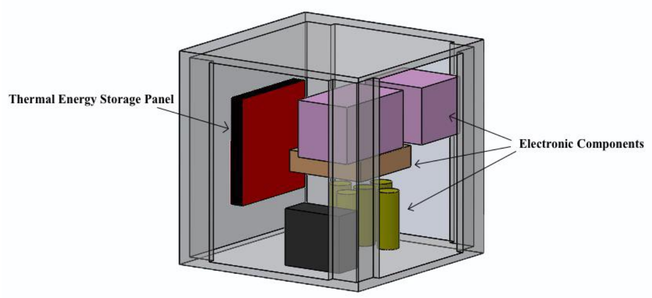

Fig-1 Placement of TESP inside the microsatellite.

Phase change materials (PCMs) are a suitable material for solving micro/nano-satellites thermal difficulty because PCMs can increase a satellite's apparent heat capacity with little mass gain and no electrical power. The major factor of increase in mass is the additional components of PCM devices; they are (i) a thermal conduction member to compensate for PCMs' low thermal conductivity and (ii) a strong container to bear the volume change that arises with phase change. One of the major challenge is to make up the low conductivity of PCM and decrease the mass of PCM devices.

A well designed PCM based heat sink for various power levels was investigated experimentally and numerically by Gong[1]. It shows that the inclusion of PCM in the cavities of the heat sinks will increases the cooling performance as compared to the cases without involved PCM when the input power level is relatively high. A new design for thermal storage using multiple PCMs was first proposed by them for power generation in space-based activities by Shatikian[2]. Bogdan [3] found that the increase of the overall thermal efficiency could theoretically be doubled, or even tripled by use of multiple PCMs. Duan[4], performed an investigation of thermal management with phase change materials for their feasibility and effectiveness for electric vehicle battery modules. Two different PCM designs for the heater temperature management were investigated: one with a PCM container surrounding the heater, and another with a PCM jacket wrapping the heater. It was shown that both designs are effective in maintaining the heater temperature within a defined range. Experimental Investigation of a new thermal control device called a heat storage panel (HSP) for micro/nano satellites by Yamda [5]. The internal PCM was used to increase the apparent heat capacity, whereas the high-thermal-conductivity CFRP was used to enhance heat dissipation. The HSP temperature change was moderate around the phase change temperature of eicosane (36.4°C). Two samples were compared; the temperature range of the HSP with eicosane was less when compared with sample without eicosane.

Methodology on improving thermal conductivity in phase change materials was based upon the inclusion of fixed, stationary highly conductive inserts/structures into PCM. Paraffins have served as the most widely used choice for the base PCM. Rabih[6], has suspended highly-conductive silver nanoparticles in eicosane-based PCM to enhance thermal conductivity resulting in the formation of nanoparticle-enhanced PCM (NePCM). Results showed an increase in the value of thermal conductivity as the temperature increased, and when close to melting point, a sharp rise in thermal conductivity was observed. Li[7] prepared composites of nano-graphite (NG)/paraffin and the thermal properties and microstructure of the composites were evaluated. There was a relative increase in thermal conductivity of 7.41 times that of the pure paraffin. Gao [8] has conducted experimental tests on octadecane-based PCM containing dispersed aluminum oxide (Al_2O_3) nanoparticles in a vertical enclosure to study the effects of the mass fraction of the nanostructures on the heat transfer properties.

Many investigations have been carried out on thermal energy storage; however no potential benefits of using nanostructures in phase change materials as thermal energy storage panel has been conducted. The current study aims to numerically investigate the thermal characterstics of thermal control device with silver nanoparticles in eicosane-based PCM. This study aims to determine the feasibilty of adding silver nanoparticle at different weight concentration at different heat loads.

2. NUMERICAL MODEL

2.1 Physical Geometry

The geometric model used in this study consist of thermal energy storage panel, sheet heater and aluminum plate to simulate the surface of the satellite. The structure of heat storage panel consists of 25 layers of Carbon Fibre Reinforced Polymer plate with Phase Change Material injected into it. The TESP consists of three parts: one center container part which has four rooms for the PCM and two cover parts that are placed on both sides of the center part.

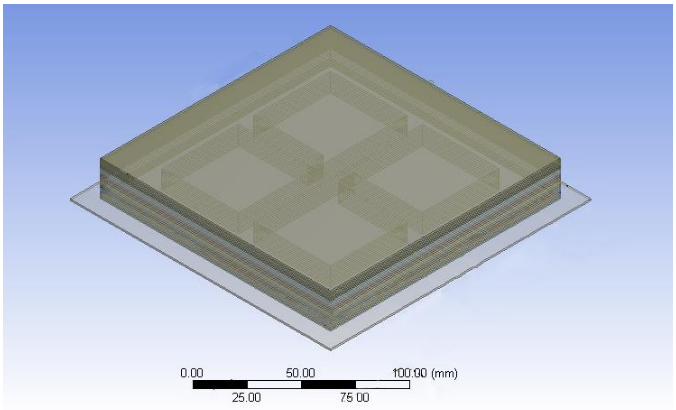

Fig-2 Geometry of the model

2.2 Governing Equations

By the commercial software ANSYS Fluent 15.0 [9], governing equations heat transfer were numerically solved based on following assumptions: melting is transient, PCM in liquid state is incompressible, the volume change with the phase change was ignored and the same value was used for the density of solid and liquid with constant thermo physical properties. The governing equations are:

Mass Conservation

$$\frac{\partial \rho}{\partial t} + \rho(\nabla . V) = 0$$

Momentum Conservation

$$\frac{\partial \mathrm{v}}{\partial \mathrm{t}} + \mathrm{v}.(\nabla \mathrm{v}) = -\frac{1}{\rho}\nabla p + \upsilon\nabla^2 V + g + S$$

Energy Conservation

$$\frac{\partial}{\partial t}(\rho H) + \nabla.(\rho v H) = \nabla.(\mathrm{k}\nabla T) + S$$

Where 'H' is the enthalpy, 'ρ' is the density, 'v' is the velocity of fluid and 'S' is the source term. The enthalpy 'H' is calculated as the sum of sensible and latent heat.

$$H = h + \Delta H$$

Where 'h' is the sensible enthalpy at a point at a given instant of time; 'ΔH' is the latent heat.

$$h = h_{ref} + \int_{T_{ref}}^{T} c_p \, dT$$

Where 'h_{ref}' is the reference enthalpy, 'T_{ref}' reference temperature and 'c_p' is the specific heat at constant pressure of PCM.

$$\Delta H = \beta L$$

Where β is the value of liquid fraction and L is the latent heat of Phase Change Material. The value of latent heat is zero when material is solid (β=0) and L when material is liquid (β=1).

$$\beta = 0 \qquad \text{if } T<T_{solidus}$$

$$\beta = 1 \qquad \text{if } T>T_{liquidus}$$

$$\beta = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \qquad \text{if } T_{solidus}<T<T_{liquidus}$$

where $T_{solidus}$ and $T_{liquidus}$ are the propeties of material.

2.3 Thermo-Physical Properties

Thermo-physical properties of the material used in the model are taken from [1] and [6]. Model comprises of a carbon fibre reinforced polymer panel with silver suspended nanoparticle based phase changing material is encapsulated in it. The Thermophysical properties are as follows:

Table -1: Thermophysical Properties of NePCM

Wt% of Ag	Thermal Conductivity (W/m K)	Density (kg/m³)	Specific Heat(s) (J/g K)	Specifc Heat(l) (J/g K)
1	0.4396	847.8	1.9658	2.3300
2	0.4951	855.7	2.0312	2.3598
3.5	0.4798	867.9	2.1291	2.4044
5	0.4365	880.5	2.2273	2.4490
6.5	0.4601	893.4	2.3259	2.4940
8	0.5057	906.7	2.4244	2.5389
10	0.5152	925.11	2.5552	2.5983

Table -2: Thermophysical Properties of CFRP

Material Properties	CFRP
Thermal Conductivity (W/m K)(Fiber Direction)	347
Thermal Conductivity (W/m K) (Orthogonal Direction to Fiber)	3
Specific Heat (J/g K)	0.86
Density (kg/m³)	1780

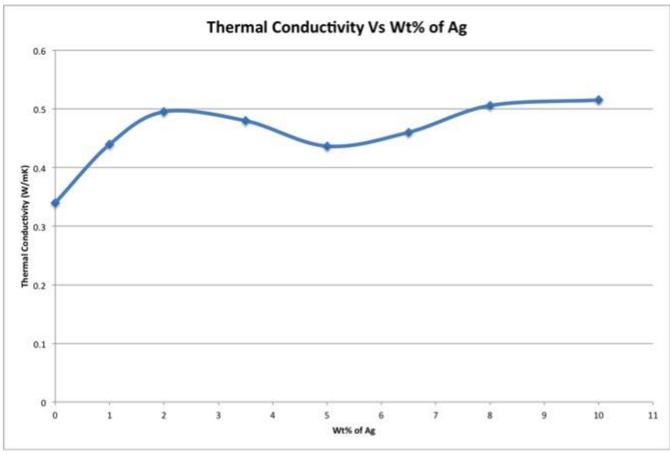

Chart -1: Variation of Thermal conductivity vs Wt% of Ag

2.4 Boundary Condition

Numerical investigations were carried out using silver nanoparticles (Ag-NePCM) and eicosane as base PCM. 10 repetitions of 5800s cycle heating program was performed. Maximum of 20W sinusoidal curve is given as first half of the cycle and the latter was the constant at 0 W. In order to study the heat load capacity of the NePCM double the load is given, maximum of 40W sinusoidal curve is given as first half of the cycle and the other is given constant OW as shown in figure 3.

Table -3: Boundary conditions

Parameter	Value
Nanoparticle	Ag
Nanoparticle Wt concenteration (%)	0, 1, 2, 3.5, 5, 6.5, 8, 10
Transient Heat Load (W)	20, 40
Shroud Temperature (°C)	-180
Emmisivity of CFRP ε [9]	0.85

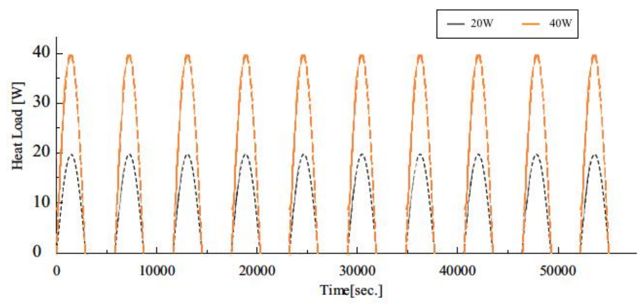

Chart-2 Transient heat load applied

3. SIMULATION

The governing equations were solved using commercial software ANSYS Fluent 15.0[9]. In order to predict the values, the same material properties, boundary condition, model and different heat loads were used. Reflecting the fiber direction to the setting of the thermal conductivities of each layer simulated anisotropy of the CFRP. Various simulations have been run to establish the best configuration, to test different operational modes, and to validate the assumptions for the thermal model. All of them have been performed both for steady state conditions and for transient conditions. For simplicity, only the most relevant simulations and the transient results are described here.

3.1 Grid Independence Study

Different meshes were considered for establishing the grid independence of the model under the present study. In each case, the maximum temperature was recorded and tabulated as shown in table 3 to achieve the grid independency. From the tabulated results, it was concluded that grid independency was achieved for mesh-4 and this mesh was used for further numerical computations.

Table -4: Grid independence study

Grid	Maximum Temperature (°C)
Mesh-1 (305472)	4.0555
Mesh-2 (595566)	4.2813
Mesh-3 (696742)	4.6941
Mesh-4 (744247)	5.1093
Mesh-5 (1064966)	5.1108

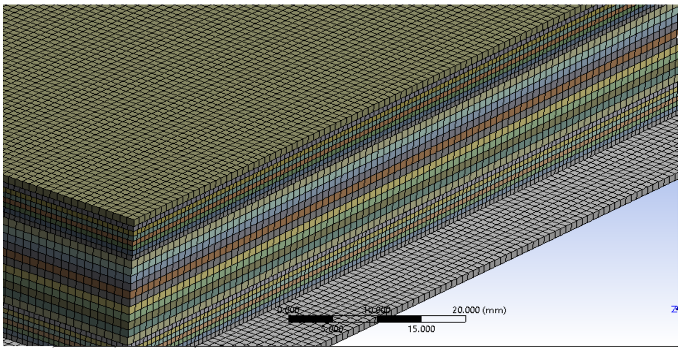

Fig-3 Meshed View of the generated model

3.2 Model Validation

The numerical results obtained from the present study were compared with the experimental results of Yamda et al. [5]. Experimental study was performed to investigate the thermal characteristics of eicosane as a PCM in the heat storage panel. Comparison was conducted using the maximum temperature measured when the first half of the cycle made the maximum 20 W sinusoidal curve, and the latter was the constant at 0 W. The numerical results showed virtuous similarity with the experimental results. The maximum deviance of the numerical results from the experimental study in the literature was less than 12%. From this result, the analytical model was sufficiently effective to predict the temperature of the HSP.

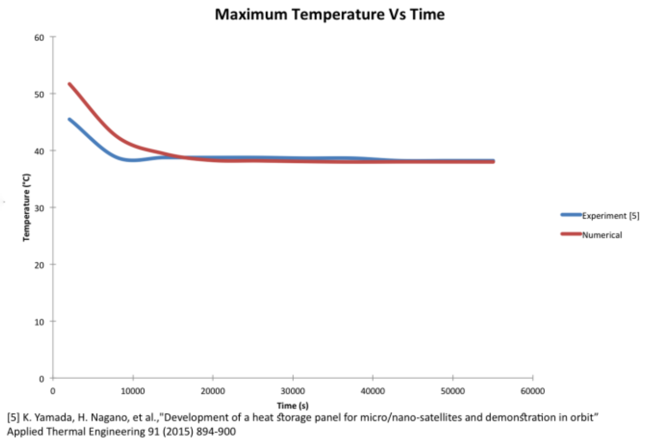

Chart-3 Variation of maximum temperature of 20W Heat load

4. RESULTS AND DISCUSSIONS

Thermal characteristic of thermal energy storage panel with nanoparticle enhanced phase change material at different concentration was evaluated in terms of maximum temperature distribution at different heat loads. The maximum temperature of the simulation at regular intervals was recorded. Influence of nanoparticle based on the melting point in the heat transfer of the system is studied.

4.1 Variation of Maximum temperature with change in material properties

Chart 4 shows the maximum temperature achieved by the system for different materials for an input heat load of 20W. Being concerned with the operational range of electronics, controlling the maximum temperature of the system is important. Results shows that use of phase changing materials reduce the maximum temperature of the system. Model with and without nanoparticle enhanced phase change material are having lower temperature when compared with the model without any phase change material. Nanoparticle enhanced phase change material gave a lower temperature range. A constant temperature was obtained when a constant sinusoidal heat load was applied. At all particle concentrations the maximum temperature of the panel was lesser than that of the base PCM. Increased concentration of nanoparticles enhanced the effective thermal conductivity and reduced the melting point. These properties lead to a better heat transfer and the temperature range decreased with any further increase in nanoparticle concentration. Furthermore there was an increase in temperature of NePCM by 8% and 10% as the time advances.

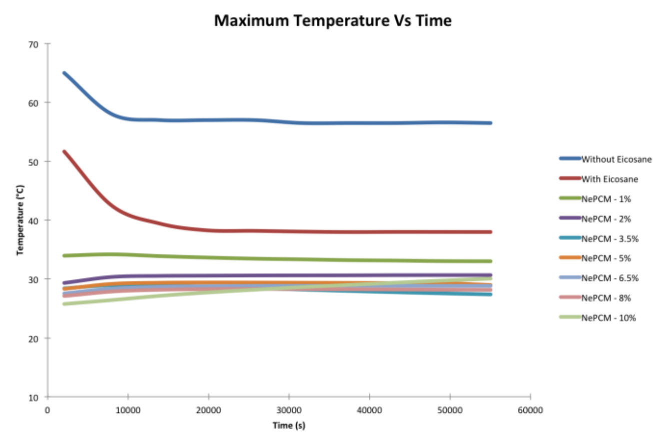

Chart-4 Variation of maximum temperature of 20W heat load

Results showed that none of the NePCM attained its melting point for the maximum heat load of 20W. Therefore it is possible to have higher heat transfer rate with marginal increase in heat loads with the use of NePCM. This enhanced the performance of the thermal energy storage panel.

4.2 Variation of Maximum temperature with increase in applied heat load

A heat load of 40W was applied to the model with Ag-NePCM in order to study the heat load capacity and the thermal characteristic of the model. The variation of maximum temperature with different nanoparticle concentrations for 40W heat load is depicted in chart 5.

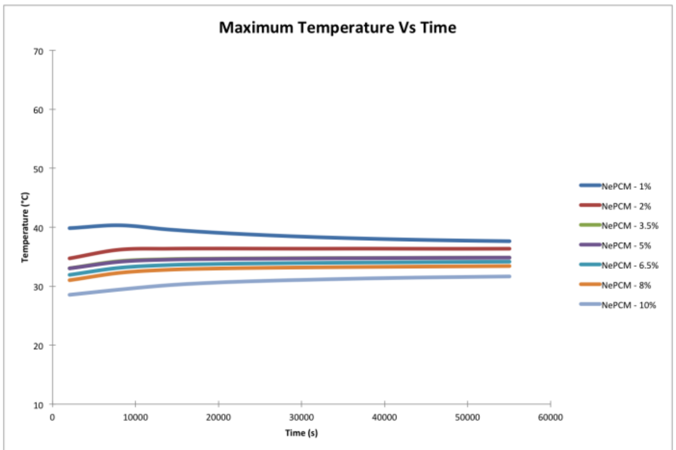

Chart-5 Variation of maximum temperature of 40W heat load

At all particle concentrations the maximum temperature was higher than the other heat load. The TESP maintained a constant temperature for a long duration at corresponding NePCM melting point. The deviation between the maximum temperature and the melting point was maximum during initial time period, but as the time advanced the maximum deviation reduced considerably and the temperature became constant and showed good agreement with the literature.

5. CONCLUSIONS

In the present study, a numerical model was developed to compute and analyze thermal characteristics of a thermal energy storage panel using nanoparticle enhanced phase change material. The influences of the nanoparticle weight concentration in the base phase change material were examined. The results showed that, the thermal characteristics of the panel improved with the use of nanoparticle enhanced phase change material compared to the base phase change material.

The numerical results showed that the maximum temperature were dependent on the melting point of NePCM at various weight concentrations. The thermal energy storage panel with nanoparticle enhanced phase change material could decrease the peak temperature of components through the phase change of NePCM. In the analysis, the uniformity of temperature of the TESP was shown. When the TESP acts as a thermal regulator this uniformity of temperature is an important factor. The main significance of using Ag-NePCM is that it allows maintaining a peak temperature required in an operational range, by varying the weight concentration of silver added to the base PCM. By altering the weight concentration of the Ag-NePCM it is possible to create an optimum operating temperature required for the effective working of the electronics components. At weight concentration of silver particle 1-6.5% uniformity of peak temperature is found; whereas there is an increase in peak temperature for weight concentration above 8%. Increase of weight concentration of silver in base PCM increases the thermal conductivity and reduces the melting point; which results in maintaining the maximum temperature at the phase change temperature.

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