International Journal of Engineering and Technical Research (IJETR)
ISSN: 2321-0869, Volume-2, Issue-10, October 2014

Thermal Management Methods of Nanosatellites

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***Abstract*— Nanosatellite technology is opening the door for research and educational institutions to access space. The development cycles for these satellites is relatively short and may require the use of technology which is not space proven. In order to increase the reliability of these satellites an array of testing and analysis must take place including that of thermal management. The aim of this paper is to outline a number of thermal management techniques which may be used within the design of a nanosatellite by defining how heat is transferred to the satellite and from sources, and then providing information on methods which may be used to control this heat transfer. Within passive thermal control optical coatings are found to be of greatest use, while within active thermal control louvres are of great value to future thermal designs.**

***Index Terms*—Nanosatellite, Thermal, Heat, Active, Passive**

I. INTRODUCTION

With the new emergence of nanosatellite technology and their usage within research and education due to their low cost and short development cycle, there is an increased focus on system testing and management to increase reliability. The success rate of successfully launched nanosatellites is relatively low and so the focus on nanosatellite specific systems is building [1]. The thermal analysis and design of these satellites require an understanding of their unique requirements as well as an understanding of the modes of heat transfer and sources of heat acting upon the satellite. This combination of sources and their heat transfer modes provide a scenario to which the thermal management systems must regulate to the thermal requirements. The possible usage of thermal management solutions developed for larger satellites also require an understanding of the requirements unique to nanosatellites. These solutions, both electrically passive and active, allow the functionality of the satellite and its systems within orbital conditions. Each project shall have a set of requirements which may necessitate a different solution, but an understanding of each possible solution will simplify the thermal design process.

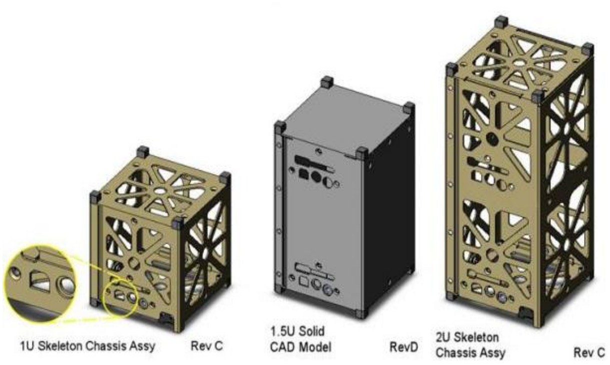

Figure 1: CubeSat Units [2]

Manuscript received October 11, 2014.

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II. NANOSATELLITE REQUIREMENTS

Nanosatellites are defined as a satellite between 1 and 10 kg [3]. The major differences in the requirements of nanosatellites as compared to larger satellites are in the power usage, allowable mass and overall size. The power usage of nanosatellites is restricted due to the power generation ability of each satellite and the power which may be delivered to systems, usually less than 30 W [4]. The allowable mass of a nanosatellite is restricted by project definition and launch capabilities as well as by satellite category, being between 1 and 10 kg thereby limiting the mass of onboard systems [5]. The overall size of a nanosatellite is restricted by delivery method as well as mission guidelines, such as a CubeSat being restricted to 10x10x10 cm per unit at launch, as shown in Fig. 1, and must be reviewed and considered for each project before design commences. These requirements which are unique to nanosatellites as compared to larger sized satellites will place restrictions on which thermal management solutions may be used and as such each solution must be considered against these requirements.

III. HEAT TRANSFER MODES

When analysing the thermal management capabilities of a satellite in low Earth orbit, it is necessary to consider each mode of heat transfer. These modes are convection, conduction, and radiation. Within the scope of nanosatellite technology only conduction and radiation are generally applicable.

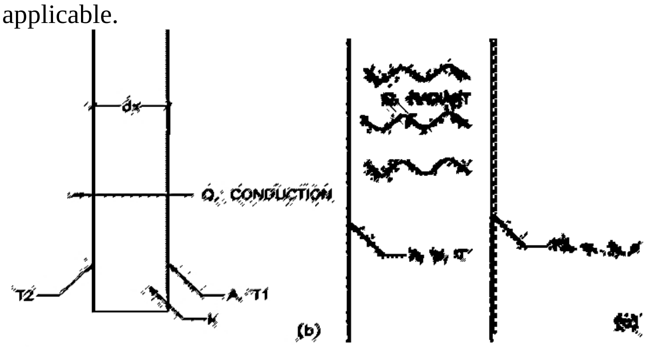

Figure 2: Heat Transfer Modes

A. Conduction

Conductive heat transfer is the method of transferring heat through a medium in the direction of a temperature gradient [6], as in Fig. 2, (b). Conductive heat transfer can be calculated by Fourier's Law in which:

$$\frac{dQ}{dt} = -kA\frac{dT}{dx},$$

where $\frac{dQ}{dt}$ is the heat transfer rate, k is the thermal conductivity of the material, A is the area normal to the direction of heat flow, and $\frac{dT}{dx}$ is the difference in temperature in the direction of heat flow, per thickness of material [6].

Each nanosatellite, being composed of materials, undergoes conductive heat transfer. Variations in the conductive properties of the satellite structure and systems have the effect of varying temperatures across these structural and system components, and as such is an important topic to cover within the scope of this paper.

B. Radiation

Radiant heat transfer is the method of transferring heat via electromagnetic waves from one surface to another, without need for a medium [6], as in Fig. 2, (c). Radiant heat transfer can be calculated by the Stefan-Boltzmann relationship:

$$\frac{dQ}{dt} = e\sigma AT^4,$$

where $\frac{dQ}{dt}$ is the heat transfer rate, e is the emissivity of the surface, σ is the Stefan-Boltzmann constant (5.6703x10^-8 W/(m^2 K^4)), A is the area of the surface, T is the temperature of the surface. The amount of radiation absorbed by a second surface is dependent on the absorption (α), transmittance (τ), and reflectance (ρ) of the surface material [6].

Due to the low temperature of space surrounding the satellite, as well as the high amount of surfaces exposed to vacuum relative to the amount conductively connected, radiant heat transfer is of the highest importance during the thermal analysis of a nanosatellite and as such the scope of this paper.

IV. Heat Sources

The thermal analysis of nanosatellites requires calculating the effect of heat sources on the satellite temperatures. The heat sources to be considered are solar radiation, albedo radiation, and the internal heat generation of the satellite systems [7].

A. Solar Radiation

Solar radiation emanates from the Sun as electromagnetic waves which spread out from the source and lose intensity over distance, as shown in Fig. 2. At the Earth's mean distance from the sun the solar radiation has an intensity of 1368 ± 0.65 W/m^2 [6].

Although nanosatellites have small external surface areas which are exposed to solar radiation at any one time, the radiant heat flux due to this exposure is likely to cause large temperature changes within the satellite due to its low thermal mass and the extended times that solar radiation is incident upon its surfaces. As such, the primary concern during the thermal analysis of a nanosatellite is the effect of solar radiation.

B. Albedo Radiation

Albedo radiation is the heat radiating from Earth due to the reflectance of solar radiation, as shown in Fig. 2. Albedo

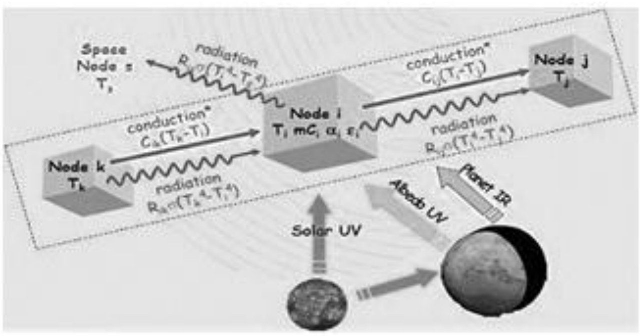

Figure 2: Satellite Heat Sources [8]

itself is a measure of how much solar radiation is to be reflected, and each part of the Earth has a different value. For simplified thermal analysis an average value should be used rather than attempting to simulate the varying values across the planet. Due to the reflectance of ice, water, and clouds a value of 0.3 average Earth albedo may be used [9]. The radiation from Earth itself may be included within this value for simplification of the thermal analysis. This combined planetary heat and albedo value corresponds to radiation with an intensity of 410 W/m^2.

For nanosatellites this value, although 70% less than the intensity of the direct solar radiation, is a major contributor to the temperature changes within the satellite and as such must be included within thermal analysis.

C. Internal Heat Generation

The internal systems of nanosatellites consume power in order to function. Conservation of energy requires the power input of each system to be equally output, though does not require the form to be equal and may therefore be output as a form other than electrical [10]. In each system a portion of the input energy is output as heat due to inefficiencies within the electronic circuits. The amount of heat generated depends on factors such as system outputs and design, but for nanosatellites making use of solar power generation this amount is limited by the power generation capabilities of the satellite, or by the power output of the batteries. As an example, the power systems designed by GomSpace for nanosatellites allow for power of 30 W to be distributed to the satellite [4]. The heat generated internally by the satellite is limited by this value and as such places a limit on the temperature changes able to be produced. This effect is important for satellite operations and must be included within thermal analysis.

V. Thermal Management Systems

Each system within a satellite has a manufacturer defined safe operating temperature range which defines the temperatures for which each system is designed to operate. As an example, the GomSpace Nanomind onboard computer has a defined operating temperature range of between -45° C to +85° C [11]. The purpose of a thermal management system is to maintain the temperatures within each system to their operating range to allow uninterrupted satellite operations. The categories of thermal management solutions available are passive and active thermal control.

Table 1: Example Multilayer Insulation Properties [12]

Layer:	*Material:*	*(α):*	*(e IR):*	*(ρ):*
Outer	Beta Cloth	0.45	0.80	NA
Reflector	Aluminized Kapton	0.12	0.03	~0.90
Inner	Double Nomex	<0.14	<0.04	NA

VI. Passive Thermal Control

Passive thermal control defines any method of thermal management which does not require an energy input to function. This scope of this paper shall cover multilayer insulation and optical coatings.

A. Multilayer Insulation

Multilayer insulation is a material comprised of multiple insulating barriers. Each barrier has an insulating effect which cumulates with subsequent barriers to provide a high performance insulating effect [12].

The insulating effect of multilayer insulation may be used to mitigate radiant or conductive heat transfer. Radiant heat transfer is mitigated by having a high overall material reflectance (ρ), while also having a high material emissivity (e), as in Table 1[12]. Conductive heat transfer is mitigated by composing the material of layers each with low thermal conductivity (k). The conductive mitigation effect is then increased by the addition of subsequent layers, increasing the overall thickness [13].

Multilayer insulation is a low mass, simplistic thermal management solution. It requires no power consumption and is therefore attractive to missions with low power allowances. If the insulating effect becomes detrimental to satellite operations during the mission, however, it is unable to be removed and so the effect must be necessary for the entirety of the mission. With sufficient thermal analysis and testing of nanosatellite systems, multilayer insulation is an appropriate thermal management solution.

B. Optical Coatings

Optical coatings are layers of material added to satellites in order to change the optical properties of a surface for increased radiant performance. These coatings are usually highly emissive, and with low solar absorption in order to radiate excess heat and lower the temperature of the satellite surface and systems therein [14].

Nanosatellites which are manufactured from materials which do not possess the required optical properties required for a passive thermal solution may be coated with a material which changes these optical properties. A surface which has a high absorption of solar radiation may increase the satellite temperature to beyond the required range while coating this surface with a material of high reflectance may reduce this temperature to within requirements.

Optical coatings provide the benefits of multilayer insulation in terms of radiant heat, though they do not provide a barrier against conductive heat. This may be useful under some conditions but may also be limiting. Optical coatings also do not require power but are set before the mission and cannot be changed during flight. The printed circuit boards to which solar cells are mounted may make up a majority of the external surfaces. In order to modify the optical properties of these surfaces to better maintain the thermal properties of the satellite, optical coatings are a simplistic solution which may be used in nanosatellite designs.

VII. Active Thermal Control

Active thermal control defines any method of thermal management which requires an energy input to function. The scope of this paper shall cover heaters, Peltier elements, and louvres.

A. Heaters

Heaters are systems for delivering energy into environments in the form of heat. Thermoelectric heaters, as used within satellites, convert input power into heat in order to maintain the temperature of the satellite or its components.

Thermoelectric heaters function following the principle of resistive dissipation in which:

$$\frac{dQ}{dt} = I^2R,$$

where $\frac{dQ}{dt}$ is the heat transfer rate, I is the current provided to the heater, and R is the resistance of the element. To dissipate heat over an area, the resistive components are installed between sheets of insulation or within a metallic housing. The operation of these heaters can be manually controlled from the ground, automatically controlled by thermostats, or by a combination of both [15].

Within nanosatellites a passive thermal management solution is preferred due to limited power budgets, but thermoelectric heating may be necessary within systems that require higher temperatures than available during cold periods, or to prevent propellants from freezing [15]. The inclusion of heaters within a thermal management design increases the mass of the satellite, increases the complexity of the satellite operations, and adds a new point of possible failure. Usage of these systems should be restricted where possible unless no passive solution is possible, though it is a simplistic active solution and as such is suitable for nanosatellite designs.

B. Peltier Elements

Peltier elements are thermoelectric devices which make use of N and P-type semiconductors, and an applied current to create a heat flux across the element, drawing heat from one side to the other to be dissipated by another method [16].

While thermoelectric heaters function following resistive dissipation of the form:

$$\frac{dQ}{dt} = I^2R,$$

Peltier elements produce a heat flux which varies linearly with the current and as such matches the polarity:

$$\frac{dQ}{dt} = pI,$$

where $\frac{dQ}{dt}$ is the heat transfer rate, p is a coefficient of performance, and I is the provided current [16].

Due to the conservation of energy the overall effect of a Peltier element within a closed system is to produce heat equal to the power consumed by element as well as the heat drawn from the targeted system. This effect may be used to cool selected components while heating others, but unless the heat of the Peltier element is drawn away from the device, this heat will increase the overall temperature of the element which will then provide the functionality of a heater. The power requirements of a Peltier element as well as this requirement to draw heat away from the heated side are a disadvantage of using these elements within nanosatellites compared to passive solutions, and should be avoided unless no other passive or active solutions are possible.

C. Louvres

Electromechanical louvres allow the optical properties of a surface to be changed by covering or revealing different surfaces in situations where the properties required for cold and hot situations conflict [17].

In a situation where systems are overheating a surface may have the optical properties of high emissivity, allowing the surface to radiate the excess heat. If the system was to then overcool the louvres may be actuated and a secondary surface with high insulating properties can take the place of the original and allow the system to contain its internal heat generation.

A louvre system adds additional complexity to the thermal management system design and as such adds another point of possible failure to the satellite design as well as adding extra mass. The ability to vary the optical properties of a surface, however, would allow the thermal design of the satellite to be modified to suit unexpected thermal conditions during flight [17]. Usage of these systems should be avoided in preference of passive thermal solutions but presents a viable option when these solutions are not possible as they only require power when actuated.

VIII. Conclusion

Within the aerospace industry a number of thermal management solutions have been created for satellites. The thermal management design of nanosatellites requires an understanding of their unique situations and requirements which include the mass of between 1 to 10 kg, the size which must suit project requirements, and the power distribution restrictions which is limited by the installed power systems. Before beginning the design of a nanosatellite thermal management system, an understanding of the heat transfer methods and heat sources of the nanosatellite is needed. The major heat sources to be considered within thermal analysis are the solar radiation of the Sun as well as the albedo radiation of the Earth. The largest temperature fluctuations within the satellite will be due to these two heat sources, though the internal heat generation of the satellite will affect the satellite temperature through conduction as well as radiation. As part of the thermal design and analysis various thermal management solutions must be considered from the categories of passive and active thermal control. Due to their lack of electrical requirements passive thermal controls are of a higher priority than active controls. Optical coatings are a simple passive solution which do not add large masses to the satellite design and should be a first option for thermal control. A secondary option due to its increased mass is that of multilayer insulation which also has no electrical requirements. Further to this active thermal management solutions may be considered though these solutions are more complex, and are of higher mass than the passive solutions. Heaters are a simplistic active solution which may be necessary within subsystems of nanosatellites and can be easily integrated when a passive solution cannot be found. Peltier elements have high electrical requirements and though may be feasible for larger satellites, are not generally practicable for nanosatellites. Louvre systems are not common within nanosatellites and are an active solution due to the power required when actuating, though they allow a more complex thermal design and should be further developed for future use within nanosatellites.

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