Development of Modern Thermal Control Technologies for Next Generation of Spacecraft

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***Abstract*— Thermal design of spacecraft is required to meet and maintain the required temperature of the component in varied thermal environments and also variable thermal fluxes for entire mission. Temperature of components is controlled by active as well passive thermal control system. Though passive thermal control has high reliability & consume no electrical power, but it works for limited range of heat fluxes and limited range of temperature controls .Active thermal system are able to control higher power with better accuracy but have lower reliability and consume power also. Modern space craft particularly for inter terrestrial applications are required to withstand hostile environment of high heat flux, varied cyclic temperatures while utilizing much lower power. Requirements are further complicated due to further variable thermal energy, varied temperature distribution and requiring precision control of temperatures within the system. The paper proposes several exciting thermal control systems for variety of applications. It includes Aero gel material for higher degree of insulation, electro chemical devices (ECD) for varying the thermal characteristics of the surface, nano suspended materials to improve heat transfer rate, hybrid system for further improvement in heat transfer, micro heat pipes for removing heat from isolated hot spot from high density circuits, parallel operating system for higher rate of heat transfer, thermal switches for removing & stopping of heat flow. These systems have vast applications for thermal control of spacecraft even for inters terrestrial's applications.**

Keywords—Next generation spacecraft, micro heat pipes, thermal switches, varying surface characteristics,nano fluids

I. INTRODUCTION

The design of thermal control system (TCS) in a space craft has the function to keep all spacecraft components within acceptable temperature ranges during all mission phases .These components need to withstand large variation of thermal environment and heat dissipation within the spacecraft itself. The thermal control is essential to obtain the optimum performance of devices and success of the mission since the performance of electronic components is severely affected, if it encounters a temperature which is beyond their operation range. Moreover, different components need different temperatures within space craft to provide optimum performance [1]. The temperature of operation needed for a battery is very different than a detector or low noise amplifier. These variations in temperature require specific strategy & technology to manage & maintain required temperatures of a system for mission life. Thermal stability within a specified temperature is another feature which needs to meet the requirements of specific components, such as, optical sensors, atomic clocks, etc.

The external environment also varies right from the launch conditions to operation in the final orbit. In the case of deep space or planetary mission thermal flux varies considerably. In the Apollo program systems are required to be insulated from lunar day time temperatures approaching +1300C and night time temperatures falling to –1100C

Satellites orbiting the earth are subjected to extreme temperature variations due to sun exposure, sun shadow and eclipse conditions. The delicate electronics on man-made satellites will not operate efficiently over such temperature variation and therefore, it is necessary to insulate the satellite from such space environment.

Thermal control systems are also required to perform their intended functions even in cyclic variation of thermal fluxes. A portion of satellite may experience high flux due to direct exposure of sun light where as other portion may face deep space of few Kelvin temperature. During eclipse period, whole satellite will face only the deep space of few Kelvin temperatures. The system like antenna works in a temperature range of + 1250c to – 1500 c.

In a near future, it is envisaged that even telecommunication satellites will be requiring much high power and therefore, expected power dissipation may be more than three times the existing system. Such a high power need to be dissipated in optimized fashion and ensure required multiple temperature zones are maintained as per system requirements. At the same time, space craft components have other constraints such as lower mass to strength ratio, minimum electrical power consumption and very high reliability requirements. Most of the process involved in fabrication & development of system need to approach unity to meet over all mission reliability.

Thermal control is further handicapped due to heat transfer mechanism in space is mainly due to radiation since convection heat transfer is negligible in high vacuum condition in space. Satellite is isolated from other object and therefore conduction heat transfer exists from component to component within space craft. These components need to be thermally coupled/ decoupled to operate in different temperature zones.

The philosophy of thermal control is to protect the equipment from high temperatures is by thermal insulation from external heat fluxes from sun and heat removal from internal heat dissipation by thermal coupling to radiator exposed to space environment. In case of equipment to be protected from lower temperatures they are thermally insulated from external sinks and coupled with heat dissipating devices or external source.

Passive thermal control mechanisms are used for satellite using lower power of the order of 500W where as high power consuming satellite adopts both active and passive power thermal system. Passive thermal controls have the advantage of high reliability and also electrical power is not needed. Indian satellite developed in early days like Aryabhatta, Bhaskara were using passive thermal controls. It includes multi layer insulation (MLI) to protect from planetary environments, optical coating & louvers for selective thermal emission & absorption, thermal fillers/doublers for thermal coupling/ spreading , surface mirrors for reflecting and reducing the absorption of thermal radiation. These devices/ processes suffer from the fact that they have lower level of thermal control, limited temperature range and also degrade with time.

Satellite requiring high power is using both active and passive thermal control system. Most of the communication satellite including INSAT are using these system. Active control system include thermostatically controlled resistive heater, fluid loops & heat pipes to disperse heat, thermoelectric coolers, sterling cryogenic coolers. These systems handle higher power, better control of temperature but consume valuable electrical power and reliability is also lower. These systems also have out grown in their applications for modern & future spacecraft. They are able to handle thermal load of few kilowatts, temperature control in limited range and performance is affected when encountering wide fluctuation in thermal load. Further limitations are visualized when localized thermal and accurate temperature controls are required in highly dense electronics circuitry.

Modern spacecraft particularly for inter terrestrial applications [2] are operating at severe thermal condition and needs higher accuracy for temperature control. The present paper discusses modern tools which are being developed for higher order of insulation with lower mass, controlling the heat rejection rate when thermal fluctuations are encountered, variable thermal property of surface, high rate of heat transfer, variable thermal conduction and dissipation.

II. THERMAL INSULATION

Thermal Insulation of component is commonly needed to protect them from hazardous environment within & outside the satellite to maintain their temperature. Insulation for very low temperature operating devices like Cadmium – mercury detectors [3] needs to be carefully designed and implemented since they operate in the temperature range of 100 K to 120 K where as electronics operating temperature range is 273K to 313 K. Multilayer insulation (MLI), was the most common & effective method of insulation technology which provides an effective insulation with a well-established flight history. MLI blankets are highly reliable, but require a tedious design and installation process due to its inherent fragility.

MLI is now being replaced by aero gels due to very high thermal resistance and it was successfully used in Mars rovers also. Aero gel components are formed by replacing the liquid phase in a silica gel with air. The pore structure of the gel is maintained by drying above supercritical conditions. The interfacial tension between liquid and vapor phases are significantly reduced by almost eliminating capillary forces which may result in shrinkage and pore collapse. Besides, exhibiting outstanding thermal insulation & noise insulation characteristics, it becomes one of the lightest solid material which has the density around 0.03 gm/cm^3. It has achieved a thermal conductivity of 0.74 mW/ m-K in the normal operating temperature range of satellite, moderate vacuum levels and can handle up to 200 psi of compression before the thermal performance is noticeably affected. It can also withstand repeated flexure loads which are much higher than MLI. Furthermore, the out gassing characteristics of aero gel blankets are significantly lower than MLI. However aero gels have limited flight history and are also significantly higher in cost than MLI blankets.

Aero gels are also used for surface glazing, although the largest window produced is 1 m^2. It is found an evacuated aero gel glazing provides about 19% reduction in energy transfer in comparison to an equivalently sized triple-layered argon-filled glazing. Though, it does not meet the visual quality of conventional glazing systems, but has potential for large applications. Based on performance alone, aero gel technologies are also well suited for a wide-range of terrestrial applications. However, market penetration is slow due to high cost which is not important for space technology.

III. VARIABLE HEAT-REJECTION SURFACES

Large variations in thermal load and environment temperatures of the spacecraft needs to modify thermal characteristics or/and view factor of the surface. In present scenario passive thermal control system is difficult to use and thermal characteristics of surface is not modified. These modifications were usually carried out by active thermal control system. In one of the system, surface view factor was modified by given on board command to the louvers. They modify the view factor and therefore heat transfer characteristic of the surface. However modification in vie factor is limited. The movement of louvers & command requires electrical power and also affects the reliability of the system.

A novel method [4] which is now being adopted is to vary surface absorptivity and emissivity which controls heat rejection and absorption from outside environment. The surface emissivity is varied by adopting electro chromic devices (ECDs) which is a chemical process to vary the surface property. ECDs consist of series of layers of chemicals to vary the surface property as required for thermal control. Initial layer is a reflective electrode (RE) that has a mirror like reflectance in the thermal infrared region and is formed on the spacecraft skin. Other layers are active surfaces which are mounted on the RE. They consist of electro chromic (EC), ion conductor (IC), and ion storage (IS) layers. The IC layer thermally conducts, but provides electrical insulation between layers. The EC and IS layers are electrochemically active metal oxides that are composed of electrons and ions. Finally, a transparent electrode with high conductivity and transmissivity protects the under laid layers from atomic oxygen. The ECD operates by applying a small voltage of the order of 2 volts to move the ion and electron pairs between the EC and IS layers.

When a voltage is applied, one of the active metal oxide layers will experience increase in absorptivity due to intercalation and the other active metal oxide layer simultaneously experiences an increase in absorptivity also due to ion extraction. In case, the process is reversed, the emissivity of the active layers increases. Proper design of these layers makes the surface thermal property to change an order of magnitude from the original magnitude at will. Thermal control methodology exposes such surfaces to maximum extent for controlling large variation in thermal energy. It is desirable to have a transparent electrode on the outer surface of the ECD to protect it against the atomic oxygen effects. The ECD not only has a low density of about 5 g/m^2, but also achieved large range of emission characteristics .These layers are having high reliability since moving parts are eliminated and variation in surface property is obtained by applying small amount of voltage.

ECD technologies have potential [5] for normal terrestrial applications [6] by integrating them into building windows. It is based on transmissivity modulation in the visible spectrum for both interior lighting and space-cooling improvements. It needs integration of the ECD technology [7] with dynamic window within building systems and also development of control algorithms, diagnostic tools, and feedback evaluation & modulation. Though it saves energy and provides more comfort but requires costly coatings and programming.

IV. NANO FLUIDS FOR HEAT PIPES

Heat pipes are being used to transfer large amount of heat from between components. To further increase in heat transfer one location to other without affecting temperatures of in rate nano fluids are being incorporated in the heat pipes. Various fluids used in heat pipe include mercury / sodium in temperature range of 500-1500^{0}C to cryogenic fluid using Helium and Nitrogen, for few Kelvin temperatures. Considerable improvements in heat transfer rates are recently reported by the development of nano fluids [8], or fluids consisting of a conventional heat transfer base with nanometer sized oxide or metallic particles suspended in the liquid. Li, et al [9] demonstrated through their experiments significant improvements in heat transfer characteristics of heat pipes by dispersing copper, alumina- silver suspended in water. Moreover, further study by Shukla [10] et, al revealed that copper suspended in ethylene glycol further improves the heat transfer rate which looks like a thermal conductivity which is not possible to achieve by any known metals. These systems reported more than 20- 30 % increase of the thermal conductivity by dispersing about 0.1% nano particles. Furthermore, the magnetic affinity of the solid particles in suspensions allows for their manipulation by electromagnets, thereby eliminating the need for conventional pumps.

Such experiments have created interest in the application of a nano fluid-based heat pipes for thermal management system for satellite applications. Considering theses advantageous effects, the fluid with ultra fine suspended nano particles will be the advanced fluid for satellite applications of the heat pipe. Such improvement in heat transfer will result in oil-less operation, compact size, reduced weight, and hardly any power consumption. NASA [11] has therefore set a road map for the development of high temperature heat pipes with nano fluids for the high heat flux encountered during ascent and reentry of the space vehicle.

V. MICRO HEAT PIPES

The development of high density electronic fabrications and innovative control devices has led to high thermal cavities formation in several circuits for various applications. These isolated spots are location of high density thermal dissipation which affects the adjoining components and circuitry. It becomes all the more complicated in space application where convective heat transfer is almost eliminated due to absence of environment. These hot spots have been studied by different research groups to dissipate thermal energy by passive and active cooling mechanism. The study include several aspects such as package design , thermal interface, material of low thermal resistance, heat sinks and cooling systems . It is now considered, the most effective way to spread these heats with the low thermal resistance by micro heat pipes.

In late nineties, Cotter has come out with the definition of micro heat pipes which has the dimension in the range of 10 to 500 µ cross sections and length of 10 to 20 mm. Several researchers have introduced series of developmental methodology of these micro heat pipes [12]. One of the hot favorite is now based on silicon wafer and copper deposited channels to form a micro heat pipe. It provides high wetting of the surfaces [13] for ease in flow of liquid . These heat pipes have the problem of wick drying which prevents the fluid to come back from condenser to evaporator section. A novel design is adopted by introducing side channels which are called arteries to wet the wick and flow back of liquids is established. These arteries [14] have further smaller cross section than the main heat pipes but establish a sound uninterrupted flow of fluid for continuous operation without any power. The water used as liquid could achieve the thermal conductivity of about 290 W/m·K while the mercury filled heat pipes have achieved thermal conductivity of 790 W/m · K.

VI. PARAFFIN BASED HEAT SWITCHES

Heat switches / thermal switches are now being used as good thermal conductor as well as bad thermal conductor of heat as required by the design of the space craft. It is normally mounted between the heat dissipating component and radiator to control the heat flow as required passively. They are also used at cryogenic temperature and work as isolator in case system is not operating and good conductor in operational stage. However, the operation time of these switches are not that fast as electronics devices. But they are designed to meet thermally required time constant for specific applications.

The most common material used is paraffin which needs to be refined and synthesized to meet specific requirements. It melts at different temperature for different composition which is mainly dependent upon the number of carbon atom in paraffin chain. The ease in obtaining variety of melting point allows designer to use them in large temperature range of -90 to + 800C.

Japan aero space agency [15] have developed for their inter terrestrial application a paraffin based heat switch for their future spacecraft mission for mars. The environmental testing of their bread board model (BBM) has shown quite encouraging results. The goal set for their development requires the thermal conductivity variation of 1W/K to 100W/K in operating condition. The BBM model has proposed several alternatives which include different types of base coating including of gold and achieved the variation of 1.6 W/K to 127 W/K.

In late 2013, NASA [16] has selected eight proposals for advanced research and development for thermal controls on board space craft. Out of these 8 proposals four belong to variable thermal controls and switching as required. Each of these proposals will have first phase funding of 50,000 $

VII. HYBRID TWO PHASE LOOP TECHNOLOGY

Two-phase cooling technologies on board satellites are being used for thermal controls in heat pipes. These technologies also include loop heat pipes (LHP) and capillary pumped loops (CPL). They are passive system and therefore have high reliability. But these passive devices are not able to meet the thermal demands now required in satellites in terms of thermal fluxes, transport distances and multiple heat source capabilities.

NASA's Mars Exploration Rover has used mechanical pumps to reject heat successfully. But it suffers from the fact that system has low reliability due to large pumping pressure, flow instability in micro-channel, complex fluid reconditioning and nozzle clogging/erosion. It has significantly reduced the merit of such active system for space applications

Recently, a hybrid system using pump-assisted two-phase cooling with heat pipes is finding popularity for satellite applications. In Hybrid Two-Phase Loop [17] (HTPL) technology, a small active mechanical pumping system is added with passive capillary pumping heat pipe. Such a system consists of evaporators, a condenser, a liquid reservoir and a mechanical pump. The heart of the system is evaporator where heat needs to be absorbed. It has inlet fluid connection, an excess liquid outlet and a vapor outlet. The evaporator has capillary structure which distributes liquid while separating vapor from excess liquid. It provides the best boiling condition regardless of varying heat inputs. Further improvement in the technology is carried out by adding more than one evaporator which removes heat from more than one source. Similar system with evaporator added in parallel has demonstrated hybrid loop which is capable of managing multiple heat sources. The result projected for such system is quite encouraging and have potential for space applications. It has dissipated 4kW of heat load per evaporator from the source area of 135cm². It is equivalent to the heat flux of 30W/cm².

The minimum thermal resistance in evaporator was 0.17°C-cm²/W which was relatively constant even for various heat loads from 500W to 4000W. The hybrid two-phase loop also demonstrated the operation of asymmetric heat input multiple evaporators which insignificantly affect the loop operation.

The hybrid two-phase loop has demonstrated a robust operation system which has high reliability, compact cooling systems with large design flexibility and transferring large heat transfer. It has wide applications for various space crafts under zero gravity conditions.

CONCLUSIONS

The existing active and passive thermal control systems for on board satellites have out lived their application particularly for inter terrestrial applications. These systems have limited range of thermal control and to withstand variable heat fluxes require active processes. Aero gel is a good replacement of passive thermal control system using MLI to provide high degree of insulation, higher operative temperature range and variable heat fluxes.

Development of ECD technology makes it possible to change the thermal characteristic of surface of the satellite as required to meet various environment and operating conditions. Inclusion of nano fluid & hybrid technology in heat pipes have great potential for much higher rate of heat transfer and parallel operation of thermal control system. Micro heat pipes with arteries are the exciting prospects to dissipate heat from hot spot within high density circuitry to radiator. Passive thermal switches could initiate and stop heat transfer from one location to another on board satellites without the use of power.

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