Advanced Thermal Control Technologies for Space Science Missions at JPL

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Abstract. A wide range of deep space science missions are planned by National Aeronautics and Space Administration for the future. These missions include planetary orbiters, planetary landers/rovers, planet/comet flybys, and planet/comet sample return missions. Many of these missions are being planned under strict cost caps and advanced technologies are needed in order to enable these challenging missions. Because of the wide range of thermal environments the spacecraft experience during the mission, developing an appropriate thermal control system for the spacecraft is both complicated and challenging. Advanced thermal control technologies are the key to enabling many of these missions. Such technologies are being developed at the Jet Propulsion Laboratory for a wide range of spacecraft thermal applications. These applications include: temperature control, minimizing heat losses, precision temperature control of large structures, universal thermal architecture for future missions, microspacecraft thermal technologies, and micro-electromechanical systems based thermal technologies for micro/nano spacecraft.

INTRODUCTION

Future deep space science exploration envisioned by National Aeronautics and Space Administration includes a diverse set of missions to several planets, moons, comets, and the Sun. The thermal requirements of the science and engineering equipment for these missions are so stringent and challenging that traditional thermal control technologies can not meet them. Furthermore, the need to meet the new NASA objective of "faster, better, and cheaper missions" has forced the spacecraft designers to consider advanced thermal control technologies as a means to meet the new requirements. Jet Propulsion Laboratory (JPL) has been investigating advanced thermal control technologies for the last five years for use in future deep space science missions.

The individual advanced thermal control technologies under development at JPL are being examined for specific thermal control application such as landers, rovers, orbiters, flybys, sample return vehicles, and earth orbiting instruments. The spacecraft destinations include various planets, comets, Sun, and also the Earth. Further, there is a strong desire to make future spacecraft designs more robust and more universal thus moving toward the NASA objective of "faster, better, and cheaper". In this paper, various thermal control applications for future NASA missions are described along with the thermal technologies that need to be investigated.

THERMAL CONTROL APPLICATIONS

The future deep space science mission thermal control applications include: spacecraft temperature control, minimizing heat losses from spacecraft, precision temperature control of large structures, universal spacecraft thermal architecture for future science missions, and macro- nano sciencecraft thermal control. Furthermore, several technologies are also examined for making future spacecraft design more robust and universal. A robust spacecraft design makes the spacecraft design more reliable for any late changes in the mission or spacecraft requirements during the design phase. A robust design also makes the spacecraft overcome most of the anomalies that are normally encountered during the flight of the spacecraft. An universal spacecraft thermal control architecture makes the spacecraft design cycle faster which is essential for future NASA science missions. The frequency of science missions is expected to increase enormously in the future especially with the use of multiple number of microspacecraft planned to be missions in a single launch.

Maintaining Allowable Flight Temperatures

In the spacecraft thermal control area, applications are basically maintaining temperature sensitive equipment such as electronics, electric battery, and instrument sensors within their allowable temperature limits. Typically, electronics needs to be maintained in the range of 20 C to +50 C during operation and its non-operating allowable range is 40 C to +70 C. Secondary electric batteries have an allowable temperature range of 20 to 30 C. For long-term storage, batteries at 0 C or lower will last longer. In contrast while charging and discharging, the battery efficiency is highest at 20 C. The requirements for sensors used in instruments can range from as low as - 200 C to as high as + 40 C. The rover mechanical hardware such as motors, actuators, and mechanisms on planetary surface have a requirements of above –60 C for reliable operations.

NASA is planning to send science missions to comets and planets in the future to explore these bodies through in-situ science experiments or by bringing the sample back to earth for further investigation. One of the thermal control challenges of these missions is to maintain the sample at its original temperature until the sample recovery on earth.

Several thermal control technologies are used for maintaining sensitive equipment temperatures. In the area of heat removal and rejection the applicable technologies are high thermal conductivity materials; high heat transport devices such as fixed conductance heat pipes, loop heat pipes, capillary heat pipes, mechanically pumped cooling loops, and low absorptivity to emissivity passive coatings. The technologies used for conserving heat are high performance lightweight insulation, phase change materials (PCM) storage, heat switches, and variable emissivity coatings. Passive and active coolers provide low temperature needs.

Survival Heater Power Applications

One of the key thermal design drivers for the earth orbiting and planetary spacecraft is keeping the survival heater power low. For planetary spacecraft these conditions occur during diurnal variation of ambient temperature. The temperature during the Martian night can drop below -100 C and batteries must provide the heater power to keep the sensitive equipment above its survival temperature. In order to keep the battery size small it is important that that the survival heater power be as low as possible. For Mars rover applications an arrangement using a loop heat pipe and phase change material thermal storage is being investigated.

The temperature on comets can be as low as –200 C. The sample collection and in-situ testing periods on comets may last as much as several days. During these periods the spacecraft and its equipment need to be kept above allowable low temperature limits by survival heaters. Similarly the deep space missions to outer planets such as Jupiter, Saturn, and Pluto require survival heater power once they are farther away from the Sun (beyond 3 to 4 Astronomical Unit [AU] distance where one AU is the distance from earth to Sun). For earth orbiting spacecraft, there are several occasions where the power from the solar panel will not be available and the spacecraft has to be on survival power. Typically these are instances when the spacecraft is in 'safe mode' with its solar panels turned away from the sun. Because the survival power is provided by the batteries which have finite amount of energy, it is paramount that the amount of heat lost by the spacecraft be as small as possible.

Several thermal control technologies are employed for minimizing survival power. In the area of thermal conductance modulation, the technologies investigated are: loop heat pipes, mechanical heat switches, mechanically pumped cooling loops, and variable conductance heat pipes. In the area of radiative heat rejection modulation, the technologies being investigated are variable emittance devices and deployable radiators. In the area of heat conservation, technologies such as high performance lightweight thermal insulation and phase change material thermal storage are investigated (Birur and Novak, 2000).

Precision Temperature Control of Structures

There is a large demand for the precision temperature control of structures (both large and small) on future spacecraft. In order to obtain the science data of high fidelity, many science missions require that the mechanical hardware maintain a precise dimensional stability. The key parameter that influences the mechanical stability is the hardware temperature distribution. One way to maintain high dimensional stability is to control the temperatures very precisely. The typical spacecraft structures that require high dimensional stability include optical benches, large antennas, and large structures used in interferometry applications.

Typical thermal control technologies needed for these applications are similar to those needed in the survival power applications. These included loop heat pipes, active cooling loops, mechanical heat switches, variable emittance devices, high performance insulation, and phase change material thermal energy storage. In addition, double precision thermal modeling of the structures are also needed.

Universal Spacecraft Thermal Control Architecture

Thermal control design for spacecraft is strongly influenced by the spacecraft configuration and mission thermal environment. Usually, the configurations vary significantly for each mission; a variety of spacecraft configurations are used in order to meet the needs of the individual missions. Furthermore, the mission thermal environment varies depending on whether the mission is to a planet, comet, sun etc. This variation in mission concepts and thermal environments indicates that major benefits would be derived from a flexible thermal control design concepts that would enable faster and less expensive design cycles. JPL is investigating an universal spacecraft thermal control architecture based on thermal energy management called, the Integrated Thermal Energy Management System (ITEMS). In ITEMS, a cooling loop thermally integrates all the spacecraft subsystems 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 above what is needed is rejected at a deployable radiator system which uses variable emittance devices on its surface. This type of architecture provides the needed flexibility and accommodates low–cost overall design and implementation. This architecture is shown schematically in Figure 1.

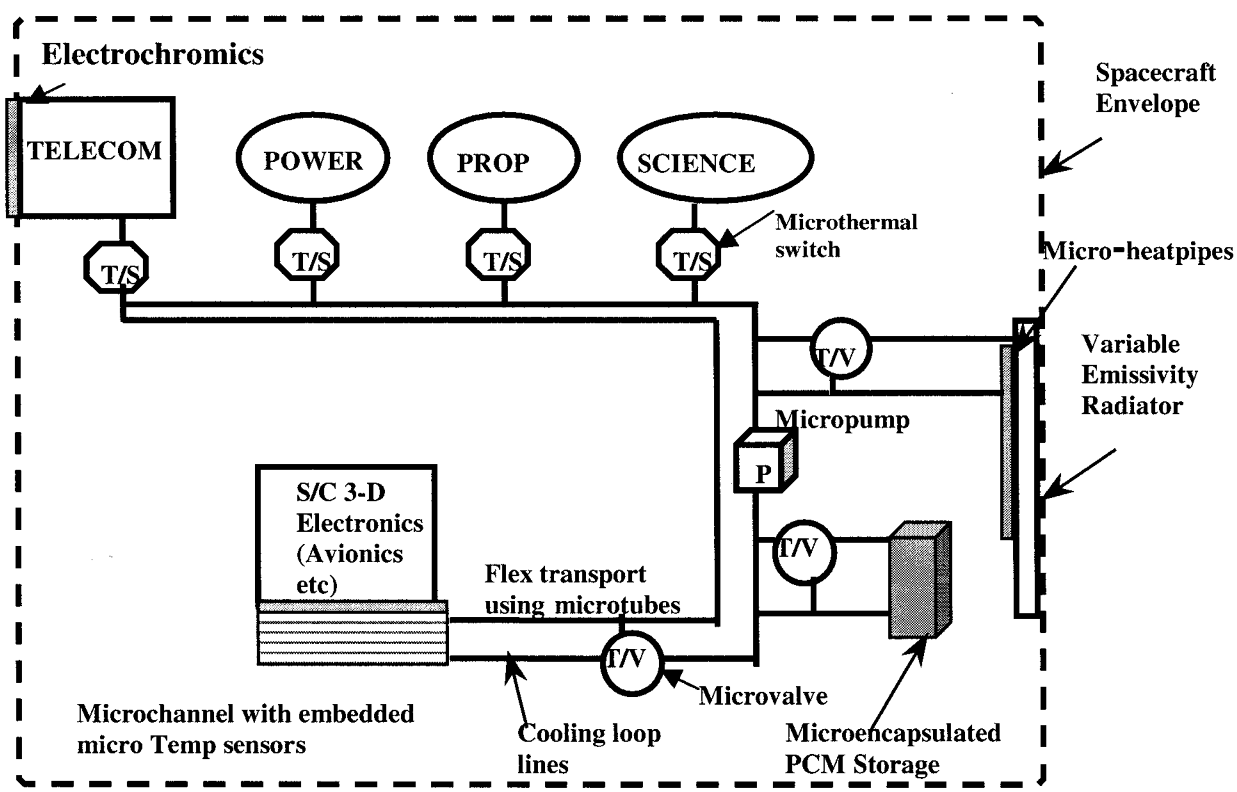

FIGURE 1. Universal Microspacecraft Thermal Control Architecture

It is expected that because of the availability of the smaller and cheaper microspacecraft, many space missions are going to be launched using microspacecraft. In order to enable these low cost missions to be launched, it is important that the cost of all subsystems, including thermal, be minimized. The universal thermal architecture provides these benefits for future microspacecraft.

Micro/Nano Spacecraft Thermal Control Applications

Thermal control applications of future micro/nano spacecraft are both complex and challenging. The future microspacecraft are expected to be less than 0.5 meters in physical size and have power levels of less than 50 Watts. These microspacecraft are going to be used for missions to inner planets with hot environment, outer planets with cold environment, for planetary landers and rovers, comet and planet sample returns, magnetosphere mapping etc. The thermal control technologies needed to meet the microspacecraft requirements include miniature heat switches, miniature thermal control valves, miniature louvers, miniature heat pipes, miniature mechanical pumps (Birur, G.C. and Bruno, R. J, 1999). These miniature technologies are of an order of magnitude smaller than the thermal hardware used in the current spacecraft.

Even though the spacecraft power levels are smaller than 50 Watts, the power densities of the electronics and some sensors can be higher than 25 Watts/m^2. Some of the examples of this are: 1) compact avionics planned for future microspacecraft, 2) compact sensors and instruments requiring demanding thermal control, 3) compact high power lasers for optical communications, and 4) System-On-A-Chip sciencecraft with high power densities. These high power density applications require that micro-electro mechanical systems (MEMS) based thermal technologies to provide the thermal control for the future microspacecraft. The MEMS based thermal technologies that are being or going to be investigated include microchannel based single and two-phase cooling systems, micropumps for circulating liquids, variable emissivity radiators to modulate heat rejection, thermal switches and valves.

THERMAL CONTROL TECHNOLOGIES

Individual technologies are being developed for specific thermal control application on the spacecraft. Some of the technologies are specifically geared towards a particular application whereas, others can be used to meet the needs of several applications. Some of the key technologies that are being investigated at JPL are described here. Some these technologies are specifically examined for a particular mission. An example of this is the variable conductance miniature loop heat pipe that is being examined for Mars rover battery thermal control application. Some technologies are examined for applications on any generic mission. An example of this is the variable emittance electrochromic device that can be used on any of the deep space or earth orbiting spacecraft.

Loop Heat Pipes

The loop heat pipes (LHP) are increasingly being used in earth orbiting spacecraft and communication satellites (Maidanik, 1995; Ku, 1999). LHP was originally developed in the former Soviet Union and since has flown in several Russian spacecraft. They are two-phase passive heat transfer devices that use capillary action of the wick structure to pump the liquid from the condenser to the evaporator. Unlike the fixed conductance heat pipes where the capillary groves or wick are located along the entire length of the pipe, the main wick in the LHP is located only in the evaporator. The LHP consists of four major elements: 1) an evaporator where heat is collected by the working fluid, changing its phase from liquid to vapor; 2) a condenser where the vapor condenses and releases heat; 3) a compensation chamber (CC) where the excess working fluid is stored, and 4) the transfer tubes which carry the vapor from evaporator to the condenser and carry the condensed liquid back to the evaporator through the CC.

A miniature variable conductance loop heat pipe (VCLHP) is being investigated at JPL for the Mars rover battery thermal control application. The VCLHP was designed and fabricated by the Dynatherm Corporation of Hunt Valley, Maryland for JPL in June 1999 (Figure 2). It is currently undergoing tests at JPL (Birur et al., 2000). The VCLHP has two condensers, one is on the battery and the other is the external radiator. The variable conductance function for the LHP is provided by a passive thermal valve integrated in the LHP. This valve allows the external radiator to be bypassed when the evaporator temperature drops below a certain temperature. The VCLHP is designed for heat transfer applications with power levels of 60 Watts or below. The battery thermal application being investigated is for power levels of less than 10 watts.

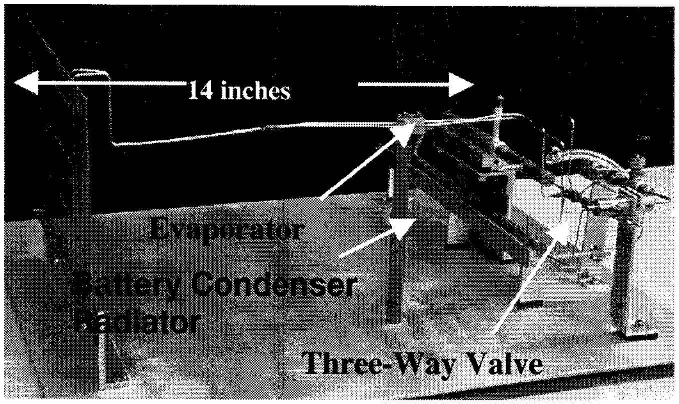

FIGURE 2. Photograph of the Miniature Variable Conductance Loop Heat Pipe.

Phase Change Material Storage

A PCM thermal storage unit was designed and fabricated for use with the VCLHP. The PCM is dodecane, which has a melting point of –9.6 °C with a heat of fusion of 217 kJ/kg and a density of 720 kg/m^3. A thermal storage enclosure containing this PCM was designed so that the batteries can be housed inside. Energy Science Laboratories Inc., (ESLI) of San Diego, California, designed and built the unit in late 1998 to JPL's specifications. Typical challenges in using PCM thermal storage are the poor thermal conductivity of the PCM in its solid phase, containment of the PCM in a leak-tight container that can handle expansion and contraction during the freeze-thaw process, and minimization of the PCM system mass. Several novel features were used in the design and fabrication of the PCM storage unit. A carbon fiber core, used to provide the PCM with a good thermal conductivity in its solid phase, also provided structural strength to the module. Thin-walled aluminum sheets were used to build the container. The construction of the unit used structural epoxies to bond the various container parts. A photograph of the PCM thermal storage unit is shown in Figure 3. The PCM unit was 350 mm long and 95 mm in diameter. The various components of the unit and their mass are as follows: carbon fiber core of 80g, dodecane PCM material of 530g; and aluminum wall material of 175g.

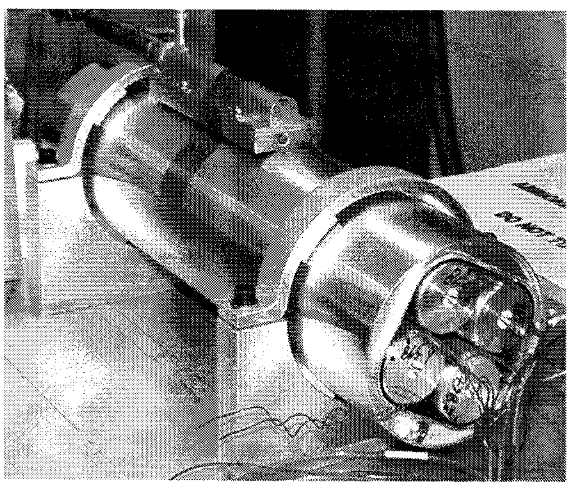

FIGURE 3. Phase Change Material (PCM) Thermal Storage System for Battery Thermal Control.

Mechanical Pumped Loop

Mechanically pumped cooling loop technology that was successfully demonstrated on Mars Pathfinder is being further developed for longer life missions (Birur, G.C. et al., 1996; Birur and Bhandari, 1998). The pump used was a centrifugal pump driven by a brushless dc motor. The pump had capacity to pump 0.2 gallons per minute (gpm) of Refrigerant 11 with a 4 pounds per square inch differential (psid) head in the temperature range of –20 to 30 C and consumed about 10 watts of power. The pump assembly unit, which weighed about 8 kg, was installed into the cooling loop on the spacecraft. The cooling loop operated continuously for over seven months on the Mars Pathfinder. In a life test setup, the pump has been successfully tested for a continuous operation of 14,000 hours.

A bearing and seal free pump is developed under NASA Small Business Innovative Research contract for space applications that require reliable long life pump. This pump technology was developed by Advanced Bionics Inc, of Minnesota for artificial heart applications. This pump is currently being life tested at JPL Thermal Technology Laboratory. The working fluid in the pump is Refrigerant 11 pump produces a pressure head of 4 psid at flow rate of 0.25 gpm. As of writing of this paper, the pump has been operating for over 1000 hours without any change in the performance of the pump

Variable Emittance Devices

In the area of variable emissivity devices and thermal switches, two specific technologies are being investigated. Electrochromic (EC) devices are being evaluated for their variable emissivity property for replacing thermal control louvers on future spacecraft. The cost and mass of electrochromic devices are an order of magnitude lower than that of the mechanical louvers currently used on spacecraft. EC devices operate on the principle that an EC material changes its reflectance infrared wavelengths by the addition or removal of ions or electrons. By applying a small biased voltage (less than 2 Vdc), the charged ions are either collected or removed from the EC layer of the device resulting in a change in the infrared reflectance of the device. Two EC materials have been investigated. One is based on an inorganic material such as tungsten trioxide and the other is an organic material based on conducting polymer (Chandrasekhar, 1999).

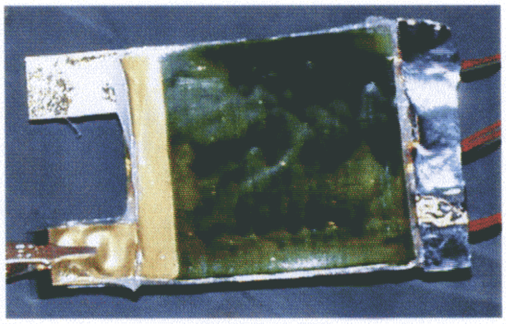

FIGURE 4. Variable Emittance Electrochromic Device (Ashwin-Ushas).

EC devices based on conducting polymers are currently undergoing tests at JPL for their performance and also for their reliability in space environment for long term operation. A sample of EC device fabricated by Ashwin-Ushas of New Jersey is shown in Figure 4. The IR emissivity change from 0.39 to 0.74 has been measured on these devices so far. Development and tests efforts are currently underway in increase this 0.3 to 0.8 leading to a dynamic range of 0.5 which is similar to what is currently obtained from mechanical louvers. Further, these EC devices weigh less than 400 gm/ sq meter compared to a mass of 5 kg/sq meter for the mechanical louvers.

Lightweight Thermal Insulation

High performance light-weight thermal insulation is another technology that is very important for the future spacecraft, especially for future Mars landed missions. New insulation types consisting of aerogel and carbon dioxide as the insulation media are currently being examined (Birur, Tsuyuki, and Stultz, 2000). These new types of insulation reduce the mass by 50% compared to the batt thermal insulation currently used for Mars surface landers. In a concept using carbon dioxide as a thermal insulating medium, the insulation is fabricated using two layers of aluminized Kapton separated 4 cm by a Mylar stand-offs. The gap between the two layers would be filled with carbon dioxide. In the Martian surface operation, the gap in the insulation is automatically filled by the 8 torr carbon dioxide that exists naturally in the environment. A thermal conductivity of 0.022 W/m C at –25 C has been measured in tests which is comparable to that of the batt insulation.

Mechanical Heat Switch

Mechanical heat switches have not been extensively used for spacecraft thermal control applications in the past. This has been due to low performance (on/off heat transfer ratio) of the switch and the large switch mass needed to conduct heat. Heat switches based on gas-gap are being investigated for situations where the heat transfer rates are small. Heat switches based on bimetallic mechanism have been occasionally used in the past but again for low heat transfer rates. Wax actuated heat switches are currently being investigated for spacecraft thermal control applications at JPL Starsys of Boulder, Colorado, which has developed the wax actuated heat switch for space applications, is modifying their design for JPL for application to Mars surface conditions. Mars surface conditions, where an 8 torr carbon dioxide atmosphere exists, requires that the gap in the switch be substantially larger than that used in space. The current Starsys actuator, which weighs about 100 grams provides a heat transfer of 0.7 watts/C and has ratio of 100 for on/off operation (Lankford, 1999). The heat switch for Mars application is expected to weigh about 60 gms and have conductance Of 0.45 Watts/C and a ratio of 25 between the closed and open position.

A miniature heat switch is being developed for use on future microspacecraft applications under the NASA SBIR program. This heat switch technology which is developed by Energy Science Laboratory Inc. of San Diego, California, is expected to reduce the heat switch mass by an order of magnitude compared to the current state-of-the-art heat switch technology. The heat switch uses phase change material (PCM) based actuator to obtain high heat transfer rates with low switch mass. A switch based on this technology has demonstrated a performance of 0.12 Watts/C with a open/close ratio of 18 and weighs under 8 gms and a contact area of less than 6 square centimeters. The current development has goals for enhancing the performance by an order of magnitude.

MEMS based Pumped Cooling Loop

The current interest in micro/nano spacecraft for future science missions by NASA has necessitated developing micro-electro mechanical systems (MEMS) based thermal control technologies for removing heat from very high power density electronics, lasers, and sensors. The main reason for this is that even with the lower power levels of these spacecraft, the electronics package power densities have increased because of the shrinking size of the spacecraft. Some of the future micro/nano spacecraft that are being investigated have dimensions as small as 10 cm to 15 cm on the side and 5 to 10 cm in height. These systems, called System-On-A-Chip could have power levels of 20 to 50 Watts and package avionics, propulsion, thermal control all as a single unit. The power densities in these future microspacecraft is expected to be as high as 25 Watts/ sq cm.

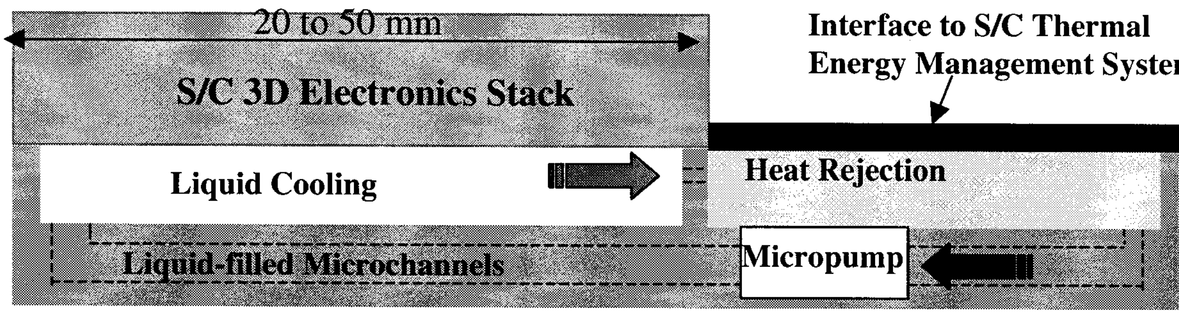

FIGURE 5. MEMS based Pumped Liquid Cooling System for Micro/Nano Sciencecraft.

A MEMS based liquid pumped cooling system is being investigated at JPL. In this technology, a single phase liquid is used to remove heat from high density electronics and reject it at a heat exchanger. The liquid is pumped through microchannels etched in silicon substrate which is attached to the electronics package. The heat removed by the liquid is rejected at another heat exchanger which is heat sunk to the spacecraft cooling system. A schematic of this concept along with a picture of the actual microchannel device is shown in Figure 5.

CONCLUSIONS

Advanced thermal control technologies are needed to meet the needs of the future NASA science missions. These are needed for various thermal control applications such as keeping the spacecraft equipment within their allowable temperature limits, minimize the spacecraft survival power, dimensional stability of large spacecraft structures, and micro/nano spacecraft thermal control. Several thermal technologies are being investigated at JPL for these applications. Some of these are improvements of the technologies that are recently demonstrated such as mechanically pumped cooling lops and loop heat pipes whereas others are new revolutionary technologies such as electrochromic devices for variable emittance properties and MEMS based devices for thermal control. At the current level of research and developmental efforts, some of these technologies are expected to be ready for flight applications in two to five years time. These technologies are expected to enable many future NASA science missions.

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