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NASA Thermal Control Technologies for Robotic Spacecraft

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Abstract

Technology development is inevitably a dynamic process in search of an elusive goal. It is never truly clear whether the need for a particular technology drives its development, or the existence of a new capability initiates new applications. Technology development for the thermal control of spacecraft presents an excellent example of this situation. Nevertheless, it is imperative to have a basic plan to help guide and focus such an effort. Although this plan will be a living document that changes with time to reflect technological developments, perceived needs, perceived opportunities, and the ever-changing funding environment, it is still a very useful tool. This presentation summarizes the current efforts at NASA/Goddard and NASA/JPL to develop new thermal control technology for future robotic NASA missions.

Key Words: advanced thermal control, capillary pumped loops, loop heat pipes, variable emissivity surface, cryogenic, heat switches

1. INTRODUCTION

The National Aeronautics and Space Administration's (NASA) Goddard Space Flight Center and Jet Propulsion Laboratory primarily support the agency's Space Science Enterprise and Earth Science Enterprise missions. These are robotic, unmanned missions that typically are in Earth orbit, go to a Lagrangian point, or go to another planet. All these missions have one overriding purpose: the pursuit of new scientific knowledge. NASA is continually trying to look further out into space, into new parts of the spectrum, investigate alien planetary and solar environments, gain better resolution than ever before, and pursue similar scientific objectives. Clearly, the pursuit of such goals requires advanced engineering to make it all possible. This is particularly true for thermal control. Many of the proposed future missions involve science that can only be obtained at deep cryogenic temperatures, with extreme dimensional stability, typically with very tight and stable temperature control, and with related requirements that drive the need for new thermal control technology. Another reason for the advanced thermal control technology are for developing lighter, less power consuming, more reliable and more capable space science missions to explore the deep space and other planets,

2. STATE-OF-THE-ART IN THERMAL CONTROL

Two-phase technology, such as Capillary Pumped Loops (CPLs) and Loop Heat Pipes (LHPs) is clearly the major thermal control innovation of the last decade and as such defines the state-of-the-art. This technology has now gained acceptance and is used in a variety of NASA and commercial applications. For example, NASA's TERRA spacecraft, which was launched in December of 1999, has three CPLs that have been in successful operation since launch. In July of 2001 one of the instruments that is thermally conditioned by a CPL, the ASTER-SWIR instrument, began to experience excessive temperatures. The temperature control point of its CPL was adjusted in-orbit to accommodate this temperature growth, thus extending the instrument's life. Other CPL applications include the Hubble Space Telescope, which has a CPL to remove heat from the NICMOS cryocooler that is located inside the aft shroud. LHP applications include the TES instrument on the AURA spacecraft, GLAS on the ICESAT spacecraft, and the BAT instrument on the SWIFT instrument. In the commercial sector Boeing Space Systems has used LHPs with deployable radiators on its series 702 communication spacecraft.

All current CPL and LHP applications involve the use of a single evaporator. This approach is somewhat limiting. To address this issue the CAPL 3 flight experiment was flown on the Shuttle in December of 2001. This experiment successfully demonstrated the use of parallel evaporators (4) and heat load sharing between them.

Other issues with current CPL/LHP technology include the need for a significant amount of custom engineering to design and integrate the technology, and the preconditioning often required prior to start-up. Nonetheless, advanced two-phase design technologies offer significant design flexibility, tight temperature control, broad heat transport capacity, diode function and isothermalization. This performance is unmatched by any other technology. CPLs and LHPs solve design problems!

Another thermal technology that is providing a robust design for short-term missions of one to two years is the mechanically pumped single-phase cooling system. In this approach a mechanical pump circulates a single-phase liquid to remove heat from the hot engineering and science equipment, and then reject it at an external radiator. This system has been used in Space Shuttle for flight durations of two to three weeks. However, it was first used in a long-term robotic mission (Mars Pathfinder) in 1996. The pumped cooling system provided a robust thermal design for the operation of the spacecraft and made the integration and testing much simpler. The pump operated continuously for over seven months during the spacecraft cruise to Mars. The same pumped cooling system will be used on the Mars Exploration Rover mission which will send two rovers on separate spacecraft to Mars in 2003.

3. FUTURE THERMAL CONTROL REQUIREMENTS

While advanced two-phase technology such as CPLs and LHPs offer major advantages over traditional thermal control technology, it is clear that this technology alone will not meet the needs of all future scientific spacecraft. Emerging trends in spacecraft and instrument design are thus engendering very challenging thermal control requirements, which require increasingly sophisticated thermal control technology. Major drivers include:

- Dimensional stability of large structures
- Deep cryogenic heat acquisition and transport (40 K and below)
- Tight temperature control (+/- 1 ^{0}C)
- Integrated thermal/mechanical/optical systems
- Common thermal design for fleets of micro/nano spacecraft
- High flux heat acquisition with tight temperature control
- Challenging thermal sink situations, especially for planetary environments
- Minimization of mass and auxiliary power use
- Thermal control of inflatable and gossamer space structures

- Thermal control of spacecraft in extreme high temperature environment

Based on surveys of proposed future robotic missions, it is clear the cryogenic structures and other large-scale applications (down to a few Kelvin) are an emerging trend, while stringent optical alignment and sensor needs are requiring ever-tighter temperature control. Heat flux levels from lasers and other similar devices are increasing. Large, distributed structures such as mirrors will require creative techniques to integrate structural, mechanical alignment, and thermal control functions. Planetary environments and missions close to the sun will create unique thermal challenges.

Nano and micro spacecraft will also drive the need for new technologies, particularly since such small spacecraft will have low thermal capacitance. This situation, combined with the need for tighter temperature control, will present a challenging situation when such spacecraft/instruments undergo transients. The use of "off-the-shelf" commercial spacecraft buses for science instruments that may have demanding requirements also presents various challenges. In general, high performance, low cost, low weight, and high reliability are the prime technology drivers.

4. EMERGING TECHNOLOGIES

In response to these perceived needs NASA/Goddard and NASA/JPL are pursuing a variety of thermal control technology development efforts to identify and mature, through flight demonstration as appropriate, promising new thermal control technologies. Current efforts include:

- Advanced thermal control coatings such as variable emissive surfaces that permit adaptive, intelligent control of radiative emissions.
- Cryogenic (3 K to 80 K) heat transport devices (loop heat pipes or capillary pumped loops) for sensor and /or optics cooling which incorporate a diode function.
- Integrated structural, alignment, and thermal control concepts for very large structures.
- Thermal switches for planetary and/or cryogenic applications
- Advanced high conductivity materials, such as diamond films, which may be suitable for cryogenic applications.
- Multi-evaporator/multi-condenser two-phase heat transport loops
- Very high heat flux evaporators such as spray cooling techniques
- Long-life mechanical pumps for single and two-phase pumped cooling loops
- Lightweight high performance thermal insulation material for planetary environment
- MEMS based pumped cooling systems for high power density heat removal
- Phase change thermal storage material for low and high temperature applications

Special thermal control coatings that can change their effective emissivity in response to a controlled signal may be the next major innovation in thermal control. System studies have demonstrated that this technology is capable of savings in make-up heater power in excess of 90%, and/or weight savings of over 75%. These technologies are generically applicable to all spacecraft but are especially suitable for micro/nano spacecraft with very limited power and mass allocations. At least three different technologies are currently under development; electrochromic, electrostatic, and a mini-louver. All three technologies are planned to be flown on NASA's ST-5 spacecraft in 2004. The electrochromic approach involves the use of a conducting polymer on a thin film with a small bias voltage used to change the redox state. The electrostatic concept involves a thin film that has an electrically conductive coating on the inside and a white paint on the outside. It can be electrostatically held off a radiative surface to act as a single layer of multi-layer insulation, or it can be held tight against the surface and radiate heat efficiently. The mini-louver is based on microelectromechanical technology (MEMS) and functions very similarly to a traditional louver, except that the louvers are on the scale of microns. The goal is to demonstrate variable emittance technologies that have a net change in emissivity of 0.4 or more *and* can survive the space environment. All three technologies are currently making good progress towards these goals.

Cryogenic CPLs and LHPs offer numerous design options. They would allow the sensor to be separated from the cryo-cooler thus reducing induced vibration and electromagnetic interference from the cryo-cooler. Improved packaging is also possible because the sensor can now more easily be located in the heart of the instrument while the heavy, and hot, cryo-coolers can be located on the skin. A cryogenic CPL/LHP would also allow a diode function to prevent back heat leaks if the cryo-cooler were turned off or malfunctioned.

A nitrogen based cryogenic CPL was flown on the Shuttle in 1998 and demonstrated reliable start-up and heat transport of over 2.5 watts at approximately 80K. Other cryogenic loops with neon and hydrogen have been built and ground tested with good results (a few watts of power and reliable startup and diode action). The goal is to develop a helium based cryogenic two-phase loop that can transport a few milliwatts at 2 to 4 K.

Thermal switches, either for isolation of cryogenic devices in a warm environment or to keep warn objects from getting too cold in a cold environment, are also under development. While different approaches to this device have been attempted over the years, current research is focusing on wax actuated devices that make/break a contact in response to an external signal. Miniature heat switches for nanosat and Mars rover applications are a key technology for such applications. Target performance is for a conductance of 0.4 W/C, a switching ratio of 30 in an 8 torr CO_2 atmosphere, and a weight of less than 120 grams.

Materials with ultra high thermal conductivity are of interest primarily for use as spreaders. Thc carbon vapor deposited (CVD) form of diamond is one material that offers considerable promise. Diamond is the hardest known material, it has the highest thermal conductivity of any material (about 4 times that of copper and about 20 times copper's diffusivity), it has excellent mechanical strength, is a superb electrical isolator, and also has the lowest coefficient of friction of any known material. CVD diamond is very close to natural diamond in many of these properties and is becoming less expensive, and easier to apply to more materials. Clearly there is a wide range of space applications, such as the first stage of a heat collection/isothermalization system for large aperture telescope mirrors, for such materials. CVD diamond was recently evaluated, with good results, as a diode heat spreader for an application on the Hubble Space Telescope (HST).

While current CPL and LHP applications have been limited to loops with a single evaporator, clearly there are many applications where a multi-evaporator loop would offer significant benefits. The CAPL 3 flight experiment, flown on Shuttle flight STS-108 in December of 2002, successfully demonstrated this concept. The CAPL 3 experiment is a CPL based design with ammonia as a working fluid and a direct condensation radiator. It has four, 2.5 cm diameter evaporators,with polyethylene wicks, in parallel. One of these evaporators is connected to a cold sink via a variable conductance heat pipe and can thus be operated in a condenser mode. Prior to flight the experiment was held in storage, in a fully charged state, for 2 years. While in orbit it demonstrated reliable start-up, continuous operation, high power (to 1400 W), low power (50W), and heat load sharing between the evaporators.

A variety of applications, such as lasers, electronic chips, and advanced propulsion devices, are expected to involve high heat fluxes (above 100 W/cm^2). These applications may require new heat acquisition devices, or at least modifications to current two-phase technology. Spray cooling technologies and electrohydrodynamic (EHD) pumping concepts are currently being investigated to meet these requirements. While spray cooling is currently being developed for ground applications, the issue of spray management in a zero gravity environment is a significant issue for space applications that has yet to be addressed. Technology development efforts in EHD have resulted in greatly improved pumping capabilities (several kilo Pascal), and a liquid nitrogen based loop has been developed and successfully demonstrated. Additionally, a MEMS based pumped cooling system is being investigated for removing heat from high power density electronics and science packages. Heat sinks with microchannels etched in silicon are attached to the heat sources to directly remove the heat by circulating a liquid through the microchannels.

The successful flight of this system on Mars Pathfinder spacecraft and the benefits offered by mechanically pumped cooling system has encouraged thermal control engineers to explore this option for long duration space missions. Long-life mechanical pumps suitable for space missions are being developed for future missions. In one technology, a pump with no bearings and seals is being tested for its suitability to future long-duration planetary missions.

In the area of phase change material (PCM) storage, two technologies based on paraffin waxes are being investigated. Dodecane (melting point, –10.5 C) and hexadecane (melting point, 18.5 C) are used in thermal storage capsules for controlling the battery temperatures in the future Mars rovers. One of the key PCM storage technology is the high conductive matrix inside the PCM storage unit that can provide a good conductive path and also survive several hundreds of diurnal thermal cycles expected on the Martian surface operation for the future rovers.

5. CONCLUSION

Two-phase, ambient temperature, single/multiple evaporator thermal control loops are here and are gaining increasing acceptance for flight applications. Numerous examples of single evaporator applications are already in-orbit and several others are in assembly. This technology is proving itself to be highly versatile and offering a performance capability unmatched by conventional thermal control technology. In response to the perceived requirements of future mission, a variety of new thermal control technologies are being developed. Chief among these are the variable emittance thermal control coatings, which probably represent the next major advance in thermal control. Other technologies actively being developed include cryogenic two-phase loops (down to 3K), thermal switches, ultra high thermal conductivity materials, mechanically pumped two-phase cooling systems, phase change material thermal storage, and technologies to accommodate very high heat fluxes. Rich opportunities exist as these and other technologies offer increasing options for the thermal engineer.

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