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Proceedings of the 13th International Heat Pipe Conference

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Shanghai, China

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CHINA ACADEMY OF SPACE TECHNOLOGY

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FOREWORD

The 13th International Heat Pipe Conference (13th IHPC) was held from September 21 till 25, 2004 in Shanghai, China. Totally 122 full papers were submitted and 203 participants from 23 different countries attended this conference. Many eminent scientists and engineers working on heat pipe science and technology presented their latest accomplishment. Moreover, there were 14 companies who exhibited their products related to heat pipes. I believe this conference could serve as a platform for all the participants to exchange information and experience. Many important issues were communicated and discussed on the conference. It will definitely contribute to the further development of heat pipe theory, technology and its wide application in the world.

The Conference Proceedings incorporate 100 papers including 4 keynote lectures. These papers are grouped into the following chapters: (1) keynotes; (2) fundamentals in heat pipes and thermosyphons; (3) CPL & LHP; (4) oscillating/pulsating heat pipes; (5) mini/micro heat pipes; (6) special heat pipes; (7) microelectronics/power electronics cooling; (8) terrestrial applications and (9) space applications. I hope the Proceedings of IHPC13 will be an important resource for heat pipe scientists and engineers and will stimulate the further development of heat pipe science and technology.

Finally, I am very happy to take this opportunity to express my sincere gratitude to the committee on International Heat Pipe Conferences, the sponsors, the participants of the 13th IHPC for their considerable support and contribution to this conference, and the local organizing committee and editors of this Proceedings for their hard work.

We are looking forward to the 14th IHPC, which will take place in 2007 in Brazil. We wish its organizers great success.

Professor Hou Zengqi

Executive Chairman of the Local Organizing Committee

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THERMAL CONTROL TECHNOLOGIES FOR COMPLEX SPACECRAFT

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ABSTRACT

Thermal control is a generic need for all spacecraft. In response to ever more demanding science and exploration requirements, spacecraft are becoming ever more complex, and hence their thermal control systems must evolve. This paper briefly discusses the process of technology development, the state-of-the-art in thermal control, recent experiences with on-orbit two-phase systems, and the emerging thermal control technologies to meet these evolving needs. Some "lessons learned" based on experience with on-orbit systems are also presented.

KEY WORDS: advanced thermal control, capillary pumped loops, loop heat pipes, heat pumps, cryogenic, moon

1 INTRODUCTION

Scientific and exploration goals continually drive the need for better spacecraft and instruments. The data and knowledge gained by one mission inevitably leads to more questions which can only be answered by more advanced spacecraft with higher performance, improved resolution, tighter pointing accuracy, increased sensitivity, and the ability to look into new parts on the electromagnetic spectrum. In the past major improvements for science missions were largely possible through new sensor technology alone. However, it is increasingly obvious that future advances will rely heavily on technology improvements in a wide range of areas, and especially in thermal management.

The implementation approach for thermal control in spacecraft is changing. Traditionally, thermal management was accomplished by discrete devices, such as electrical heaters, multi-layer insulation, and specialized radiative coatings which were selected based on a mathematical analysis of the effect on a known environment and specified operating conditions. Spacecraft operating conditions were normally rather broad (plus or minus 20℃ to 30℃) and power levels were low (in the 10's to 100's of Watts), and such simple techniques worked well enough. However, modern spacecraft and instruments are requiring much tighter temperature control (to a $1/10^{th}$ ℃) over large areas (several square meters), and possibly require rejection of several kW of waste heat. Planned exploration missions will be going to locations with very difficult thermal environments (e.g., the moon, Mars, and near the sun) and may include propulsion, power, habitats, instrumentation, and other subsystems that will place very demanding requirements on the thermal control subsystem. New technologies are required to meet these needs.

Thermal control subsystems are also becoming much more integrated with other subsystems on a spacecraft or instrument. They can no longer be developed in isolation or at the end of a spacecraft design cycle, but must be done concurrently with other subsystems. This situation is a natural evolution driven by need to improve performance and minimize mass/parasitic power of all support subsystems. The lower the mass and parasitic power of such support equipment, the greater the payload that can be accommodated.

It is also evident that identifying just what new thermal control technology is needed for such complex systems, securing funding for its development, and overcoming the obstacles to introducing such new technology is a most challenging task. This challenge is generally comparable to the technical challenge. *This perspective has profound implications for both determining just what new technology should be developed and how it is to be integrated into a spacecraft.*

The Goddard Space Flight Center (GFSC) is primarily tasked to focus on robotic spacecraft and instruments, or the human tended servicing of such equipment. Hence this paper addresses the thermal control subsystems of such spacecraft and instruments. Goddard is the National Aeronautics and Space Administration's (NASA) lead center for the Earth Science Enterprise, has a very significant involvement in the Space Science Enterprise, and an emerging role in the new Exploration Initiative. Most recently NASA Headquarters asked GSFC to assume management responsibility for the Robotic Lunar Exploration Program. The first planned lunar mission is an orbiter in 2008, to be quickly followed by a lander in 2009. Early analytical studies indicate that thermal control will be a significant issue for many of these exploration missions, as well as numerous planned future science missions.

2 PROCESS OF TECHNOLOGY INTRODUCTION

One might imagine a logical process for technology development in which needs are first identified and independently verified, then costs and schedules are established, and finally appropriate funding is provided to bring the technology vision to reality. Unfortunately, however, this scenario virtually never happens for a variety of practical reasons:

1) The principal driver for technology development is the mission and its science or exploration goals. These goals are, by necessity, increasingly vague the further out in time the mission is. This is principally due to a tradeoff between what is technically possible, the cost to fly a proposed mission, and the perceived value of the science/exploration. Often there are alternative means of collecting new science data or exploring. For example, one might use a chronograph or an interferometer in the search for terrestrial-like planets in other solar systems, and these different mission concepts will require very different thermal control technologies.
2) The perceived value of various mission concepts changes over time. One new discovery, or exploration achievement, may lead to new understandings that supplant previously perceived values.
3) Developing practical technology is not a given. Invariably there are unanticipated technical difficulties, interactions with other subsystems, and various subtleties that require extra time and money to overcome. Thus, if one is trying to develop new technology under a limited budget and firm schedule - say to support a specific planned mission - there is the very real risk of not being successful.
4) Other drivers, such as the mission itself, specific science and exploration goals, the budget, or other technical subsystems upon which a technology is dependent, may all change over time.
5) Technology is often perceived as a threat from a variety of viewpoints: technical performance, schedule, and cost. Program Mangers, who are responsible for mission success, often do not want to be the first to fly a new technology; they want proof of probable success. Hence, they are commonly reluctant to incorporate new and unproven technology.

The process of technology development may be characterized as trying to hit a moving target (the mission goals) with a wobbly arrow (the new technology). Both the end point and the means of getting there are somewhat unknown. *Nevertheless, the common phrase "technology is our future" is certainly true.* Technology enables new science and new exploration. The challenge for technologists is to realistically perceive what is possible with a given schedule and budget, convince others of its worth, and then bring it to fruition.

Given the difficulty of this process of technology development and introduction, it is often best to develop multiple technologies that have relatively broad applicability. This less focused approach provides a flexible set of technologies to meet a broad set of problems. Securing funding is a typically a multi-step process with institutional type funding supporting the early efforts. Once a technology has developed to a point where it appears promising, then support can be sought from flight programs. However, the transition from early development to flight program support is often very difficult.

3 STATE-OF-THE-ART IN SPACE-CRAFT THERMAL CONTROL

The most advanced thermal control technologies currently employed in operational spacecraft are two-phase loops, such as Capillary Pumped Loops (CPLs) and Loop Heat Pipes (LHPs). These technologies clearly represent the major thermal control innovation of the last decade as they offer orders of magnitude improvement over traditional heat pipes (Ku, 1999; Swanson, 2004; Birur, 2004). CPLs and LHPs are in many ways very similar, but do have distinct characteristics (Butler, 2002). These self-contained, two-phase devices utilize the latent heat of evaporation/condensation of a fluid to acquire and transport waste heat long distances with negligible temperature drop. See Fig. 1.

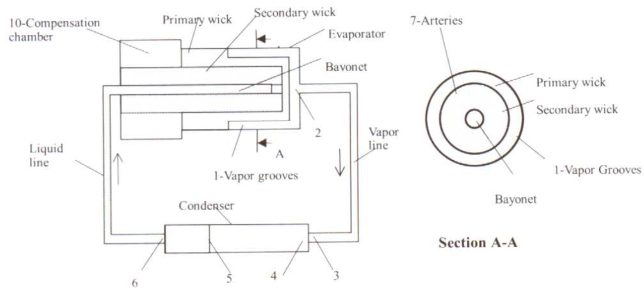

Fig.1 Generic Loop Heat Pipe

Both CPLs and LHPs consist of a closed loop with a porous evaporator, or wick, at one end and a condenser at the other. The wick may be a plastic such as polyethylene or a metal. A pair of smooth wall tubes connects the evaporator and condenser. The loop is partially filled with a refrigerant, typically ammonia or propylene for applications near room temperature. Waste heat is applied to the wick (which is saturated with the refrigerant) and is absorbed by evaporation of the refrigerant. A fluid reservoir is attached to the liquid line to accommodate fluctuating fluid inventories and also to provide a source of constant pressure against the refrigerant, thus locking the loop at a constant temperature. This temperature control is typically accomplished by cold biasing the reservoir and using make-up heaters to bring the temperature up to the desired "set point". Since the internal pressure of the loop is held constant, evaporation and condensation occur at a nearly constant temperature that is determined by the basic thermophysical properties of the refrigerant. Hence, the control set point essentially establishes isothermal conditions throughout the loop.

The resulting vapor is transported, via the non-wicked connecting tubing, to the condenser (i.e., radiator) where it is condensed back to a liquid. This condensation releases the waste heat that is then rejected to space via radiation. The liquid is then returned to the wick via a separate tube, and the process continues. A surface tension developed at the vapor/liquid interface across the menisci on the porous wick provides the pumping force to circulate the fluid. The system thus operates passively and requires no mechanical pump or flow control devices and is free from vibrations. Since it is a two-phase device a CPL or LHP can provide a very stable and constant interface temperature regardless of changes in the heat load and/or radiator sink condition.

CPLs and LHPs can operate stably and at constant temperature regardless of changing heat loads and/or thermal sink. Operationally, their most difficult issue is in startup since this involves getting the liquid and vapor to the proper locations throughout the loop (Ku, 1995).

4 ON-ORBIT EXPERIENCE WITH TWO-PHASE LOOPS

The development of CPLs was initiated in the United States in the early 1980's. The first flight experiments were conducted on the Space Shuttle in 1986 (Ku, 1986). LHP technology, which is similar but distinct from CPL technology, was initiated and developed in Russia (Maidanik, 1992). After extensive ground testing and additional flight experiments during the early 1990's, CPLs and LHPs finally reached technology readiness for space applications.

The first operational CPLs were on NASA's TERRA spacecraft, the first Earth Observing System (EOS) platform, which was launched in December of 1999 (Chalmers, 2000). The TERRA spacecraft is depicted in Fig. 2. TERRA has three scientific instruments that use CPLs for tight temperature control. Each instrument has two fully redundant, ammonia based, CPLs and several traditional heat pipes and electrical heaters. While each instrument has redundant CPLs, at any given time only one is active. Instrument waste heat loads vary from 25W to 264W.

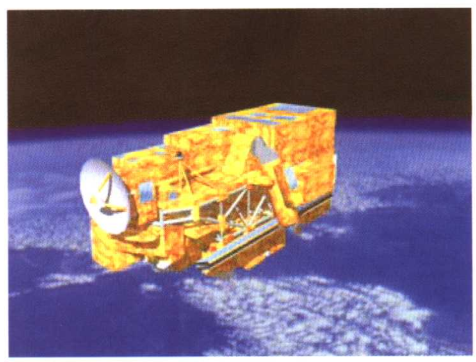

Fig.2 Conceptual Image of TERRA

In the 4+ years since TERRA was launched all three operating CPLs have provided a stable interface temperature as required by the instrument, under all modes of spacecraft operation, heat load, and environmental sink conditions (Ku, 2004). The TERRA CPLs have demonstrated an on-orbit capability to maintain temperature control within +/–0.1℃. On two of the instruments the CPL was started easily, but on one, the TIR instrument, there was some minor difficulty in maintaining operations. On January 7, 2000, one of TIR's CPL loops was started using a standard start-up procedure. However, the loop deprimed after just 62 hours. The instrument's second CPL was started on