

Heat Pipe Theory and Applications

Proceedings of the 13th International Heat Pipe Conference

September 21–25, 2004

Shanghai, China

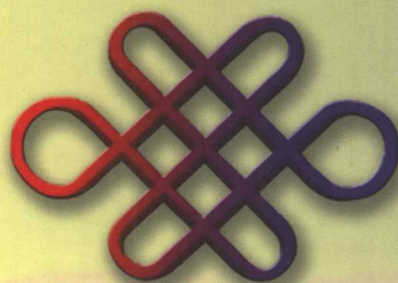
ORGANIZED BY
CHINA ACADEMY OF SPACE TECHNOLOGY

Editors

Hou Zengqi

Shao Xingguo

Yao Wei



中国宇航出版社

China Astronautic Publishing House

• Beijing •

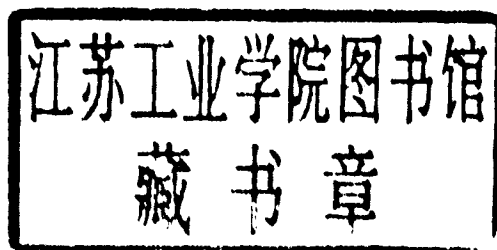
Heat Pipe Theory and Applications

Proceedings of the 13th International Heat Pipe Conference
September 21 – 25, 2004
Shanghai, China

ORGANIZED BY
CHINA ACADEMY OF SPACE TECHNOLOGY

Editors

Hou Zengqi
Shao Xingguo
Yao Wei



中国宇航出版社
China Astronautic Publishing House

• Beijing •

版权所有 侵权必究

图书在版编目(CIP)数据

热管理理论与应用:第13届国际热管会议论文集 = Heat Pipe and Applications Proceedings of the 13th International Heat Pipe Conference/侯增祺,邵兴国,姚伟编. —北京:中国宇航出版社,2005.8

ISBN 7-80144-996-7

I. 热... II. ①侯...②邵...③姚... III. ①热管理理论—国际学术会议—文集—英文②热管应用—国际学术会议—文集—英文 IV. TK172.4-53

中国版本图书馆 CIP 数据核字(2005)第 095922 号

责任编辑 易新 装帧设计 苏立峰 责任校对 王妍

出版 中国宇航出版社
发行

社址 北京市阜成路8号 邮编 100830
(010)68768548

网址 www.caphbook.com/www.caphbook.com.cn

经销 新华书店

发行部 (010)68371900 (010)88530478(传真)
(010)68768541 (010)68767294(传真)

零售店 读者服务部 北京宇航文苑
(010)68371105 (010)62529336

承印 北京博图彩色印刷有限公司

版次 2005年8月第1版
2005年8月第1次印刷

规格 880×1230

开本 1/16

印张 41.25

字数 1307千字

书号 ISBN 7-80144-996-7

定价 200.00元

本书如有印装质量问题,可与发行部调换

Local Organizing Committee

Honorary Chairman:

Prof. Dr. Min Guirong, CAS Academician, CAE Academician, CAST

Chairman:

Prof. Dr. Liu Qiang China Academy of Space Technology

Executive Chairman:

Prof. Hou Zengqi China Academy of Space Technology

Members:

Prof. Dr. Ma Tongze	Institute of Engineering Thermophysics, CAS
Prof. Li Ming	National Natural Science Foundation of China
Prof. Yin Liming	China Academy of Space Technology
Prof. Dr. Li Jindong	China Academy of Space Technology
Prof. Li Furong	Chinese Society of Astronautics
Prof. Xin Mingdao	Chongqing University
Prof. Liu Jifu	Harbin University of Technology
Prof. Wu Cunzheng	Zhejiang University
Prof. Dr. Zhang Hong	Nanjing University of Technology
Prof. Chen Enjian	Guangzhou Institute of Power, CAS
Sen. Engr. Shao Xingguo	China Academy of Space Technology
Sen. Engr. Liu Tao	National Natural Science Foundation of China
Sen. Engr. Wen Guoping	Shanghai Marin Diesel Engin Institute, CSSC
Sen. Engr. Li Laisuo	Jiangsu Shengnuo Heat Pipe Group Corporation

SPONSORED BY

NATIONAL NATURAL SCIENCE FOUNDATION OF CHINA
CHINESE SOCIETY OF ASTRONAUTICS
INSTITUTE OF ENGINEERING THERMOPHYSICS OF CAS
CHINA ACADEMY OF SPACE TECHNOLOGY

Committee on International Heat Pipe Conferences

Chairman:

Prof. Dr. M. Groll (found. member)

Stuttgart, Germany

Members:

Prof. Dr. J.H. Boo

Seoul, Korea

Prof. Dr. C.A. Busse

Leggiuno (VA), Italy, (found. member).

Dr. G.P. Celata

Rome, Italy

Prof. Dr. P.D. Dunn

London, United Kingdom, (found. member).

Prof. Dr. F. Kaminaga

Ibaraki, Japan

Prof. Dr. Ma Tongze

Beijing, China

Prof. Dr. Yu.F. Maidanik

Ekaterinburg, Russia

Prof. Dr. J.M. Ochterbeck

Clemson, USA

Prof. Dr. G.P. Peterson

Troy, USA

Dr. F. Polášek

Prague, Czech Republic

Mr. W. Supper

Noordwijk, the Netherlands

Prof. Dr. L.L. Vasiliev

Minsk, Belarus

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

CONTENTS

Keynote Lectures

Thermal control technologies for complex spacecraft.....	(3)
Theodore D. Swanson	
Micro/mini heat pipes for the cooling of electronic devices	(12)
M. Lallemand, F. Lefevre	
Miniature loop heat pipes	(23)
Yu. F. Maydanik	
Closed and open loop pulsating heat pipes	(36)
Sameer Khandekar, Manfred Groll, P. Charoensawan, S. Rittidech, P. Terdtoon	

Fundamentals in Heat Pipes and Thermosyphons

Dynamical model of RBF artificial neural network-based prediction for heat transfer	
oscillating behavior of thermosyphon	(51)
Chen Yanze, Ding Xinwei, Yu Jianliang	
Visualization of pool boiling in a confined space of a thin plate heat pipe	(56)
Chun-Ta Yeh, Chien-Yuh Yang	
Heat transfer characteristics in a looped parallel thermosyphon	(62)
Fumito Kaminaga, Atsushi Tokuhara, Kunihiro Matsumura, Chowdhury Feroz MD.	
Groove geometry effects on thin film evaporation and heat transport capability	
in a grooved heat pipe	(68)
Anjun Jiao, Rob Riegler, Hongbin Ma, G. P. Peterson	
Comparative analysis of heat transfer efficiency in evaporators of loop thermosyphons	
and heat pipes	(76)
L. L. Vasiliev, A. S. Zhuravlyov, A. Shapovalov	
Investigation of the thermal performance of single-layer mesh screen heat pipes	(82)
Wang Yaxiong, David C-Y Huang, Ching-Bai Hwang, Jim Tzeng	
Transient modeling of a closed two-phase thermosyphon for heat exchanger applications	(89)
Manfred Molz, Marcia B. H. Mantelli, Fernando Milanez, Henrique G. de Landa	
Vaporization heat transfer in biporous wicks of heat pipe evaporators	(96)
Wang Jinliang, Ivan Catton	
Experimental investigation of boiling heat transfer in bidispersed media	(105)
Merilo E. G., Semenik T., Catton I.	
Analysis of the temperature evolution at the vapor-liquid interface during a transient	
operation of a heat pipe	(111)
Gustavo Gutierrez, Yi Jia, Tien-Chien Jen	
Theoretical and experimental studies on boiling heat transfer for the thermosyphons	
with various helical grooves	(120)
Kyuil Han, Dong-Hyun Cho, Jong-Un Park, Ok-Jin Han, Sang-Jin Lee	

Application of inverse thermal analysis to heat pipes phenomena	(126)
Alain Alexandre, Manuel Girault, Christine Hao, Cyril Romestant	
The critical aspect ratio of two-phase closed thermosyphon based on the concept of sub-flooding limit.....	(132)
Yang Pan, X. M. Luo, C. Z. Wu	
Study on heat transfer oscillation phenomenon and restraining method of two phase closed thermosyphon.....	(137)
Chen Yanze, Ding Xinwei, Yu Jianliang	
Dynamic tracing method to examine maximum heat dissipate ability of heat-pipe.....	(142)
Yao-Chen Chan, Hung-Wen Lin, Wei-Keng Lin	
A simplified analysis on geyser instability of closed two-phase thermosyphons.....	(147)
Tang Zhiwei, Ma Chongfang, Jiang Zhangyan	
Characteristics of condensing and evaporating heat transfer using hydrocarbon refrigerants	(151)
Ho-Saeng Lee, M. M. A. Sarker, Jung-In Yoon, Eunpil Kim, Seok-Kwon Jeong	
Experimental study of the optimal charging mass of working fluid in heat pipe with axially grooved wick	(156)
Chang Ho Kang, Jung Kyu Hong, Jeong-Se Suh	
Heat transfer enhancement in plate fin with oval tube heat exchangers utilizing electric field effects	(161)
Chia-Wen Lin, Min-Jer Lee, Jiin-Yuh Jang	
 CPL & LHP	
Numerical analysis on the heat transfer characteristics of loop thermosyphon evaporator	(169)
Sun Zhijian, Wu Cunzhen, Cen Kefa, Eric Cho, Lai Zhentian, Xu Jianfeng	
Experimental investigation of a CPL coupled with multi loops	(174)
Liu Qingzhi, Hou Zengqi, Miao Jianyin, Zhang Jiaxun	
Experimental investigation of heat transfer characteristics of reservoir embedded loop heat pipe (RELHP) by using visual inspection model	(180)
T. Ogushi, H. ishikawa, E. Ozaki, A. Yao, H. Masumoto	
Steady-state and transient loop heat pipe performance during periodic heating cycles.....	(186)
D. Mishkinis, G. Wang, D. Nikanpour, E. MacDonald, T. Kaya	
Micro loop heat pipes.....	(192)
Shung-wen Kang, Chin-chun Hsu, Tung-fu Hou	
A two-phase loop thermosyphons with nanofluids	(198)
Seok-ho Rhi, Kyungil Cha, Ki-Woo Lee, Yung Lee	
Experimental determination of the physical properties of a porous plastic wick useful for capillary pumped loop applications.....	(203)
Randeep Singh, Aliakbar Akbarzadeh, Chris Dixon, Mastaka Mochizuki	
Development of a low-cost LHP for commercial application.....	(211)
B. J. Huang, C. H. Wang, T. T. Lin, H. H. Huang, Y. Y. Yeh	
Thermal performance of a multi-evaporator loop heat pipe with thermal masses and thermoelectric coolers	(216)
Jentung Ku, Laura Ottenstein, Gajanana Birur	
Effects of scale on the mechanism of pulsating heat pipe.....	(223)
Qu Wei, Fu Zhongchuan, Ma Tongze	

Evaluating the behavior of loop heat pipe with different compensation chamber configurations	(229)
Roger R. Riehl	
A testing of loop heat pipe with dual-evaporator and a parallel-flow condenser	(235)
Xiang Yanchao, Li Jindong, Hou Zengqi, Fan Hanlin	
Parametric analysis on LHP/CPL evaporator performance and critical heat flux by two-dimensional calculation	(240)
Yao Wei, Miao Jianyin, Shao Xingguo	
Effects of start-up on operation of loop heat pipes	(247)
Zhang Hongxing, Ding Ting, Shao Xingguo, Lin Guiping, Sudakov R. G., Maidanik Yu. F.	
Design, analysis and investigation of a medium scale capillary pumped loop	(253)
Randeep Singh ¹ , Aliakbar Akbarzadeh, Chris Dixon, Roger R Riehl, Mastaka Mochizuki	
Thermal performance of a small-scale loop heat pipe with PP wick	(259)
Boo, Joon Hong, Chung, Won Bok	
Study on working characteristics of loop heat pipe using a sintered metal wick.....	(265)
Wook-Hyun Lee, Ki-Woo Lee, Ki-Ho Park, Kye-Jung Lee	
An integrated model for dynamic behavior of CPL	(270)
Qian Jiyu, Xuan Yimin, Li Qiang	
Experimental investigation of a deployable radiator prototype with loop heat pipes.....	(276)
Guo Lin, Cao Jianfeng, Ding Ting, Lv Wei, Shao Xingguo	
 Oscillating/Pulsating Heat Pipes	
Two-phase flow modeling in closed loop pulsating heat pipes	(283)
Sameer Khandekar, Sanka V. V. S. N. S. Manyam, Manfred Groll, Manmohan Pandey	
Operational characteristics of flat plate closed loop pulsating heat pipes.....	(291)
Honghai Yang, Sameer Khandekar, Manfred Groll	
Effect of aspect ratios and bond number on internal flow patterns of closed end oscillating heat pipe at critical state.....	(298)
T. Katpradit, T. Worngatanapaisarn, P. Terdtoon, S. Ritthidech, P. Chareonsawan, S. Waowaew	
A novel design of pulsating heat pipes with improved performance	(304)
Cao Xiaolin, Cheng Ping	
Ect measurement of flow patterns and film thickness in a thermosyphon.....	(309)
Li Jingtao, Chen Huanzhuo, Dong Xiangyuan, Liu Shi	
Investigation on effective thermal conductivity of oscillating heat pipes	(315)
Ma Yongxi, Zhang Hong, Zhuang Jun	
Study of pulsating heat pipe in GIEC, CAS	(320)
Li Yuxiu, Xu Jinliang, Li Yinhui	
Thermal analysis of a micro or mini pulsating heat pipe	(327)
Qu Wei, Fu Zhongchuan, Ma Tongze	
Influence of working fluid to heat transfer characteristics of oscillating heat pipe for low temperature.....	(334)
Yong-Bin Im, Jong-Soo Kim, Yoon-Hwan Choi	
Heat transfer performance of oscillating capillary tube heat pipe with micro-channel flat tube	(341)
Soo-Jung Ha, Taek-Ki Lee, Chul-Min Park, Jong-Soo Kim	
Numerical analysis of pulsating heat pipe based on the separated flow model	(347)
Jong-Soo Kim, Euk-Soo Lee, Nae-Soo Bae, Yong-Bin Im, Ngoc-Hung Bui	

Mini/Micro Heat Pipes

Fabrication and performance analysis of metallic micro heat spreader for CPU (355)

Jung-Cheng Lin, Jiunn-Chi Wu, Chun-Ta Yeh, Chien-Yuh Yang

Heat transfer steady and transient characteristics in flat plate micro heat pipe..... (360)

Masafumi Katsuta, Tomoya Shindo, Koichiro Saito, Junji Sotani, Yuichi Kimura,
Yoshio Nakamura

Experimental study of a wire mini heat pipe for microgravity test (366)

Kleber Vieira de Paiva, Marcia B. H. Mantelli, Augusto J. de A. Buschinelli

Experimental investigation on thermal performance of flat miniature heat pipes with

axial grooves..... (372)

Zhang Lichun, Ma Tongze, Zhang Zhengfang, Ge Xinshi

Thermal-hydraulic performance of sandwich structures with crossed tube truss core and

embedded heat pipes (378)

J. Tian, T. J. Lu, H. P. Hodson, D. T. Queheillalt, H. N. G. Wadley

Special Heat Pipes (VCHP, rotating, liquid metal, etc.)

Two phase loops without capillary pumps (387)

V. M. Kiseev, A. S. Nepomnyashy

Development of a flexible metal / polymer laminate heat pipe (393)

John H. Rosenfeld, Nelson J. Gernert

Improvement on thermal performance of circular heat pipe with nanofluid (399)

Hsin-Tang Chien, Chih-Wei Chang, Ping-Hei Chen, Pei-Pei Ding

Experimental investigation of enhancement heat transfer in a heat exchanger with the high

temperature heat pipe fins..... (402)

Zhao Weilin, Zhuang Jun, Zhang Hong

Isothermal characteristic of a rectangular parallelepiped sodium heat pipes (407)

Park, Soo Yong, Boo, Joon Hong

Effect of inclination on the performance of axial rotating heat pipes (413)

F. Song, D. Ewing, C. Y. Ching

Experimental study of the thermal performance of a water-copper variable conductance

heat pipe with screen mesh wick (419)

Young-Sik Park, Kyung-Taek Chung, Jeong-Se Suh

Theory study of the optimum charge of working fluid for rotating heat pipe with stepped wall (424)

Zhang Lin

Microelectronics/Power Electronics Cooling

Raising the bar for heat pipes in notebook cooling..... (433)

Eric DiStefano, Himanshu Pokharna, Sridhar V. Machiroutu

Study of AlSiC metal matrix composite based flat thin heat pipe..... (441)

Xinhe Tang, Ernst Hammel, Walter Findl, Theodor Schmitt, Dieter Thumfart, Manfred Groll,
Marcus Schneider, Sameer Khandekar

Practical application of heat pipe and vapor chamber for cooling high performance

personal computer (448)

Masataka Mochizuki, Thang Nguyen, Koichi Mashiko, Yuji Saito, Tien Nguyen,
Vijit Wuttijumnong, Wu Xiaoping

The ultra-thin sheet-shaped heatpipe “pera-flex”	(455)
Yasumi Sasaki, Yuichi Kimura, Kenichi Namba, Tadashi Yamamoto	
100 W/cm² and higher heat flux dissipation using heat pipes.....	(460)
Nelson J. Gernert, Jerome Toth, John Hartenstine	
New composite wick heat pipe for cooling personal computers	(466)
Prasong Ektummakij, Vichan Kumthonkittikun, Hiroyuki Kuriyama, Koichi Mashiko, Masataka Mochizuki, Yuji Saito, Thang Nguyen	
Development testing of heat pipe heat exchanger for high power amplifiers	(471)
N. Gunabushanam, P. Rajya Lakshmi, R. S. Reddy	

Terrestrial Applications

Experimental investigation of the thermal performance of two-phase closed thermosyphons with addition of a liquid retention helicoidal structure in the evaporator region	(481)
Samuel Luna Abreu, Sergio Collee, João Felipe Almeida Destri	
A study on the thermal performance of a concentric annular heat pipes	(486)
Boo, Joon Hong, Kim, Do Hyoung, Park, Soo Yong	
Pulsating heat pipe panels	(491)
A. A. Antukh, M. I. Rabetsky, V. E. Romanenkov, L. L. Vasiliev	
Research and application of new type long-acting steel- water heat pipe	(498)
Zhou Lichun, Liu Qun, Yan Xiangfu	
Development of a top-heat-type long thermosyphon for cooling solar PV modules.....	(502)
Yasushi Koito, Yasuhiro Horiuchi, Tetsuhiro Yamaguchi, Hideaki Imura, Shuichi Torii	
A new methodology for measuring heat transfer coefficients-application to thermosyphon heated enclosures.....	(508)
Fernando H. Milanez, Marcia B. H. Mantelli	
Sorption heat pipe –a new thermal control device.....	(514)
Leonid L. Vasiliev	
Solar power membrane pump by application of operating principle of heat pipe.....	(519)
Keiyo Gi, Saburo Maezawa	
Application of heat pipe technology to the defrost system of a refrigerator	(525)
Chul Ju Kim, Yong Joo Park, Sung Kwan Park	
Experimental study of vertical thermosyphons for industrial heat exchanger applications	(531)
Marcia B. H. Mantelli, Geraldo G. J. Martins, Flávio Reis, Rafael Zimmermann, Guilherme K. L. Rocha, Henrique G. Landa	
Heat pipe application in thermal-engine car air conditioning.....	(537)
Cyril Romestant, Gwenaél. Burban, Alain Alexandre, David Roy, Pascale Petitjean	
Thermosyphon as an energy saver in aeroponic system.....	(543)
N. Srihajang, S. Ruamrungsri, S. Ritthdech, P. Chareonsawan, S. Waowaew, P. Kamonpet, P. Terdtoon	
Thermal performance prediction and verification of a steam-heated air-cooled ammonia-charged two-phase closed thermosyphon	(549)
R. T. Dobson, S. A. Pakkies	
A dynamic state analysis of heat transfer and numerical calculation for the heat pipes stabilizing the permafrost soil railway bed.....	(558)
Chen Peng, Xu Zhijian	

A radially rotating heat pipe as a temperature reducer in automobile disk brake	(564)
S. Waowaew, J. Klinbun, S. Ritthidech, P. Chareonsawan, P. Terdtoon, S. Maezawa	
Experiment and prediction of water-filled thermosyphon heat pipe heat exchanger performance in counterflow air streams	(569)
Than, C. F., Ong, K. S.	
Heat pipe heat exchangers for fuel gas heating in the steel industry	(575)
Heung Soo Park	
Thermosyphon as an energy saver for heat-pump type dryer.....	(581)
W. Phaphuangwittayakul, S. Ritthidech, P. Chareonsawan, S. Waowaew	
Development of heat pipe design and construction in Colombia.....	(587)
Luis S. Paris, Juan C. Cataño	
 Space Applications	
Design and manufacturing of heat pipes on ATV	(595)
B. Mullender	
Medium/high temperature heat pipes for spacecraft application	(603)
Reinhard Schlitt, Frank Bodendieck, Rudi Kulenovic, Manfred Groll, Ortwin Brost	
A comparative analysis of loop heat pipe based thermal architectures for spacecraft thermal control	(611)
Mike Pauken, Gaj Birur	
Development of loop heat pipes for thermal control system of nickel-hydrogen batteries of “yamal” satellite	(622)
K. Goncharov, V. Buz, A. Elchin, Yu. Prochorov, O. Surguchev	
Innovative axially grooved heat pipe for space application	(628)
Christine Hoa, Alain Alexandre, Cyril Romestant, Gwenael Burban	
Investigation of parameters of axial grooved heat pipes charged with propylene.....	(634)
V. Barantsevich, K. Goncharov, V. Buz	
Development and flight operation of LHP used for cooling nickel-cadmium batteries in Chinese meteorological satellites FY-1.	(640)
K. Goncharov, O. Golovin, V. Kolesnikov, Zhao Xiaoxiang	
The application study of loop heat pipe on the thermal control design of a scientific experimental satellite	(645)
Zhang Jiaxun, Yang Sujun, Cao Jianfeng, Chen Shaohua, Hou Zengqi	

Keynote Lectures

THERMAL CONTROL TECHNOLOGIES FOR COMPLEX SPACECRAFT

Theodore D. Swanson

National Aeronautics and Space Administration, Goddard Space Flight Center, Code 540,
Greenbelt, MD 20771, USA

Phone: 301-286-7854, Fax: 301-286-17017 E-mail: ted.swanson@nasa.gov

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°C to 30°C) 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 1/10th °C) 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 (GSFC) 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 Managers, 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 SPACECRAFT 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.

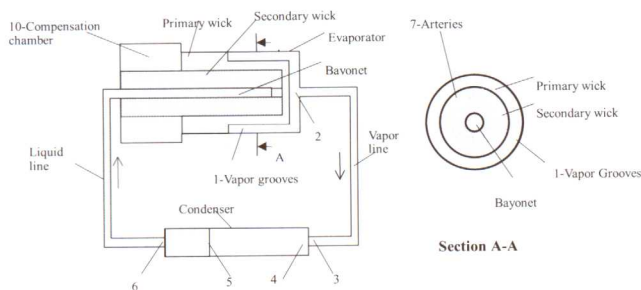


Fig.1 Generic Loop Heat Pipe

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.

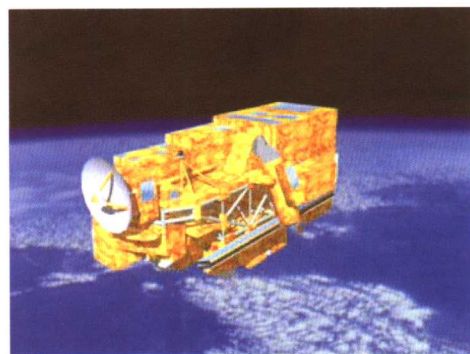


Fig.2 Conceptual Image of TERRA

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 $\pm 0.1^\circ\text{C}$. 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