DAY #2: Monday, June 11, 2018

Room A: Session #1: [TS1] – Thermosyphons #1

[324] – TS1_1

Heat and Mass Transfer for a Small Diameter Thermosyphon with Low Fill Ratio

Anthony Robinson[1*], Kate Smith[1], Turlough Hughes[1], Sauro Filippeschi[2]

[1]*Department of Mechanical & Manufacturing Engineering, Trinity College Dublin, Dublin D2, Ireland*
[2]*Department of Energy, Systems, Land and Constructions Engineering, University of Pisa, Pisa, Italy*

Abstract
Thermosyphons of smaller dimensions are more commonly sought after as electronics cooling devices. The interactions of the tube wall and working fluid become more significant as the dimension of a thermosyphon is reduced, particularly for high surface tension fluids such as water. This paper aims to experimentally investigate a water-charged, small diameter (8 mm) thermosyphon as it operates with a low (25%) filling ratio for a relatively long evaporator length of 200 mm. High speed videography provides in-situ flow pattern visualization at different heat input power. The boiling regimes for each level of heat flux are determined by analyzing the flow patterns from the high-speed video footage. The interdependence of the flow regimes and the heat and mass transfer mechanisms is evaluated using the measured wall temperature variations and derived thermosyphon performance metrics, such as the average heat transfer coefficients and thermal resistances. It was observed that the heat and mass transport was dominated by Geyser-type boiling at lower heat fluxes with associated low heat transfer coefficients in the evaporator and condenser. With increasing thermal power, less liquid was observed to return to the evaporator resulting in more aggressive boiling events which improved the heat transfer coefficients in both the evaporator and condenser. For all power levels tested, the dominant thermal resistance was found to be that associated with the condenser. The ultimate failure of the thermosyphon was a result of liquid hold-up in the condenser section and subsequent falling liquid film and evaporator dryout.

Keywords: Reflux Thermosyphon; Flow Visualization; Flow Regimes; Heat Transfer

[282] – TS1_2

Loop thermosyphons with porous coating and horizontally disposed evaporator and condenser

Leonard L.Vasiliev, Mikhail I. Rabetsky, Leonid P. Grakovich, Vadzim K. Kulikouski Alexander S. Zhuravlyov and Maxim Kuzmich

Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, 15 P. Brovka Str., Minsk, 220072, Belarus

Abstract
The scope of this study is an experimental evaluation of the evaporation and condensation heat transfer in a loop thermosyphon with porous coating of the evaporator (LTCE), its thermal resistance, temperature field along the thermosyphon, and critical heat flux (CHF). Compared with conventional loop heat pipes (LHP) and loop thermosyphons (LT), the suggested loop thermosyphon (LTCE) with porous coating of the evaporator ensures a shortened start-up time, decreases the evaporator wall temperature, has small hysteresis during the increasing/decreasing of the heat load and suppresses the temperature instability. The thermal resistance of LTCE does not exceed 0.36 K/W (evaporator – R = 0.1-0.05 k/W).

Keywords: Heat transfer; Phase change; Thermal control

Room B: Parallel Session #1: [HP1] – Heat Pipes #1

[360] – HP1_1

Heat pipe array for planar cooling of rotating radar systems

Gert Jan te Riele[1] and Wessel W. Wits[2*]

[1]*Thales Nederland B.V., P.O. Box 42, 7550 GD Hengelo, Netherlands*
[2]Faculty of Engineering Technology, University of Twente, P.O. Box 217, 7500 AE Enschede, Netherlands

Abstract
This paper presents a planar cooling strategy for rotating radar systems using heat pipe technology. The principle idea is to use an array of heat pipes. The proposed design uses six 1 m long heat pipes in parallel and top cooling through a fan-based heat sink. The heat pipes are oriented in an evaporator-down modus at an elevation angle of 85°. An analytical model based on conventional heat pipe limits is used to predict the heat pipe array's performance taking into account both gravitational and centrifugal forces, and system-level design parameters. The heat pipe array is mounted on a rotating platform of which both the mounting angle with respect to the rotational arm and rotational speed can be varied. The radial distance with respect to the rotational axis was set at 0.5 m. The set-up was tested in an environmental chamber to simulate higher ambient temperatures as well. Moreover, measurements were conducted by varying the heat sink air flow rates. The performance of the heat pipe array was determined by the temperature gradient across the planar structure. Successful heat pipe operation and experimental performances were determined for a number of application parameters. At higher rotational speeds, the influence of centrifugal forces that may assist or hinder the working fluid circulation became discernable. For higher rotational frequencies, the mounting angle proved to be of (minor) influence on the performance in agreement with the developed model. The current design was validated for effective planar cooling of a rotating radar system for planar heat loads up to 1000 W. Temperature gradients across the planar structure remain below critical limits and overall thermal resistances from planar to ambient air conditions of 0.040 K/W and below were observed.

Keywords: Electronics cooling; Flat-plate cooling; Two-phase cooling; Long evaporator section; Evaporator-down modus

[3] – HP1_2

Flex Heat Pipe East-West Deployable Radiator

Jay Ambrose[1]

[1]*Lockheed Martin Space, Sunnyvale, California, 94089, USA*

Abstract

Lockheed Martin has developed a patented solution for increasing payload power on communications satellites which introduces a coupled East-West radiator assembly with deployable radiators. The deployable radiators are deployed in integration and test phases to provide equipment access. The equipment is mounted onto internal structural panels and is thermally coupled to both east and west radiators by flexible heat pipes which have dual condensers. Coupling to both east and west radiators provides greater average heat dissipation. This application is uniquely demanding for the flexible heat pipes due to heat transport, operating temperatures, pressure cycling and deployment cycling.

This paper describes derivation of requirements for the flexible heat pipes for the radiator assembly, and qualification testing to verify that the heat pipe design will work as intended. A structural qualification unit was subjected to thermal cycling, pressure cycling, vibration, flex cycling and ultimately burst testing. The qualification unit was modified following burst test into a single condenser unit. It was then charged and subjected to thermal performance testing. The test results verify that the flexible heat pipe design meets all requirements for the East-West radiator assembly.

Keywords: Radiators, Spacecraft integration, Design of heat pipes, Flexible heat pipes

Room A: Session #2: [LHP1] – Loop Heat Pipes/Capillary Pumped Loops #1

[53] – LHP1_1

Experimental investigations of a Multi-Source Loop Heat Pipe for electronics cooling

Laura Fourgeaud[1], Raphaël Mari[1], Vincent Dupont[1], and Christophe Figus[2]

[1]*Institut de Recherche Technologique Saint-Exupéry, 118 Route de Narbonne, CS 44 248, 31432 Toulouse cedex 4, France*[2]*Airbus Defence and Space, Mechanical Design Office, 31 Rue des cosmonautes, 31402 Toulouse, France*

Abstract

We present a novel architecture of a Loop Heat Pipe in which three auxiliary smooth-pipes evaporators have been added. Auxiliary evaporators feature the hot points of an electronic chip. Such a system would allow cooling down several hot spots by using a single-LHP and is of a broad interest for electronics cooling applications. This system preserves the main advantages of multi-capillary evaporators LHPs while avoiding numerous of their downsides. Our breadboard has the following characteristics: out of the main capillary evaporator, the LHP line crosses a first condenser, the three auxiliary evaporators – referred as "micro-exchangers", a second condenser, and then returns to the evaporator. The main capillary evaporator drives the mass flow rate while auxiliary evaporators are only dedicated to heat transfer. The working fluid is R245fa. Experimental investigations allow characterizing the loop behavior and the operating limits in order to deduce the operating conditions. Measurements agree with our multi-evaporators LHP model. We also point out that, before the onset of nucleate boiling within micro-exchangers, the liquid superheating may achieve 40 °C. In some cases, however, the ONB occurs immediately after applying the power to micro-exchangers.

Keywords: Loop Heat Pipes; multi-source; phase-change; cooling device; heat transfer; two-phase flow; boiling in tube

[91] – LHP1_2

Static and dynamic liquid-vapor phase distribution in the capillary evaporator of a loop heat pipe

Masahito, Nishikawara[1], Yosuke Ueda[1], and Hideki Yanada[1]
[1]*Department of Mechanical Engineering, Toyohashi University of Technology, Toyohashi 441-8580, Japan*

Abstract
The liquid–vapor phase distribution and displacement in the capillary evaporator of a loop heat pipe (LHP) are key phenomena affecting the steady state and transient operating characteristics. This study intends to identify the liquid-vapor interface behavior in the capillary evaporator that causes operational instability and enhances the heat-transfer, and conducts optical observation in the transparent cylindrical evaporator during the LHP operation. A quartz wick-acetone LHP system is designed, fabricated, and operated successfully with a maximum heat flux of 5.9 W/cm[2]. Phase displacement on various operations such as the start-up involving nucleate boiling, capillary limit, hysteresis, step-up of heat load are observed. Binarized image processing quantitatively reveals the dynamic characteristics at the contact surface between the wick and case. Comparing of phase displacements during the start-up involving nucleate boiling and the nucleate boiling after normal start-up, equilibrium vapor phase at the contact surface between the evaporator case and wick is formed by imbibition and drainage, respectively. On the step-up-down test of heat load, visual evidence of the hysteresis of the evaporator heattransfer coefficient due to phase distribution in the wick is discovered. It is found in the simulation that residual liquid phase along the three phase contact line within the case, wick, and grooves, which are observed in the visualization experiment, is low temperature, therefore the distribution of the residual liquid can lead to enhance the evaporator heat-transfer coefficient. This characteristic is key to optimize porous structure of the wick.

Keywords: Drainage; Loop Heat Pipe; Nucleate boiling; Pore network model; Porous media; Start-up; Visualization

[90] – LHP1_3

Experimental Validation of a Loop Heat Pipe designed with Two-phase Flow Pattern based Modeling

Chih-Yuan Weng [1], Tzong-Shyng Leu[2*]
[1] *Assistant professor, Department of Mechanical Engineering, Air Force Institute of Technology, Kaohsiung 82063, Taiwan*
[2] *Professor, Department of Aeronautics and Astronautics, National Cheng Kung University, Tainan 70100, Taiwan*

Abstract

A new two-phase flow pattern based theoretical modeling is proposed to analyze the thermodynamic performance of loop heat pipes (LHP) by the current authors. The new modeling is based on energy balance equations of the system, and adopted proper two-phase flow pattern map, for condensation tube diameter of LHPs designed ranging from 1 to 5 mm. In this study, two-phase flow pattern based steady-state model loop heat pipe was validated by comparison with experimental studies. For validation purpose, a loop heat pipe with a transparent condenser region was designed in this study. The test LHP consisted of a cylindrical evaporator, compensation chamber, vapor/liquid lines and a transparent concentric annulus condenser. Ethanol was selected as working fluid and the wick structure was sintered by PTFE powders. The results showed that the theoretical model can well predict the LHP thermal behavior. The minimum value of total resistance at 140 watt was 0.7 ºC/W, which was very close to prediction. As working fluid condenses and progresses from vapor phase toward liquid phase over a range of qualities, different flow patterns were established at different regions of the condenser. The modeling revealed that most of the predicted flow regimes in the condenser of LHP were stratified wavy flow and stratified flow. The experimental observation of LHP shows changing from stratified flow to stratified wavy flow as heat load applied. A good agreement has been met between the simulation and the experimental results. And through the analytical modeling, the two-phase flow characteristics in the condenser of LHP system can be understood more deeply on the design of LHP.

Keywords: Two-phase flow visualization; Two-phase flow pattern modeling; Theoretical prediction; Experimental validation

[294] – LHP1_4

Effect of Particle Morphology on Transport Parameters of Loop Heat Pipes

Bhimashankar Wangaskar[1], Sameer Khandekar[1*] and Kantesh Balani[2]

[1]*Department of Mechanical Engineering, Indian Institute of Technology, Kanpur 208016, India*
[2]*Department of Materials Science and Engineering, Indian Institute of Technology, Kanpur 208016, India*

Abstract
Development and miniaturization of electronic devices lead to constraints on the thermal management of electronic components. Loop Heat Pipe (LHP) is a promising solution for contemporary and future thermal management problems. LHP is a passive, flexible and robust two-phase heat transfer device. Porous wick present in the evaporator is the heart of LHP, as it generates the capillary pumping pressure required to transport the working fluid passively. Design and development of efficient porous wicks is a challenging contemporary problem. In the present study, we investigated the effect of powder morphology on the wick transport properties. Spherical, dendritic and irregular shaped copper metal powders of particle size 45-53 μm were used. An experimental set-up was developed to compare the rate of capillarity speed, which is a good indicator of wick performance. The permeability of all the samples was calculated experimentally and reverse estimation was done for obtaining the Kozeny-Carman constant. It was found that spherical powder wicks had higher permeability due to proper alignment of metal particles and lower resistance to the fluid flow. Due to the lower value of tortuosity and higher value of roundness factor (~1.0), the capillarity speed was also found to be higher. The paper presents a systematic procedure to experimentally analyze porous wicks for potential LHP usage.

Keywords: Transport parameters; Shape factor; Tortuosity; Permeability; Capillary speed; Evaporation.

[353] – LHP1_5

Loop heat pipe dynamics modeling and analyses

Vasily Buz, Konstantin Goncharov

TAIS Ltd, Khimky, Moscow region, Russia

Abstract

The report presents mathematical model and computational analysis of dynamic processes in the loop heat pipe, as well as some ways of regulating its work. This is considered a one-dimensional unsteady model of the loop. For each element of loop the model contains the energy equation for flow of fluid and to the walls, and the equation of conservation of momentum of the working fluid. The joint solution of a system of such equations for all elements of the loop allows to calculate the temperature distribution and pressure contour at any point in time. The calculations showed that under certain conditions in the loop heat pipe can be auto-oscillations of different nature. Analyzed methods of eliminating these auto-

oscillations. One way to regulate the loop heat pipe is the use of a control valve on the additional bypass line. The analysis showed that this method can significantly improve the quality of temperature control and reduce energy consumption by regulation, or do without energy consumption. Presents a model of the dynamics of loop heat pipe gives physically reasonable results of calculations and is consistent with the results of the tests.

Keywords: Loop heat pipe; Modeling; Autooscillations; Thermostabilization

Room B: Session #2: [HP2] – Heat Pipes #2

[36] – HP2_1

Water-Filled Heat Pipes for CubeSat Thermal Control

Henk Jan van Gerner[1], Hugo Brouwer[2], Zeger de Groot[2], and Jian Guo[3]
[1]*NLR – Netherlands Aerospace Center, Voorsterweg 31 Marknesse, Netherlands*
[2]*ISIS – Innovative Solutions In Space, Motorenweg 23 Delft, Netherlands*
[3]*Faculty of Space Engineering, University of Technology Delft, Netherlands*

Abstract
Currently, the amount of electrical power that is available for CubeSat's is very small and for this reason, simple thermal conductance through the frame of the CubeSat is sufficient for most CubeSat missions. However, deployable solar panels have been developed recently and peak powers up to 40W can now be generated. This higher generated electrical power results in more waste heat and potentially too high temperatures inside the CubeSat. For this reason, the use of water-filled heat pipes is studied, since these are cheap, widely commercially available, and can be bended in the desired shape. Both the condenser and evaporator thermal resistance and the total heat transfer capacity of these heat pipes have been measured for a wide range of temperatures with a unique automated setup that uses Peltier elements to control the temperature. Furthermore, the heat pipes have been subjected to multiple freeze/thaw cycles and start-ups from a frozen state. After these successful tests, a heat pipe was integrated in a CubeSat and tests were carried out in several orientations. The tests show that commercially available water-filled heat pipes are suitable for CubeSat thermal control.

Keywords: Heat pipe; Water; CubeSat; thermal resistance; Experiment.

[158] – HP2_2

Ultra-thin flattened heat pipe with spiral woven mesh wick for smartphone cooling

Wenjie Zhou[1], Yong Li[1*], Zhaoshu Chen[1] and Yuying Yan[2]
[1]School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510640, China
[2]Fluids & Thermal Engineering Research Group, Faculty of Engineering, University of Nottingham, Nottingham NG72RD, UK

Abstract
This study investigates the thermal performance of ultra-thin flattened heat pipes (UTHPs) with spiral woven mesh (SWM) wick structure. The UTHPs are fabricated by flattening cylindrical heat pipes with outer diameter (OD) of 2 mm. The thickness, width and length of UTHP samples are 0.4, 2.9 and 80 mm, respectively. The SWM is made by 96 copper wires (OD 0.04 mm) through the spiral woven according to a certain rule, namely 4 wires arranged to a spindle side by side and 24 spindles are spiral woven to the three-dimensional mesh. The SWM is very suit for flattening and bending process and easy to realize mass production. The axial temperature distribution, evaporation and condensation thermal resistance, the optimum filling ratio and maximum transport capacity of UTHP samples under different filling ratios

(80%, 100%, 120% and 140%) were investigated experimentally. The UTHP has the best start-up performance with the filling ratio of 100%, the temperature of the testing point can reaches 57 °C after about 10 s, and the equilibrium temperature is the highest with the value approximate to 60 °C. The maximum heat transfer capacity and the maximum temperature difference of the UTHP are 3.6 W and 4.39 °C, respectively, at the optimum filling ratio of 120%.

Keywords: Ultra-thin flattened heat pipe; Wick; Spiral woven mesh; Filling ratio; Thermal performance.

[190] – HP2_3

Development of a Novel Wick Structure to Enhance the Thermal Performance of Thin Heat Pipe at Vertically Top Heat Mode Application

Mohammad Shahed Ahamed[1], Yuji Saito[1], Thanh-Long Phan[1], Makoto Takahashi[1] and Masataka Mochizuki[2]
[1]Thermal Technology Business Unit, Electronics Company, Fujikura Ltd.
1-5-1 Kiba, Koto-Ku, Tokyo 135-8512, Japan, Phone: +81-3-5606-1174, e-mail: shahed.ahamed@jp.fujikura.com
[2]The Heat Pipes, Shiohama 1-4-33-1022, Koto-ku, Tokyo 135-0043, Japan

Abstract
Recently dual PC (laptop + tablet) is becoming very popular because of its several user friendly features and applications. Regardless to the trend of compactness in size; the heat dissipation rate and the density factor of chipsets are increasing year by year for such dual PC. On the other hand, the space available for the cooling solution is becoming very much limited because of its compact and smart design. For the past few years, thin heat pipe is used as a common cooling solution for this kind of compact electronic devices. However, the required flattening thickness of thin heat pipe for this kind of application is close to 1.5mm. In addition, to meet the demand of using this kind of electronic device in several directions, high thermal performance of thin heat pipe is required even in the top heat mode orientation. In this paper, two novel wick structures are proposed and evaluated to check its possibility of meeting the demand of high thermal performance. Properties of the proposed wick are studied experimentally and the heat transfer capacity of the heat pipe is studied both experimentally and theoretically.

Keywords: Heat pipe; Heat Transfer Capacity; Portable Electronic Devices; Fiber Wick.

[235] – HP2_4

Investigation on Micro-Grooved Wicks with Needle-like Thorns Structure for Aluminum Vapor Chamber

Jie Li, Heng Tang, and Gong Chen

Intelligent Manufacturing Engineering Laboratory of Functional Structure and Device in Guangdong, School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510640, China

Abstract

Micro-grooved wicks with needle-like thorns structure (MGTs) were fabricated with Milling/ Ploughing method for the application in the ultra-thin aluminum vapor chambers. Scanning electron microscopy was used to investigate the morphology of the MGPs. Capillary rise tests using acetone as the working fluid were conducted by a novel IR-thermal imaging method. The results showed that the micro-thorns on the bottom of the groove can enhance capillary pressure over the traditional micro-grooved wicks(MGs) and the capillary height of MGT-2 was as twice as high than the micro groove without thorns. Furthermore, the permeability was characterized in the force flow tests. It was found that the MGTs obtained comparable permeability to that for the MGs, revealing that they were able to enhance the capillary rise with little penalty of pressure drop. With regard to the capillary limited heat flux, the capillary parameter $K \cdot \Delta P_{cap}$ was employed to evaluate the performance of the wicks comprehensively and the gravitational effect also be taken into account when comparing the samples in the vertical capillary rise tests. In this case, the MGTs yielded higher $K \cdot \Delta P_{cap}$ than that for the thornless grooves. The MG-2 exhibited the largest capillary parameter K·ΔPcap (the value is triple that

of the MGs), though it failed to gain the highest capillary rise height, due to the well balance between the capillary pressure and permeability.

Keywords: Design of wick; Capillary; Permeability; Heat transfer; vapor chamber

[266] – HP2_5

A comparative study of performance of heat pipes with rectangular and omega-type grooves

Valeri Vlassov, Jorge Bertoldo Junior and Nadjara dos Santos

National Institute for Space Research, S.J.Campos-SP, Brazil

Abstract

Aluminum axial grooved heat pipes (HP) are widely used in space applications for heat spreading in the honeycomb structural panels of satellites, where electronic equipment is installed. The heat pipe grooves may be of rectangular, trapezoidal, or omega-type cross-section. The omega-type grooves usually give a better performance, however the developing capillary pressure may be sensitive to volume of fluid charge. Under ground test conditions, the HP thermal resistance may be affected by partial drying of upper grooves and eventual pool formation at the bottom area of the vapor core, especially for the heat pipes of relatively large groove size and diameter. This possible HP performance degradation must be carefully evaluated when satellite is submitted to the thermal vacuum tests. In this paper we present results of theoretical and experimental studies performed on HPs with rectangular and omega-type grooves using acetone as a working fluid. Experimental results were obtained on two similar HPs of the same external diameter but different grooves. Detailed finite element models of two types of grooves were built and simulation results were compared with obtained experimental data. Effects of partial drying and over-flooding were evaluated with the aim of a developed finite-element mathematical model of the grooves with different degrees of filling. Finally, the possible effects of using nanofluids were studied for both types of the grooves.

Keywords: extruded heat pipes; space applications; ground test performance; mathematical model of filled grooves.

Room A: Session #3: [PHP1] – Pulsating Heat Pipes #1

[310] – PHP1_1

Vapor thermodynamics and fluid merit for pulsating heat pipe

Vadim S. Nikolayev[1], Iaroslav Nekrashevych
Service de Physique de l'Etat Condens_e, CEA, CNRS, Universit_e Paris-Saclay, CEA Saclay, 91191 Gif-sur-Yvette Cedex, France

Abstract
In this communication, we discuss a theoretical description of the vapor phase thermodynamics in the pulsating heat pipe (PHP), to be used in the numerical simulations. We advance a theory based on simulation results that allows us to derive a theoretical expression for a dimensionless quantity showing elastic properties of the vapor for a given uid. One can use this quantity to evaluate the uid merit for use in the PHP. This theory is confronted to the simulation results obtained with the PHP simulation code CASCO. We compare the merit of water, ethanol, and FC-72 and show that water possesses better properties for use in PHP.

Keywords: Pulsating heat pipe, Oscillation, Merit number, Numerical simulation.

[315] – PHP1_2

Oscillation of a Completely Wetting Isolated Liquid Plug in a Square Capillary Tube

Asmita M. Rahatgaonkar, Vyas Srinivasan and Sameer Khandekar*
Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur, 208016, India.

Abstract
Discerning the local hydrodynamics of oscillating Taylor bubble flows forms an important element in the building block of the studies that focus on understanding Pulsating Heat Pipes (PHPs). In this background, an experimental study focusing on the effect of oscillations on the interface shape of a completely wetting (silicone oil) isolated liquid plug (L/D = 2.25) in a square glass capillary (1 mm × 1 mm) tube is carried out. The effect of oscillation frequency and amplitude on the liquid-air interface is studied. Due to completely wetting nature of silicone oil, it is observed that, the contact line stays pinned during the oscillation and the liquid meniscus slides over a thin-film. In addition, the oscillating liquid meniscus exhibits dynamic hysteresis. This hysteresis is seen to be a function of Capillary number, which in turn is affected by both oscillation frequency and amplitude. Farther, the hysteresis factor is critical for estimating the pressure drop characteristics of oscillating Taylor liquid plugs.

Keywords: Pulsating heat pipes; Oscillating liquid plug; Completely wetting; Pinning; Hysteresis.

[111] – PHP1_3

Influence of an Electrohydrodynamic pump on a pulsating heat pipe

Nicolas Chauris, Vincent Ayel, Christophe Louste, Cyril Romestant, Yves Bertin
Institut Pprime, CNRS – ENSMA - Université de Poitiers, UPR 3346, Département Fluides, Thermique, Combustion, 1 av. Clément Ader – BP 40109 86961Futuroscope - Chasseneuil Cedex, France

Pulsating heat pipe enhancement using an electrodynamic pump is investigated in this paper. A vacuum-tight electrohydrodynamic (EHD) pump has been developed and its performances evaluated by means of a dedicated hydraulic test bench. The voltage applied to the pump is up to 14 kV. For this voltage, the EHD pump provides a static pressure about 2100 Pa and a volumetric flow rate about 7 mL/min. In both cases, the electrical consumption of the pump was lower than 20 mW. Furthermore, we designed a flat plate pulsating heat pipe (FPPHP) made with copper and filled with 50% of HFE-7100 as working fluid. We connected the EHD pump between the condenser and the evaporator. The aim of this new device is to increase the current dry-out limitation and to provide better performances of FPPHP. The first tests were achieved in both horizontal and with an unfavorable inclination of 5° for the FPPHP, meaning the evaporator above the condenser. A real effect of the EHD pumping on the evaporator temperatures has be observed, with a decrease down to 12 K. New tests will be performed in order to optimize the EHD pump and deeply investigate the influence of the EHD on FPPHP thermal performances.

Keywords: Pulsating heat pipe, capillary, two-phase flow, Electrohydrodynamic, Electric field, Heat transfer enhancement.

[405] – PHP1_4

Large Diameter Pulsating Heat Pipe for Future Experiments on the International Space Station: Ground and Microgravity Thermal Response

Mauro Mameli[1], Andrea Catarsi[1], Daniele Mangini[2], Luca Pietrasanta[2], Davide Fioriti[1], Marco La Foresta[3], Lorenzo Caporale[3], Nicolas Miche[2], Marco Marengo[2], Paolo Di Marco[1], Sauro Filippeschi[1]
[1]University of Pisa, Largo Lucio Lazzarino 2, 56122 Pisa, Italy.
[2] School of Computing, Engineering and Mathematics, University of Brighton, Lewes Rd, Brighton BN2 4AT, UK.
[3]AAVID Thermalloy, Via del Fonditore, 4, 40138, Bologna, Italy.

Abstract
This work describes the thermal characterization on ground and under a varying gravity field (parabolic flights) of a large diameter Pulsating Heat Pipe (PHP) especially designed for its future implementation on the heat transfer host module of the International Space Station (ISS) for long term microgravity experiments. A multi-turn compact closed loop PHP is made of aluminum and partially filled with FC-72 (50% vol.). The 3mm tube internal diameter is larger than the static capillary limit evaluated on ground conditions for the above working fluid, with the objective of dissipating larger heat power inputs compared to smaller diameter channels, under microgravity conditions, allowing the typical slug flow pattern of PHPs to occur. To provide a detailed insight on the thermo-hydraulics phenomena during the device start-up under the occurrence of microgravity, the PHP is equipped with a transparent sapphire tube insert, two miniature pressure transducers and two micro-thermocouples. The flow pattern and the liquid bulk temperature distribution are detected by a fast VIS camera and a medium wave IR camera respectively. The data

recorded on the 67th ESA-NOVESPACE parabolic flight campaign are analyzed in the light of a future implementation on the ISS in 2020 and for the validation of actual numerical models. The device is continuously active during the whole microgravity periods without any stopover. The start-up tests (the heat power is provided after the 0-g occurrence) proved that the PHP operation is not primed by inertial effects. Finally, the thermal energy due to the sensible heat of the liquid phase is estimated showing a lower level than existing theoretical values.

Keywords: Pulsating Heat Pipe; International Space Station; Start-up; Microgravity; Parabolic Flight; Infrared Analysis.

[105] – PHP1_5

ASETS-II Oscillating Heat Pipe Space Flight Experiment: The First Six Months on Orbit

Brenton S. Taft[1] and Kevin W. Irick[2]
[1]*Senior Mechanical Engineer, U.S. Air Force Research Laboratory, Kirtland Air Force Base, NM 87117, United States*
[2]*Thermal Engineer, Applied Technology Associates, Albuquerque, NM 87123, United States*

Abstract
On September 7th, 2017 the U.S. Air Force Research Laboratory launched the second Advanced Structurally Embedded Thermal Spreader (ASETS-II) flight experiment to space on Orbital Test Vehicle 5. The ASETS-II experiment is made of three low-mass, low-cost oscillating heat pipes (OHPs) and an electronics/experiment control box. The three primary science objectives of the experiment are to measure the initial on-orbit thermal performance, to measure long duration thermal performance, and to assess any lifetime degradation. The three OHPs on ASETS-II are of varying configuration (center heating with single- and double-sided cooling) and working fluids (butane and R-134a) in order to isolate specific performance parameters of interest. OHP #3 was specifically designed in order to explore the Bond number limit on OHP operation in microgravity without requiring excessive operating temperature or pressure. Data collected during the first 6 months of on-orbit operations are presented in this paper. It is shown that each OHP performed as expected, where on-orbit data for OHPs #1 and #2 mirrored ground-truth performance, and the OHP #3 on-orbitmaximum operating evaporator temperature increased from ground-truth. The OHPs experienced no significant hysteresis effects and OHP #1 performed successfully in six-week long continuous operation.

Keywords: ASETS-II; Oscillating heat pipe (OHP); Pulsating heat pipe (PHP); Microgravity; Space flight experiment.

[128] – PHP1_6

Thermo-hydraulic analysis of semi-transparent Flat-Plate Pulsating Heat Pipes tested under normal and microgravity regimes

Vincent Ayel[1*], Luca Pietrasanta[2], Gildas Lalizel[1], Benjamin Medrinal[1], Cyril Romestant[1], Yves Bertin[1], Marco Marengo[2]
[1]*Pprime Institut CNRS – ENSMA – Université de Poitiers, UPR 3346, Futuroscope-Chasseneuil, France*
[2]*University of Brighton, School of Computing, Engineering and Mathematics, Brighton, UK*

Abstract
An experimental study is reported of a series of four Closed Loop Flat Plate Pulsating Heat Pipes tested under ground, hyper and microgravity conditions, during the ESA 64th parabolic flight campaign. Four channel diameters and three condenser lengths have been tested and compared for the same operating conditions (heat power applied, cooling fluid temperature, vertical BHM orientation). Like in a previous study [5], it was found that during normal gravity phases, the fluid stratifies with the liquid in the bottom zones, and the thermo-hydraulic transfer mode in this operation is either purelypool boiling inside completely filled channel, whatever the diameter. During microgravity phases, the fluid distributes naturally into a slug-plug flow pattern, with almost immediate trend to dry-out, followed by fast fluid overall motions leading to heat and mass transfers from evaporator towards the condenser zone, caused by some liquid small plugs moving towards the evaporator. Comparative analysis as regards temperatures and menisci velocities through video post-processing show the influence of the diameter on the heat and mass transfers occurring inside the different PHPs.

Keywords: Flat Plate Pulsating Heat Pipes; Flow Pattern; Channel diameter; Microgravity; Visualizations.

[308] – PHP1_7

Thermal Performance of Extra-thin Oscillating Heat Pipe

Naoko Iwata[1*], Yoshiro Miyazaki[2] and Hiroyuki Ogawa[3]
[1]*Research and Development Directorate, Japan Aerospace Exploration Agency, 2-1-1, Sengen, Tsukuba, 305-8505, Japan*
[2]*Thermal Control Laboratory Inc., 6-13-608 Bunkyo, Fukui 910-0017, Japan*
[3]*Institute of Space and Aeronautical Science, Japan Aerospace Exploration Agency, 3-1-1, Yoshinodai, Sagamihara, 252- 5210, Japan*

Abstract
In recent years, many astronomical satellites and earth observation satellites requires higher pointing accuracy and observation performance than past years. It is required not to conduct the micro disturbance and thermal distortions generated by components to the spacecraft structures though the heat dissipation from the components should conduct to the spacecraft with high thermal conductivity. A flexible thermal strap can solve such a conflicting demand. In this study, the oscillating heat pipes that consists of extra-thin metallic pipes are manufactured to develop an innovative flexible thermal strap in three axial directions. The metallic pipes with an inner diameter less than 0.4 mm are used for oscillating heat pipes. HFC-134a is used as a working fluid. The submicron-sized check valves are also manufactured to be inserted into the oscillating heat pipes for improvement of the thermal performance under the gravity condition. The thermal performance test results of the extra-thin oscillating heat pipes without the check valves will be reported. The performance of the check valve itself will be also reported.

Keywords: Oscillating heat pipe; Flexible thermal strap; Submicron; Thermal performance test.

Room B: Session #3: [HP3] – Heat Pipes #3

[169] – HP3_1

Experimental Investigation of the Effect of Gravity on Heat Pipe Startup

Jentung Ku
NASA Goddard Space Flight Center, Greenbelt, Maryland, 20771, USA

Abstract
This paper describes an experimental investigation of the startup behavior and subsequent operation of a heat pipe under the reflux mode. In this study, a heat pipe with internal axial grooves was placed in an upright position with two different tilt angles relative to the horizontal plane. Heat was applied to the evaporator at the bottom where liquid pool was formed and cooling was provided to the condenser at the top. The liquid-flooded evaporator section was divided into seven segments along the axial direction, and electrical heaters were attached to each segment. Heat was applied to evaporator segments in various heat flux combinations and sequences. Test results showed that as long as an individual evaporator segment was flooded with liquid, a superheat was required to vaporize the liquid through nucleate boiling in that segment. The required superheat for nucleate boiling was a function of gravity pressure head imposed on that evaporator segment. The most effective and efficient method to initiate nucleate boiling over the entire evaporator section and start the heat pipe was to apply a high heat flux to the lowest evaporator segment.

Keywords: Heat Pipe; Startup; Reflux Mode; Gravity Effects.

[309] – HP3_2

Thermal Control System with Variable Conductance Heat Pipes for Small Spacecraft

Konstantin A. Goncharov[1], Yuriy V. Panin[1*],Kirill N. Korzhov[1], Adik R. Gutkin [2], Alexander V. Vorontsov [3]
[1] *Heat Pipe Center of Lavochkin Association, 24 Leningradskaya street, Moscow region, Khimki, 141400 Russia*
[2] *Research Institute of Electromechanics (JSC "NIIEM"), Moscow region, Istra, 143502 Russia*
[3] *Research and Production Corporation named after A.G. Iosifian (JC "VNIIEM"), Moscow, 107078 Russia*

Abstract
Development of variable conductance heat pipes (VCHP) started with the first experiments of the heat pipes [1, 2 , 3]. It is well known that one of methods of providing passive control of HP conductance is injection of non-condensable gas into HP. Non-condensable gas (NCG) blocks a part of condenser preventing vapor condensation in the HP zone occupied by NCG [4]. VCHPs designed for the small space craft (SC) "Kanopus-V-IK" are described in this paper. VCHP parameters were determined during numerous experiments, tests and investigations. Investigation results obtained when carrying out VCHP autonomous ground tests, VCHP vibration and lifetime tests, tests in exposure to ionizing radiation, ground tests of VCHP integrated into thermal control system (TCS) and comparison of ground and flight test results of TCS with VCHP are presented in this paper.

Keywords: axial groove heat pipe (AGHP); variable conductance heat pipe (VCHP), gas-controlled heat pipe (VCHP), non-condensable gas (NCG), ammonia, neon.

[327] – HP3_3

Thermo-fluid dynamics in a wettability-enhanced evaporator based on microscale infrared/visible observations

Kimihide Odagiri[1*], Chiemi Oka[2], Chieko Kondou[3] and Hosei Nagano[2]
[1]*Department of Aerospace Engineering, Nagoya University, Furo, Chikusa, Nagoya, Aichi, 464-8603, Japan*
[2]*Department of Mechanical System Engineering, Nagoya University, Furo, Chikusa, Nagoya, Aichi, 464-8603, Japan*
[3]*Graduate School of Engineering, Nagasaki University, 1-14 Bunkyomachi, Nagasaki, Nagasaki 852-8521, Japan*

Abstract
In this paper, an effect of wettability improvement on a thermo-fluid behavior in an evaporator of a loop heat pipe (LHP) is studied experimentally and theoretically. Based on the numerical model developed in our previous study, it is known that an improvement of wettability between the evaporator case and working fluid enhances the heat transfer performance of the evaporator. In order to verify this trend, the experiments are conducted. In the experiment part, three kinds of heating plate, that have the different morphology of the surface: normal flat plate, a sandblasting plate and a short-pulse laser irradiation plate are used. The contact angles between ethanol and them are 8.2 ± 1.3 °, 0 °, and 0 ° respectively. The porous sample is made of stainless steel whose pore radius is 4.5 μm. The measurement of the heat transfer performance and liquid-vapor interface behavior is conducted with a microscopic infrared camera and a microscope. As results, the sandblasting plate and the short-pulse laser irradiation plate show higher heat transfer performance than the normal flat plate. In addition, it is found that there are different liquid-vapor interface behaviors between them. In the modeling part, the predicted heat transfer coefficient is calculated for each case. The calculation results are in good agreement with the experimental results. The mechanisms of the enhancement of heat transfer performance are discussed. Based on the experimental and numerical study, this paper represents a new approach for enhancement of heat transfer coefficient of a capillary evaporator.

Keywords: Loop heat pipe; Evaporator; Wettability improvement; Thermo-fluid behavior.

[337] – HP3_4

The effect of disjoining pressure on the condensing film in a flat grooved heat pipe

Mobin Alipour, Zafer Dursunkaya[1]
Department of Mechanical Engineering, Middle East Technical University, Turkey, Ankara

Abstract
In condensing and evaporating thin films, the shape of the interface profile is dominated by the capillary pressure. Disjoining pressure becomes significant when the liquid film is excessively thin. Thickness of the liquid film on the fin top of a grooved heat pipe reaches small magnitudes at the fin edge, where the fin top liquid meets the in-groove profile. In this study a model including the effect of disjoining pressure is used to study the condensation of a thin film that exists on a fin top. The results show that unlike models where only the capillary pressures are included, presence of disjoining pressure restricts the existence of solutions to a maximum value of the film profile angle at the fin edge, beyond which no solutions can be found. The reasons for this behavior are analyzed and discussed and a comparison between the results of the current research and the predictions available in the literature is presented.

Keywords: Condensation, Micro-grooved heat pipe, Disjoining pressure, Micro region.

[172] – HP3_5

Heat and Mass Transfer in Polygonal Micro Heat Pipes under Small Imposed Temperature Differences

Sai Sashankh Rao, Harris Wong
Department of Mechanical and Industrial Engineering, Louisiana State University, Baton Rouge, LA 70803, United States

Abstract
A micro heat pipe is a closed microchannel filled with a wetting liquid and a long vapor bubble. Micro heat pipes have been used to cool microelectronic devices, but their heat transfer coefficients are low compared with those of conventional heat pipes. We model heat and mass transfer in triangular, square, hexagonal, and rectangular micro heat pipes under small imposed temperature differences. We find analytic solutions for the temperature profile and vapor and liquid pressure distributions along the pipe in terms of two dimensionless numbers. The solution reveals the evaporating, adiabatic, and condensing regions commonly observed in conventional heat pipes and which are almost absent in micro heat pipes. We explain the reason for the poor performance of these devices and suggest ways of improving them by defining a design criteria. We also find a dimensionless optimal pipe length for maximum evaporative heat transfer. We compare our model to four published micro-heat-pipe experiments, and find encouraging support for our design criteria.

Keywords: Micro heat pipe; Two-phase flow; Contact-line evaporation; Nusselt number.

[244] – HP3_6

Theoretical and experimental investigations of the effect of an electric field on the performance of a grooved flat heat pipe

Nicolas Cardin[1,2], Stéphane Lips[1*], Samuel Siedel[2], Laurent Davoust[2], Jocelyn Bonjour[1]
[1]*Lyon, CNRS, INSA-Lyon, Université Claude Bernard Lyon 1, CETHIL UMR5008, F-69621, Villeurbanne, France*
[2]*Univ. Grenoble Alpes, CNRS, Grenoble INP, SIMaP, F-38000, Grenoble, France*

Abstract
The present communication reports on the investigation of the effect of an electric field on the performance of a flat heat pipe (FPHP). In the studied configuration, an electric force is imposed on the liquid-vapor interface, which affects the pumping of the liquid together with the capillary force. The ability of the electric field to change the shape of the liquid-vapor interface is investigated by means of a numerical and an experimental approach. The numerical approach consists in the strong coupling between the Laplace equation - corrected by the normal electric stress - and the equation for the electric potential. The former is solved for the calculation of the shape of the liquid-vapor interface while the latter is solved for the determination of the electric stress distribution. The results of the numerical study for an application inside a FPHP are discussed. The experimental bench consists in a tilted grooved aluminum plate equipped with a horizontal electrode pair and filled with HFE 7100. The effect of the electric field on the liquid distribution is observed by confocal microscopy.

Keywords: Meniscus recession; Capillary limit; Electrohydrodynamics; Confocal microscopy.

[304] –HP3_7

Towards a durable polymeric internal coating for diabatic sections in heat pipes

Fabio Villa*[a], Marco Marengo[b], Joël De Coninck [a]
*Correspondence to joel.deconinck@umons.ac.be
[a] University of Mons, Laboratory of Surface and Interfacial Physics (LPSI), 19 avenue Maistriau, 7000 Mons, BE
[b] University of Brighton, School of Computing, Engineering and Mathematics, Lewes Road, BN2 4GJ Brighton, UK

Abstract
In this work the effect of surface wettability in pool boiling heat transfer is studied. The pool boiling phenomena is characterized by three important parameters: onset boiling temperature (T_{ONB}), the heat transfer coefficient (HTC) and the critical heat flux (CHF). All these parameters are influenced by the wettability characteristics of the surface. This work analyses the effects of surface wettability on these three parameters and proposes a new super-hydrophobic polymeric coating which can have a very important effect in improving the heat pipe start-up power load and increasing the thermal performance of heat pipes when the flux is lower than the critical heat flux.

Keywords: Pool boiling; heat pipe; surface wettability, bubble characteristics; super-hydrophobicity.

Room A: Session #4: [LHP2] – Loop Heat Pipes/Capillary Pumped Loops #2

[100] –LHP2_1

High performance loop heat pipe with flat evaporator for energy-saving cooling systems of supercomputers

Zhihu Xue*, Wei Qu and Minghui Xie
China Academy of Aerospace Aerodynamics (CAAA), Beijing 100074, China

Abstract
Two high performance loop heat pipes (LHPs) are developed for direct cooling of the chips in supercomputer. The two LHPs using flat evaporator are: one called water cooling loop heat pipe and another one called water cooling loop heat pipe. The working fluid of loop heat pipe is ammonia. The water cooling LHP can well work at a heat load up to 663 W and wind cooling LHP can well work at a heat load up to 513 W. The two LHPs applying to the real computer servers are realized and tested. The server test results with water cooling LHP have shown that the operating temperature of CPUs can be controlled to about 67 ℃ to ensure the reliable operating and acceptable level for electronic chips, even at condenser cooling water temperature of 40 ℃ with low water flow rate of 0.055 m^3/h. The server test results with wind cooling LHP have shown that the operating temperature of CPUs can be controlled to about 51 ℃ even at condenser cooling wind temperature of 30 ℃ with wind flow rate of 41.88 m^3/h.

Keywords: Loop heat pipe; Two-phase device; Electronics cooling; Temperature control; Thermal resistance.

[388] –LHP2_2

Novel Modular Evaporator Architecture for Electronics Cooling Applications

Donatas Mishkinis*, Igors Ušakovs and Dmitry Nasibulin
Allatherm, Torres de la Alameda, 28813, Spain

Abstract
Novel concept of modular multi-evaporator thermal architecture where several evaporators can be assembled with two (or more) compensation chambers in line or/and in parallel by common secondary wick gives possibility quickly develop new products for thermal management of different heat generating elements in power electronics and microelectronics areas. Thermal system (circuit) with 0.7 m vapor and liquid lines and air-cooled condenser has been connected to three different evaporators: single, double and triple modular designs for performance investigation. Non-toxic Refrigerant R600 has been used as a working fluid. Results of experimental investigation of three evaporators in the same thermal loop are presented and discussed in the article.

Keywords: Loop Heat Pipe, Capillary Pumped Loop, Multi-evaporator design, Thermal management.

[144] –LHP2_3

Experimental and Numerical Analysis of Start-up of a Capillary Pumped Loop for Terrestrial Applications

Flavio Accorinti[1*], Nicolas Blet[2], Vincent Ayel[1], Sebastien Dutour[3], and Yves Bertin[1]
[1]*Pprime Institut CNRS – ENSMA – Université de Poitiers, UPR 3346, Futuroscope-Chasseneuil, France*
[2]*Université de Lorraine, CNRS, LEMTA, F-54000 Nancy, France*
[3]*University of Toulouse, CNRS, UPS, INPT, LAPLACE (Laboratory of Plasma and Conversion of Energy), 118 route de Narbonne, F-31062, Toulouse cedex 9, France*

Abstract
A transient study on the start-up phases of a Capillary Pumped Loop for Terrestrial Application is proposed in this paper. Experimental analysis and numerical modelling, using a 1-D spatial discretisation model based on Navier-Stokes equations resolution by electrical analogy, are presented to study the thermal and hydraulic behaviour of the loop for methanol and npentane as working fluids, during start-up transient phases. The experimental observations are backed up with the numerical model to help with the transient and steady analysis of this kind of loop. The precise numerical study allows us to have a better understanding of the complicated phenomena happening during the start-up, to have a global view of the system during these phases and also to have a better understanding of the influence of the gravity on the behaviour of the CPLIP.

Keywords: Capillary Pumped Loop; Start-up; Terrestrial Application; Gravity Field.

[80] –LHP2_4

Development of Flat-plate Loop Heat Pipes for Spacecraft Thermal Control

Hongxing Zhang, Guoguang Li, Ling Chen, Guanglong Man, Jianyin Miao*, Xiaozhi Ren, Jiang He, Yuhua Huo

Beijing Key Lab of Space Thermal Control Technology, China Academy of Space Technology, Beijing 100094, P.R. China

Abstract

This paper describes the development, ground experiment results and on-orbit test plan of stainless steel-ammonia flat-plate loop heat pipes for space applications. The pressure-proof evaporator with reinforced structure was designed to endure the high pressure of the working fluid. The cylindrical compensation chamber and the primary sintered nickel wick were connected by the secondary wick for liquid supply under microgravity. To validate the startup and operation capability in space, the on-orbit tests of two FLHPs will be carried on in the reentry capsule of the Chinese next generation spaceship. Specifically, the FLHPs are used to transfer the dissipated heat of the laser gyro and fiber optic gyro to the cold capsule wall. Extensive ground experiments were conducted to investigate the startup and operation characteristics and the heat transfer capability. Test results indicate that there are only two startup situations for the FLHP. A superheat degree of above 10℃ is required to initiate the nucleate boiling in the evaporator when the vapor channels are flooded by liquid. The auxiliary startup measure by locally heating on the top surface near the evaporator outlet is effective to obtain the required superheat, not affecting the equipment's temperature. The orientation of the evaporator and the CC has negligible effect on the startup and operation of the FLHP, and the secondary wick can provide effective liquid supply to the primary wick even at an unfavorable position. Moreover, the heat transfer capacity of the evaporator is greater than 330 W and the critical heat flux is greater than 20 W/cm^2.

Keywords: Spacecraft; Thermal control; Flat-plate loop heat pipe; on-orbit experiment.

[404] –LHP2_5

Parabolic flight experiment for graphene LHP evaporator characterization

F. Iermano[1], M. Christian[2], Y.A. Samad[3], L. Lombardi[3], F. Esposito[1], D. Sarica[1], C. Papakonstantinou[1], V. Miskovic[1], C. Minetti[1], P. Queeckers[1], V. Morandi[2], M. Molina[4], V. Palermo[2], A.C. Ferrari[3], C.S. Iorio[1]

[1] *Université Libre de Bruxelles, Chimie-Physique E.P. CP 165/62 Avenue P.Heger, Bat. UD3, Bruxelles 1050, Belgium*
[2] *CNR Bologna, via Gobetti 101, 40129 Bologna, Italy*
[3] *Cambridge Graphene Centre, 9 JJ Thomson Avenue, CB3 0FA, Cambridge, UK*
[4] *Leonardo S.p.a., Airborne and Space System Division, 20131 Nerviano MI, Italy*

Abstract
Loop Heat Pipes (LHP) are passive heat transfer devices used in thermal control of spacecraft equipment and instruments. Graphene, deposited on the porous structure known as *capillary pump*, has shown to be a suitable mean to increase the LHP operation stability and start-up reliability. Test in vacuum have been complemented, late in 2017, by a microgravity experimental campaign, with more than 30 minutes data collected in zero-g conditions. The paper describes the experimental set up to characterize the LHP evaporator performance.

Keywords: LHP; Graphene; Microgravity; Evaporators

[397] – LHP2_6

Development and thermal testing of a breadboard LHP with a low CTE Evaporator

Estefanía Turrión[1], Saúl Campo[1], Andrei Kulakov[1], Alejandro Torres[1], David Valentini[2], Benoit Demolder[2], Paul Atinsounon[2] and Amaury Larue De Tournemine[3]
[1]IberEspacio, Avenida Premios Nobel 53, 28850, Torrejón de Ardoz, Spain
[2]Thales Alenia Space, 5 Allée des Gabins 06156 Cannes La Bocca, France
[3]*Centre National d'Etudes Spatiales, 18 Avenue Edouard Belin, 31401 Toulouse, France*

Abstract
The need of low Coefficient of Thermal Expansion (CTE) heat transport systems in current space technologies for Earth Observation satellites demands the use of materials such as CFRP, ceramics and certain metals. The main objective is to minimize the CTE mismatch on the I/F. This issue is of key relevance when a stable and uniform temperature is requested along Focal Plane (FP) assemblies. Standard evaporator saddles on Loop Heat Pipes (LHP) that performs the I/F with the thermal dissipation unit are manufactured in aluminum. The selection of this material is mainly driven by its high thermal conductivity, which allows reducing the overall LHP temperature gradient. Unfortunately, the aluminum CTE is high in comparison with those of materials typically used on FP, such as SiC. A saddle in DISPAL (aluminum/silicon alloy) is proposed instead. This material shows a lower CTE while keeping a good thermal conductivity. In order to validate the assembly between both components, evaporator DISPAL saddle and focal plane, and to prove the solution in terms of mismatch due to CTE differences, a LHP was designed, manufactured and tested by IberEspacio. In addition to this, a thermal mathematical model was developed in EcosimPro to predict and correlate the thermal test campaign. As part of the test campaign, a thermal cycling was performed in order to validate the mechanical link between the FP and the low CTE evaporator with successful results. The thermal test campaign in vacuum conditions showed good LHP performance with a stable operation in both steady state and transient conditions (in orbit operation). Finally, the thermal control system on the FP led to an acceptable small gradient of temperatures along it, ranging from 2°C to 5°C during testing.

Keywords: Coefficient of Thermal Expansion; Ceramic; Focal Plane; Loop Heat Pipe Modeling.

Room B: Session #4: [HP4] –Heat Pipes #4

[27] –HP4_1

Dynamic Modelling of the Heat Pipe Assisted Annealing Line

Metin Celik[1*], Mrunal Patki[1], Geert Paulussen[2], Wiebren de Jong[1], Bendiks Jan Boersma[1]
[1]*Process & Energy Department, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, The Netherlands.*
[2]*Research & Development, Tata Steel, IJmuiden, The Netherlands.*
[*]*Corresponding author. Email: M.Celik@tudelft.nl.*

Abstract
In a conventional continuous annealing line, the energy applied to steel during heating is not recovered while cooling it. Therefore, an alternative technology for energy efficient continuous annealing of steel was developed. This technology enables reusing the heat extracted during cooling of the strip in the heating part of the process. This is achieved by thermally linking the cooling strip to the heating strip via multiple rotating heat pipes. In this context, the dynamic simulation of a full heat pipe assisted annealing line is developed. The dynamic simulation consists of the interaction of building blocks, each

comprising of a rotating heat pipe and strip parts wrapped around the heat pipe. The simulations are run for different installation configurations and operational settings, with the heat pipe number varying between 50 and 100 and varying the line speed and strip dimensions. The typical heat pipe dimensions are 0.5 m of diameter and 3 m of length. The simulation results show that the equipment is capable of satisfying the thermal cycle requirements. With this concept, energy savings of up to 70% are feasible.

Keywords: Rotating heat pipe; Continuous annealing; Energy efficiency; Numerical model.

[21] –HP4_2

Review of thin vapor chamber design, performance and lifetime reliability

Masataka Mochizuki[1*], Thang Nguyen[2] ,Yuji Saito[2],Yoji Kawahara[2],Yuichi Yokoyama[2], and Makoto Takahashi[2]

[1]*The Heat Pipe, 1-4-33-1022 Shiohama, Koto-ku, Tokyo 135-0043, Japan*

[2]*Fujikura Ltd, 1-5-1 Kiba, Koto-ku, Tokyo 135-8512, Japan*

Abstract

The cooling device for computers and electronics is getting smaller and thinner year after year, especially for the mobile handheld device such as smartphone which is the most popular gadget and widely use nowadays. It seems that in the current trend every 6-12 months a new model of smartphone is introduced and it was packed with faster processing processor, memories, and graphics, higher density battery, higher resolution for camera and video and so on. The drawback is the device getting hotter due to the increase of heat dissipation caused by faster computing. The traditional method of cooling by purely metal heat conducting maybe no longer viable. In the recent year thin heat pipes had been introduced to smartphone for better transfer and spreading heat for cooling. Thin vapor chamber becoming more attractive for smartphone cooling due to its potential superior heat transfer than thin heat pipe. Typically heat pipe or vapor chamber for cooling smart phone is less than 0.4 mm thick. This paper is a review and comparison on the structural design and thermal performance of various thin vapor chambers on development or available off the shelves. Discussion on material compatibility, non-condensable gas generation and lifetime reliability of heat pipe and vapor chamber will be also included.

Keywords: Heat pipes; Vapor chamber; Two-phases heat transfer; Smartphone cooling; Non-condensable gas; Life time reliability.

[73] –HP4_3

Battery Cooling Architectures for Electric Vehicles Using Heat Pipes

Randeep Singh[1]*, Gero Lapp[1], Phan Thanh Long[2], Tien Nguyen[2], Yasuhiro Horiuchi[2], Makoto Takahashi[2], Yuji Saito[2], Masataka Mochizuki[3], Karsten Mausolf[5], Kristin Busse[5]

[1]*Fujikura Automotive Europe GmbH, Manchinger Strasse 114, D-85053 Ingolstadt, Germany, *Tel: +49 (0) 841 98 121 547, Email: randeep.singh@jp.fujikura.com*

[2]*Fujikura Ltd., 1-5-1, Kiba, Koto-Ku, Tokyo 135-8512, Japan*

[3]*The Heat Pipes, Shiohama 1-4-33-1022, Koto-ku, Tokyo 135-0043, Japan*

[5]*Volkswagen AG, Brieffach 013/37610, D-38112 Braunschweig*

Abstract

Cooling demands in Electric Vehicles (EVs) are more profound than conventional gasoline vehicle due to full electric functionalities and features. Most components of electric propulsion system in EV need thermal control including battery system which has utmost cooling demand owing to system power, size and complexity. In this paper, different options based on heat pipes for thermal management of battery cell/module in EV has been explored, analysed and compared. Heat pipe based design architectures have been explored at three different level: 1) cell level: to remove heat from individual cells directly using capillary heat pipes, 2) module level: to remove heat (locally) from stack of cells collectively using capillary heat pipes or pulsating heat pipes, 3) system level: to remove heat from bank of modules to remote location (for dissipation) using single phase liquid cold plate or loop heat pipe. Variant combinations of these design options have been evaluated w.r.t cooling targets and system design, for 40 to 400 W output heat load from

battery module. Cooling architecture based on embedded capillary heat pipe and single phase pumped cold plate will be most adaptable for range of EVs while embedded heat pipe and loop heat pipe based solution will provide most high performance design for high-end carlines. Experimentally it was shown that embedded heat pipe would have x2 lower thermal resistance than pulsating heat pipes while loop heat pipe evaporator exhibits 2 to 4 times higher heat removal performance than single phase cold plates. In summary, two phase thermal management system, for lithium-ion battery, based on different designs of heat pipe will help to improve overall system cooling performance, reliability, safety and reduce design complexity.

Keywords: Automotive thermal control; Hybrid electric vehicle; Lithium-ion battery; High voltage batteries; capillary heat pipes Loop heat pipe; Pulsating heat pipes.

[217] –HP4_4

Experimental Investigation on Startup and Thermal Performance of a High Temperature Heat Pipe

Huan-Ming Yeh[1], Chun-lin Chang[1], Meng-Chang Tsai[2], His-Hsiang Wu[1] and Shung-Wen Kang[1]*
[1]Department of Mechanical and Electro-Mechanical Engineering, Tamkang University, Taipei 25137, Taiwan, ROC
[2]Dual-use Technology Cooperative Development Program, National Chung-Shan Institute of Science and Technology
Taoyuan 32544, Taiwan, ROC

Abstract
Heat pipe play an important role in high temperature energy transfer system and storage system. It can be applied to the areas such as solar energy storage system and waste heat recovery. High temperature heat pipes with 420mm in length, 13mm in outer diameter and 2mm in tube thickness have been developed and tested. The device was made of Inconel 600 equipped with a 316 stainless-steel 100 mesh wick. The working fluid was metal sodium with a filling ratio of 10% (2.86g). Heat pipes start-up and thermal characteristics were investigated at different orientations with slopes of -15°, 0°, +45° and +90° while heat sink temperatures were kept at 27°C air environment. The evaporator temperature of 800°C was achieved when the input power was set at 790W. It has been found that the lowest value of the heat pipes thermal resistance was 0.11 °C/W when the inclination angle was at 90°.

Keywords: high temperature heat pipe; metal sodium; stainless steel screen

[242] –HP4_5

Regulative Characteristic of Methanol–Copper Heat Pipes for Asteroid Lander "MASCOT"

Volodymyr Baturkin[1*], Vitali Feidelheimer[2], Kaname Sasaki[1], Eugen Mikulz[1] and Tra-Mi Ho[1]
[1]*DLR – Institute of space systems, Bremen, 28359, Germany*
[2]*FH Aachen – University of Applied Sciences, Aachen, 52064, Germany*

Abstract
Variable conductance heat pipes (VCHPs) are the main part of MASCOT (Mobile Asteroid surface SCOuT) lander ther-mal control system (TCS). They provide variable conductivity by utilizing the heat transfer limitations. This allows the heat pipes to act as thermal switches without additional constructive elements. The advantage is simplicity and compactness of conventional heat pipe design. Two cylindrical copper-methanol heat pipes with shell length of 0.482 m and 0.438 m and external diameter of 0.006 m, having copper discrete metal fiber wick and copper shell were constructed and verified in the temperature range between −75 and +60 °C. The purpose is to apply this design into the MASCOT thermal control system and to investigate their regulative characteristics and heat transfer limitations. VCHPs show a change of thermal resistivity from 70 K/W, at a heat sink temperature of −60 °C, to 0.8 K/W at a heat sink temperature of +60 °C; with a obtained maxi-mal heat transfer rate of 5 W and 16 W, respectively. It is found, that the switching effect of the heat pipes is governed by the sonic velocity limitation, the saturation vapor pressure of the working fluid and the maximal capillary pressure of the wick. Operation of heat pipes as the part of TCS has confirmed their variable thermal properties.

Keywords: Heat transfer limitations; Variable conductance; Metal fiber wick; Space application; Methanol-Copper.

[227] –HP4_6

Two-phase heat transfer systems for future human space exploration applications: validation on board the International Space Station

Fabio Lepore*[1], Valerio Di Tana[1], Filomena Iorizzo[1]

[1]*Argotec s.r.l., Turin, 10155, Italy*

Abstract

Heat pipes represent candidates for future spacecraft thermal control, due to their low complexity and limited maintenance requirements, as well as their lightness and reliability. Heat pipes are used on board the International Space Station (ISS), but they are installed on the external part of the ISS. This is because they contain anhydrous ammonia that would create a catastrophic scenario in case of leakage. For this reason two-phase heat transfer devices for manned space modules have been developed and their performance in the microgravity environment of the ISS has been validated. The payload Thermal Exchange was designed for the validation of axially Grooved Heat Pipes using different low toxicity working fluids and internal grooves used to enhance the capillary forces, thus increasing the heat transfer performance. Thermal Exchange was delivered to the ISS on March 2016 and it was operated successfully in the Microgravity Science Glovebox in April 2016 and again in September 2017. Because of the results obtained in terms of reliability and temperatures, this technology reached an adequate TRL level for integration into existing on board systems in the short term, and for use in future human space exploration applications in the long term.

Keywords: Heat pipes; Low toxicity fluid; Thermal Exchange; Spacecraft thermal control.

DAY #3: Tuesday, June 12, 2018

Room A: Session #5: [PHP2] – Pulsating Heat Pipes #2

[4] –PHP2_1

Study of diffusion bonded flat plate closed loop pulsating heat pipes with alternating porous media

Luis Betancur[1]*, Arthur Facin[1], Priscila Gonçalves[1], Kleber Paiva[1], Marcia Mantelli[1], and Gustavo Nuernberg[1]

[1] *Department of Mechanical Engineering, Federal University of Santa Catarina, Florianopolis 88040-900, Brazil*

Abstract

The present paper has two main objectives: to discuss the application of diffusion bonding process in the fabrication of pulsating heat pipes (PHPs) and to analyze the thermal performance of PHPs with porous media structures applied to alternating channels in the evaporator section. For that, two different copper flat plate closed loop PHPs with five turns and 1.5 mm of inner diameter channels were fabricated, using diffusion bonding. Samples were made with different diffusion process to evaluate the ability of the resulting device to keep the vacuum, avoiding the use of filler material during the soldering process, which could result in contamination and, therefore, undesirable corrosion on both internal and external heat pipe surfaces. The results allow evaluating the quality of the bonded interface using different configurations of the diffusion process. Metallographic results obtained on controllable pressure furnace and pressure control were analyzed taking advantage the diffusion process with controlled pressure. One of the PHP constructed was assisted by internal sintered copper wick, applied in alternating channels at evaporator region. A comparison with the heat transfer characteristics of another PHP with smooth tubes was performed. For the wicked PHP, the thermal resistance in horizontal position showed to be similar to heat transfer of pure conductive copper plate. However, PHPs containing alternating porous media in evaporator zone showed the lowest thermal resistance in vertical position, with less thermal oscillations.

Keywords: Diffusion Bonding; Thermal Resistance; Porous Media; Alternating Channels.

[20] –PHP2_2

Two-dimensional numerical analysis of common header pulsating heat pipe

Sameer Ranjan Sahu and Manoj Kumar Moharana
Department of Mechanical Engineering, National Institute of Technology Rourkela, Rourkela 769008, India

Abstract
A Common Header Pulsating Heat Pipe (CHPHP) is a novel two phase passive heat transfer device made by replacing the multiple turns of a conventional Pulsating Heat Pipe (PHP) by common header at both ends. A numerical analysis was carried out by using the volume-of-fluid (VOF) multiphase model along with continuum surface force model with wall adhesion to account for the surface tension dominance in the device. The present CHPHP geometry consists of ten parallel channels with ammonia and acetone as the working fluid (filling ratio 50 %). The configuration simulated for condenser temperatures of 278 K and 283 K under varying heating loads in the range of 50 -150 W. Equivalent thermal conductivity as high as 9000 W/m- K approx. was achievable using acetone when working at 125 W. The thermo-hydrodynamic behavior in the CHPHP was found to be surface tension dominated.

Keywords: Common header; VOF; Surface tension; Pulsating heat pipe, Multiphase.

[224] –PHP2_3

Experimental investigation of a flat-plate closed-loop pulsating heat

Wessel W. Wits[1,2,3*], Gerben Groeneveld[2] and Henk Jan van Gerner[3]
[1]*Thales Nederland B.V., P.O. Box 42, 7550 GD Hengelo, Netherlands*
[2]*Faculty of Engineering Technology, University of Twente, P.O. Box 217, 7500 AE Enschede, Netherlands*
[3]*Netherlands Aerospace Centre (NLR), P.O. Box 153, 8300 AD Emmeloord, Netherlands*

Abstract
The thermal performance and operating modi of a flat-plate closed-loop Pulsating Heat Pipe (PHP) are experimentally observed. The PHP is manufactured through CNC milling and vacuum brazing of stainless steel 316L. Next to a plain closed-loop PHP also one that promotes fluid circulation through passive Tesla-type valves was developed. Each channel has a 2×2 mm^2 square cross section and in total 12 parallel channels fit within the 50×200 mm^2 effective area. During the experimental investigation, the power input was increased from 20W to 100W, while cooling was performed using a thermo-electric cooler and thermostat bath. Three working fluids were assessed: water, methanol and ammonia. The PHP was charged with a 40% filling ratio. Thermal resistances were obtained for different inclination angles. It was observed that the PHP operates well in vertical evaporator-down orientation, but not horizontally. Moreover, experiments show that the minimum operating orientation is between 15-30°. Two operating modi are observed, namely the thermosyphon modus, without excessive fluctuations, and the pulsating modus, in which both the temperature and pressure responses oscillate frequently and violently. Overall thermal resistances were determined as low as 0.15 K/W (ammonia) up to 0.28 and 0.48 K/W (water and methanol, respectively) at 100 W power input in the vertical evaporator-down orientation. Infrared thermography was used to visualize the working fluid behaviour within the PHPs. Infrared observations correlated well with temperature and pressure measurements. The experimental results demonstrated that the developed flat-plate PHP design, suitable for high-volume production, is a promising candidate for electronics cooling applications.

Keywords: Oscillating heat pipes; Two-phase flow; Plug/slug flow; Evaporation/condensation

[31] –PHP2_4

Experimental Study on Flow and Thermal Characteristics of Pulsating Heat Pipes

Soohwan Jun[1] and Sung Jin Kim[1*]
[1]*Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea*

Abstract
Experiments are performed to investigate the flow and thermal characteristics of micro pulsating heat pipes (MPHPs) with 10 turns. To form a closed loop, a rectangular microchannel is engraved on the silicon wafer with a thickness of 1 mm. The width and height of the channel are 1 mm and 0.5 mm, respectively. Ethanol is used as the working fluid, and a transparent glass is used as a cover to allow for flow visualization. The time variations of vapor pressures are

measured using pressure transducers at the adiabatic section. Simultaneously, the temperature variations of vapor plugs and liquid slugs were obtained by micro-thermocouples, which have a wire diameter of 50 μm. The measured pressure and temperature of the two-phase mixture are synchronized with the flow behavior obtained by a high-speed camera. The experiments are performed in vertical and horizontal orientations. The thermodynamic states of the vapor plugs are examined using the measured pressure and temperature data. The experimental results show that the thermodynamic states in MPHPs depend on the flow behavior and the liquid film. In a vertical orientation, the MPHP exhibits a stable operation with the large amplitude. As a result, it is identified that vapor plugs are alternately saturated and locally superheated due to continuous liquid supply. On the contrary, the MPHP shows a relatively short large-amplitude oscillation followed by a long-term stopover phenomenon repeatedly in a horizontal orientation. It results in a dryout in the evaporator section, and the vapor plugs are superheated in the stopover region.

Keywords: Pulsating heat pipes, Thermodynamic states, Flow visualization, Pressure measurement.

Room B: Session #5: [SP1] – Special Two-phase Devices #1

[193] –SP1_1

On-orbit Experiment Plan of Loop Heat Pipe and the Test Results of Ground Test

Atsushi Okamoto[1], Takeshi Miyakita[1], Koki Sato[2] and Hosei Nagano[3]

[1]*Research and Development Directorate, JAXA, Tsukuba 305-8505, Japan*

[2]*Department of Aerospace Engineering, Nagoya University, Nagoya 464-8603, Japan*

[3]*Department of Mechanical Engineering, Nagoya University, Nagoya 464-8603, Japan*

Abstract

The LHP can transport much heat for a long distance against gravity and has many other excellent characteristics, such as high controllability of operating temperature and a shutdown function. In this study, 100W-class LHP for space application has been developing. As a part of the study, bread board model (BBM) of LHP was designed and fabricated. As a result of on-ground test of BBM, it is confirmed that BBM can satisfy all requirement (e.g. maximum transport rate, minimum required heat load for start-up, operating temperature control and shutdown function). To apply the LHP to the thermal control system of spacecraft, the thermal characteristic under the micro-gravity condition should be examined in advance. On-orbit experiment of a LHP radiator system is planned. This paper describes the test plan of on-orbit experiment of a LHP radiator system and the results of ground test of ground test model (GM).

Keywords: Loop heat pipe; Heat transfer; Space; Thermal control; Satellite; On-orbit experiment.

[355] –SP1_2

Experimental validation of two-phase spreader performances operating under high gravity field

Mikael Mohaupt[1,*], Stéphane Van Oost[1] and Laurent Barremaecker[1]
[1]*Euro Heat Pipes, Rue de l'industrie 24, B-1400 Nivelles, Belgium*

Abstract
The design of a two-phase spreader with remarkably stable performances is presented to operate under gravity field up to 10g, power up to 500W and cold source temperature up to 70°C. Tests have been performed in centrifuge facilities and dedicated jig has been used to test the flat heat pipe already characterized in laboratory conditions under high gravity field oriented in three different directions. The chosen orientations represent the most stringent conditions in which gravity field is supposed to degrade the heat pipe operation mode. The innovative design to manage high gravity field demonstrates its benefits. Indeed the improvement validated in lab conditions are met, namely up to 50% gain on thermal resistance stable whatever the gravity field, demonstrated by tests upt to 10g.

Keywords: Flat Heat Pipe; Vapor Chamber; Gravity Experimental Validation; Reservoir.

[316] –SP1_3

Development of a Thermosyphon Based Window Mounted Solar Water Heater

Siddharth Paralikar[2], Divyansh Tripathi[3] and Sameer Khandekar[1*]
[1]*Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India*
[2]*Siddharth Solar Technergies, Plot 366, Sector 27A, PCNT, Pune 411044, India*
[3]*Golden Star Technical Services Pvt. Ltd., T204, MIDC, PCMC, Pune 411026, India*

Abstract
This paper highlights the design, development and testing of a novel solar water heating system, in which the collector is mounted outside, below the window of an apartment and the heat is transported to the storage tank placed inside, through a thermosyphon assembly. In this design, a novel thermosyphon assembly is incorporated, consisting of a single flat plate evaporator manifold (acting as the collector) and multiple condensers. To avoid mounting of a heavy or bulky structure, a Fresnel lens is used to concentrate the solar radiation on a small size collector, thus giving higher heat flux. To make it a low-cost arrangement, a uniaxial manual tracking system with a flat plate collector is used instead of a Bi-axial continuous tracking. Flat plate collector instead of a point or a line collector, compensates for the absence of biaxial real time tracking. Automated tracking is avoided for simplicity and cost. The location of Fresnel lens can be manually adjusted along the guide rails every few days. To improve the absorptivity of evaporator manifold, a selective absorption coating was applied. For testing, shadow analysis was performed at different locations to find a suitable place. Experiment was run daily from 11:30 AM to 3 PM IST during February, March 2018 when the solar insolation was ~ 750 W/m2. Average efficiency of the system and water temperature at the end of experiments were observed to be around 15% and 52°C respectively, whereas the maximum efficiency and temperature were recorded to be 23% and 54°C respectively.

Keywords: Compact Solar Water Heater; Novel Thermosyphon Assembly; Fresnel Lens; Uniaxial Solar Tracking.

[408] –SP1_4

Vaporization heat transfer in a closed two-phase thermosyphon

Andrea Padovan[2], Stefano Bortolin[1], Marco Rossato[3] and Davide Del Col[1]
[1]*Department of Industrial Engineering, University of Padova, Padova 35131, Italy*
[2]*Onda SpA, Via Lord Baden Powell 11, 36045 Lonigo (VI), Italy*
[3]*Aermec SpA, Via Roma, 996, 37040 Bevilacqua (VR), Italy*

Abstract
This paper deals with heat transfer in a closed two-phase thermosyphon with a long evaporator and a short condenser, filled with water as operating fluid. The ratio of length to inside diameter of the evaporator is equal to 166. A similar geometry is commonly used in vacuumed tube solar collectors. In the present investigation the input power to the evaporator is provided by means of an electrical resistance wire wrapped around the external wall of the tube, while a water jacket is built at the condenser to reject the heat. An adiabatic section, placed between evaporator and condenser, is used to measure the saturation temperature. The thermosyphon is fully instrumented with thermocouples to measure the wall temperature in the different sections of the tube. The overall performance of the thermosyphon is described by using the wall temperature and overall thermal resistance for different operating conditions: input power at the evaporator, cooling water temperature at the condenser and inclination of the thermosyphon (30°, 60° and 90° tilt angle to the horizontal plane). The experimental study is focused on the evaporator: data of heat transfer coefficient are reported, covering a range of heat flux between 1700 and 8000 W/m² and saturation temperature between 29 °C and 72 °C. The measured vaporization heat transfer coefficients are compared with some correlations for closed two-phase thermosyphons. A new correlation is presented, which accurately predicts the present experimental heat transfer coefficients and other data by independent labs taken in closed two-phase thermosyphons, with different geometries and operating fluids (water and R134a).

Keywords: Closed thermosyphon; Two-phase heat transfer; Evaporator.

DAY #4: Wednesday, June 13, 2018

Room A: Session #6: [TS2] – Thermosyphons #2

[279] –TS2_1

Experimental study on heat transfer characteristics of long two-phase closed thermosiphons related to passive spent fuel pool cooling

Claudia Grass, Rudi Kulenovic, Joerg Starflinger
Institute of Nuclear Technology and Energy Systems, University of Stuttgart, 70569 Stuttgart, Germany

Abstract
The basic operational behavior of two long two-phase closed thermosiphons of different diameters (32 mm and 45 mm) including water and methanol as working fluid is experimentally investigated. The filling ratios 50%, 70% and 100% relating to the evaporator volume are tested for identical boundary conditions. Measuring campaigns for heat sink temperatures 10 °C, 20 °C and 30 °C and electrical heat inputs from 1000 W up to 3000 W are carried out and compared. The mass flow and the inlet and outlet temperature of the heat sink are measured and used to calorimetrically determine the transferred heat. A pulsating geyser boiling and a steady-state nucleate boiling are observed according to filling ratio and heat input.

Keywords: thermosiphon, spent fuel pool cooling, long-length pipes, stainless steel-water/methanol system.

[212] –TS2_2

The influence of geyser boiling on performance of the two-phase-closed thermosyphon filled with R134a

Karolina Wojtasik[1], Agnieszka Wlazlak[1] and Bartosz Zajaczkowski[1*]
[1]*Wroclaw University of Science and Technology, Wroclaw 50-370, Poland*

Abstract
Increase of thermal energy efficiency and transition to localized energy sources are vital steps leading to the development of net-zero buildings. Passive heating systems are one of the most interesting technologies that can substantially improve thermal behavior of both modern and revitalized buildings. Noticeable reduction of energy consumption during cold seasons can be achieved with an introduction of strategically located two-phase-closed thermosyphons (TPCT) that can become independent heat sources or assist existing HVAC systems. One of the factors that influences performance is the accuracy of its installation in vertical position. In the paper, we have conducted experiments and measured the performance of a skewed thermosyphon at different lean angles (up to 20 degrees). At certain angles and under specific thermal conditions we have observed occurrence of the geyser boiling that is characterized by cyclic fluctuations of pressure and wall temperatures. The paper studies the interdependence of working parameters and the geyser effect. We reveal how heating water temperature and the lean angle affected amplitude and frequency of pressure and wall temperature fluctuations.

Keywords: Thermosyphon; Heat transfer; Geyser boiling; Pressure and temperature fluctuations; Net-zero buildings.

[388] –TS2_3

Performance of a small diameter two-phase closed thermosyphon in geyser boiling condition

Nelson Yurako Londoño Pabón[1*], Gabriel Serafin Couto Vieira[1], Kênia Warmling Milanez [1] and Marcia Barbosa Henriques Mantelli[1]

[1] *Department of Mechanical Engineering, Federal University of Santa Catarina, Florianopolis 88040-900, Brazil*

Abstract

In the present article, the geyser boiling phenomenon is experimentally investigated in a small diameter two-phase closed thermosyphon. The studied thermosyphon has an inner diameter of 4.8 mm and total length of 918 mm. Three specific filling ratios and four temperatures for the thermal bath used to provide cooling water to the condenser were tested. Power was inputted in steps of 20 W, up to 100 W. Variation of the temperatures on the walls of the evaporator, adiabatic and condenser sections as well as variations on pressure, obtained from a pressure transducer installed on the thermosyphon, indicated the presence of Geyser boiling. The results show that the studied variables affect directly the intensity and periodicity of the geyser boiling phenomenon.

Keywords: Two-phase closed thermosyphons, Small diameter tubes, Geyser boiling phenomenon.

Room B: Session #6: [HP5] – Heat Pipes #5

[340] –HP5_1

Copper-Water and Hybrid Aluminum-Ammonia Heat Pipes for Spacecraft Thermal Control Applications

Mohammed T. Ababneh[1,*], Calin Tarau[1], William G. Anderson[1], Jeffery T. Farmer[2], Robert Hawkins[2], Angel R. Alvarez-Hernandez[3], Stephania Ortega[3] and Jesse W. Fisher[4]
[1]*Advanced Cooling Technologies, Inc., 1046 New Holland Ave., Lancaster, PA, USA 17601,*
**Corresponding author: Mohammed.Ababneh@1-ACT.com , Phone: +1-717-295-6061*
[2] *NASA Marshall Space Flight Center, Huntsville, AL 35808, USA*
[3] *NASA Johnson Space Center, Houston, TX 77058, USA*
[4] *Lockheed Martin Coherent Technologies, Louisville, CO 80027, USA*

Abstract
Copper-water heat pipes are commonly used for thermal management of electronics systems on earth and aircraft, but have not been used in spacecraft thermal control applications to date, due to the satellite industry's requirement that any device or system be successfully tested in a microgravity environment prior to adoption. Recently, Advanced Cooling Technologies Inc., (ACT), NASA Marshall Space Flight Center, and the International Space Station office at NASA's Johnson Space Center demonstrated flight heritage in Low-Earth Orbit. The testing was conducted aboard the International Space Station (ISS) under the Advanced Passive Thermal eXperiment (APTx) project. The heat pipes were embedded in a high conductivity (HiK™) aluminum base plate and subject to a variety of thermal tests over a temperature range of -10 to 38 ºC for a ten-day period. Results showed excellent agreement with both predictions and ground tests. In addition, novel hybrid wick aluminum-ammonia heat pipes are developed to handle heat flux requirements for spacecraft thermal control applications. The 5-10 W/cm^2 heat density limitation of aluminum-ammonia grooved heat pipes has been a fundamental limitation in the current design for space applications. The recently demonstrated 50 W/cm^2 capability of the hybrid high heat flux heat pipes provides a realistic means of managing the high heat density anticipated for the next generation space designs.

Keywords: Copper-water heat pipes; Spacecraft thermal control; International Space Station (ISS); Advanced Passive Thermal experiment (APTx); Aluminum-ammonia heat pipes; Hybrid high heat flux heat pipes.

[330] –HP5_2

Application of sodium/GH4099 heat pipes for nose cap cooling

Longfei Hu[1], Jiatong Shi[1], Hantao Han[1], Qin Lu[1], Siyuan Chen[1], and Bangcheng Ai[1]
[1]*China Academy of Aerospace Aerodynamics, Beijing, 100074, China*

Abstract
In this study, sodium/GH4099 heat pipes are proposed for nose cap cooling. X-51 nose cap-like sodium/GH4099 heat pipe spreaders were designed and prepared in China Academy of Aerospace Aerodynamics. And their startup properties were tested at a 500 kW quartz lamp calorifier. It was found that the sodium/GH4099 heat pipes startup successfully at heat flow of about 75 kW/m^2, displaying a uniform temperature of 748-806^{o}C. On the other hand, startup failures were also found. Working fluid of sodium leak from the GH4099 shell, resulting in a temperature distribution of 684-946^{o}C. Under the application of heat pipe cooling, the operating temperature decreased from 946^{o}C to 806^{o}C, reducing the thermal gradient and stress effectively. A further simulation indicated that these nose cap-like heat pipes can also

startup successfully at aerodynamics conditions of Ma5, Ma6 and Ma7. Thus, it is concluded that sodium/GH4099 heat pipes have potential applications on nose cap cooling.

Keywords: Sodium; GH4099; Heat pipe spreader; Nose cap; Startup.

[378] – HP5_3

Study of transport phenomena in the evaporator of two phase capillary devices using thin film evaporation model

Shahnawaz Ahmed and Manmohan Pandey*
Department *of Mechanical Engineering, Indian Institute of Technology Guwahati, India*

Abstract
Thin film evaporation model has been used by several researchers to study the transport phenomena of two-phase capillary devices, such as heat pipes and capillary pumped loops. The present work is focused on mathematical modeling of the evaporation phenomena in such devices. Liquid-vapour interface in the evaporator is modelled using a thin film model and the lubrication approximation, along with a slip boundary condition at the wall and a shear boundary condition at the interface. Different models are used for the evaporating mass flux and the vapour pressure gradient at the liquid-vapour interface is considered. An attempt is also made to determine the non-evaporating film thickness that satisfies the underlying physics. The film thickness profile and the pressure components are obtained by numerical simulations. It is found that the choice of the evaporating mass flux model has a significant effect on the results, and is very important for heat transfer characterization.

Keywords: Wayner model; Lubrication approximation; Disjoining pressure; Capillary pressure.

Room A: Session #7: [LHP3] – Loop Heat Pipes/Capillary Pumped Loops #3

[106] –LHP3_1

Supercritical startup strategy of cryogenic loop heat pipe and lessons learned

Yuandong Guo[1,2,3,*], Guiping Lin[3], Haoran Pan[3], Jianyin Miao[3], Jiang He[3], Hongxing Zhang[3]

[1] *Laboratory of Fundamental Science on Ergonomics and Environmental Control, School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, PR China*
[2] *Shenyuan Honors School, Beihang University, Beijing 100191, PR China*
[3] *Beijing Key Laboratory of Space Thermal Control Technology6, Beijing Institute of Spacecraft System Engineering, China Academy of Space Technology, Beijing 100094, PR China*

Abstract
Next generation space infrared sensor and detector have pressing requirement for cryogenic heat transport technology in the temperature range of 30-40K. As a highly efficient cryogenic thermal control device for space application, cryogenic loop heat pipes (CLHP) has wide and effective application in infrared detection system. This paper discussed the design procedure of CLHP and produced a CLHP prototype in accordance with design principles. Both common and special operating characteristics in its supercritical startup process were investigated using nitrogen, neon and hydrogen as working fluid, with which the CLHP system could operate at 20-120K. The effect of heat sink controlling measure and auxiliary heat load was studied. The automatic cooling characteristics of primary evaporator was found in H2-CLHP, which did not appear in other two experiments.

Keywords: Cryogenic loop heat pipe; Design Factors; Supercritical startup; Experiment; Auxiliary heat load

[153] –LHP3_2

Performance prediction of a loop heat pipe considering evaporation from the meniscus at the three-phase contact line

Yuya Yamada[1*], Masahito Nishikawara[1], Hideki Yanada[1] and Yosuke Ueda[1]
[1]*Department of Mechanical Engineering, Toyohashi Univ. of Tech., 1-1, Hibarigaoka, Tempaku-cho, Toyohashi, Aichi 441-8580, Japan*

Abstract
This study experimentally and numerically investigates the effect of the meniscus on the heat transfer of a loop heat pipe (LHP) evaporator for performance prediction. The meniscus on the three-phase contact line (TPCL) within the case, wick, and grooves is observed by a visualization experiment using a glass tube evaporator and a microscope. Acetone is used as working fluid. Evaporator heat-transfer coefficient decreases as heat flux increases in low heat flux. Thereafter, it rapidly increases until a certain middle heat flux and reach the maximum, then decreases again. This trend is due to the change of the meniscus size and the transition of the phase state on the contact surface between the case and wick. In the analysis, a one-dimensional heat transfer model of the meniscus is proposed based on thin liquid-film evaporation theory. The amount of evaporation from the meniscus calculated by the one-dimensional model is integrated with the macroscopic numerical model of the evaporator. Considering the meniscus, the amount of evaporation increases, and, therefore, the evaporator heat-transfer coefficient increases. The amount of evaporation increases as the wetting width increases. The wetting width is affected by the surface tension of the working fluid. Therefore, it can be explained that the surface tension is important not only for enhancing the maximum heat transport (i.e., the capillary limit), but also for enhancing the heat-transfer coefficient. The predicted evaporator heat-transfer coefficient agrees well with the measured one. This prediction method would improve the analysis accuracy of the evaporator which is governed by heat transfer at the TPCL and would advance wick shape design.

Keywords: Capillary evaporator; Loop heat pipe; Meniscus; Thin liquid-film evaporation; Three-phase contact line.

[236] –LHP3_3

Numerical Investigation on Thermo-Hydraulic Phenomena in Loop Heat Pipes during Temperature Oscillation

Takuya Adachi[1*], Koji Fujita[2] and Hiroki Nagai[2]
[1]*Department of Aerospace Engineering, Tohoku University, Sendai 980-8577, Japan*
[2]*Institute of Fluid Science, Tohoku University, Sendai 980-8577, Japan*

Abstract
Loop heat pipes (LHPs) are the heat transport devices, which utilize the latent heat of a fluid. Since the LHPs can control temperature precisely, the LHPs are used to control temperature of the equipment in spacecraft. However, when a heat load or a sink temperature is changed, the LHP temperature sometimes oscillates. Temperature oscillation disturbs the precise temperature control of the LHP. Although some researchers have experimentally investigated the cause of temperature oscillation, the cause is not clearly understood because it is difficult for the experiments to examine the LHP internal flow. In this study, the transient mathematical model was developed to understand the thermo-hydraulic phenomena and the cause of temperature oscillation. The mathematical model can calculate a vapor quality of each node in the transport lines and condenser. As a result, it is found that when the temperature oscillation starts, a two-phase flow is generated in the liquid line. This result can support the knowledge deduced from previous experiments. In addition, when the LHP temperature oscillates, the liquid line temperature oscillates with the largest amplitude. This largest oscillation in the liquid line is caused by the change of the condensation length. The large temperature oscillation in the liquid line leads to the reservoir temperature oscillation, and the whole LHP temperature oscillates. The change of the condensation length is related to the temperature amplitude. When the condensation length can be short, the amplitude becomes large.

Keywords: Loop heat pipe; Temperature oscillation; Transient model; Internal flow.

[261] –LHP3_4

Transient and steady-state characteristics of a loop heat pipe having a flat evaporator with methanol as a working fluid

Joon Hong Boo[1*], Jang Hyun Bae[2] Young Tak Cho[2], Kyung Taek Im[2], Dong Hoon Oh[3], Jiwon Yeo[3]
[1]*School of Aerospace and Mechanical Engineering, Korea Aerospace University, Goyang 10540, Korea*
[2]*Graduate School, Korea Aerospace University, Goyang 10540, Korea*
[3]*Advanced System Team, Hanon Systems Inc., Daejeon 34325, Korea*

Abstract
A loop heat pipe (LHP) having a flat evaporator was investigated experimentally, with methanol as working fluid, for steady as well as transient characteristics. The wall and the transport lines were made of stainless steel. The evaporator surface was 40 X 40 mm, and the distance between the evaporator and the condenser was 0.6 m. Sintered nickel powder wick was used which had pore diameter and porosity of 2.7 micron and 55 %, respectively. The maximum heat load was 360 W for an adverse height of 0.37 m. The working fluid charge and the heat sink temperature were considered as influencing factors on the transient performance. The evaporator wall temperature, vapor temperature, and thermal resistance of the LHP were investigated against variations in heat load and tilt angle. Analysis of the transient characteristics includes observation and discussions during cold as well as hot startup periods.

Keywords: Loop heat pipe; Flat evaporator; Methanol; Transient; Steady state; Experimental; Thermal resistance.

[295] –LHP3_5

Effect of Vibrations on Thermal Performance of mLHP for Avionics Cooling: An Experimental Analysis

Prem Kumar[1], Sameer Khandekar[1*] and Yuri F Maydanik[2]
[1]*Department of Mechanical Engineering, Indian Institute of Technology, Kanpur, India.*
[2]*Institute of Thermal Physics, Ural Branch of the Russian Academy of Science, Pervomaiskaya St. 91 Ekaterinburg 620219, Russia*

Abstract
Loop Heat Pipe (LHP) is an efficient passive, two-phase heat transfer device which can transport heat up to large distances (over ~ 5 m) even in anti-gravity mode. It is necessary to miniaturize the LHPs to make them suitable for space-constrained terrestrial/avionics applications. However, before incorporating these devices under high-vibrational environmental conditions such as those encountered in avionics applications, it is imperative to study their thermal performance under such loads. A contextual experimental study has been reported here using an ammonia charged mLHP (evaporator and transport line diameter as 8 mm and 2 mm) in horizontal orientation for two cases: (a) without vibration and (b) with vibrations (sinusoidal waveform, accelerations 1 g to 4 g, frequencies 15 Hz to 45 Hz, amplitudes 0.25 - 2.0 mm). A successful start-up of mLHP is observed at ~ 5 W of heat load for both the cases. The heat transfer capacity is found to be 120 W for evaporator temperature of 70ºC (safety limit). A set of experiments are performed to study the effect of acceleration rate and frequency of imposed vibration on thermal performance of mLHP. Results show that acceleration rate and frequency of imposed vibrations in the above parameters does not affect the thermal performance of mLHP.

Keywords: Heat transfer; mLHP; Vibration; Thermal performance.

[374] –LHP3_6

Design and Experimental Investigation of a Thin Loop Heat Pipe

Shuto TOMITA[1*], Ai UENO[1], Hosei NAGANO[1], Takeshi SHIOGA[2] and Tsukasa ITANI[2]
[1] Department of Mechanical System Engineering, Nagoya University, Furo, Chikusa, Nagoya, Aichi 464-8603, Japan
[2] Fujitsu Laboratories Ltd. 10-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0197, Japan

Abstract
In this paper, a thin loop heat pipe with a flat evaporator is proposed for small electronic devices. The thin LHP (TLHP) based on the proposed evaporator structure was designed, fabricated and tested so that the amount of heat by CPU and shape requirements of small electronic devices are met. The designed TLHP has a one-way transport length of 200 mm, an evaporator size of 26mm × 24 mm with a

thickness of 1.0 mm, and a heat transport capability above 10 W. Two types of glass wick were selected and applied to the TLHP. The test results showed the TLHP can be transferred up to 14 W. The results of the experimental data were compared with the computational results from the numerical model.

Keywords: Capillary force; CPU cooling; Flat evaporator; Heat transfer; Loop heat pipe.

Room B: Session #7: [HP6] –Heat Pipes

[259] –HP6_1

Ethane Constant Conductance Heat Pipe Qualification according to ECSS for Two-Phase Heat Transport Equipment

Francisco Javier Martín-Portugués*, Juan Martinez and Alejandro Torres
IberEspacio, Avda de los Premios Nobel, 53; Torrejón de Ardoz, Spain

Abstract
Temperature control at cryogenic level is often required by Earth observation, scientific and weather satellites. Often, instruments embarked on these satellites need to operate at temperatures below the operation temperature range of ammonia heat pipes. One of the cases where this need has been manifested is the FPA cooling system of Sentinel 4 / UVN Instrument, developed for ESA by Airbus Defence & Space and OHB System AG, where ethane working fluid has been selected and in which this campaign has been executed. The ability to operate at temperatures as low as -130 ºC, together with the possibility to act as a thermal switch at temperatures above the fluid critical temperature, are clear interesting facts that identify ethane as a very interesting cooling solution for systems operating in this temperature range. This paper presents the qualification campaign carried out according to the ECSS-E-ST-31-02C standard requirements for Two-Phase Heat Transport Equipment. The temperature range studied covers from -130 ºC to +50 ºC. Among others, the campaign comprises a full thermal characterization, thermal environmental, fluid compatibility and life test, pressure and ethane leakage tests.

Keywords: Heat Pipe, Cryogenic, Ethane, Two-Phase, ECSS, Qualification.

[347] –HP6_2

Titanium Water Heat Pipe Radiators for Space Fission System Thermal Management

Kuan-Lin Lee[1], Calin Tarau[2] and William G. Anderson[1*]
[1]*Advanced Cooling Technologies, Inc., Lancaster, PA 17601, United State*

Abstract
For future space transportation and surface power applications, NASA Glenn Research Center (GRC) is currently investigating a small fission system (Kilopower system), which has operable range of 1 to 10kW$_e$. The Kilopower system uses alkali metal heat pipes to transport heat from a nuclear reactor to the Stirling convertors to produce electricity and titanium water heat pipes to remove the waste heat from the convertors to the radiators. In a Small Business Innovation Research (SBIR) program, Advanced Cooling Technologies, Inc. (ACT) developed the titanium/water heat pipes for Kilopower waste heat rejection. These heat pipes are featured with bi-porous screen in the evaporator, and a screen-groove hybrid wick for the rest of the pipe, that allow the Kilopower system to survive and function under following four conditions: (1) space operation with zero gravity (2) ground testing with slight adverse gravity orientation (3) surface operation with gravity-aided orientation (4) and launch, with the against-gravity orientation and below freezing temperature. This paper presents the development of the titanium water heat pipes with radiator for Kilopower waste heat rejection, including the hardware design, heat pipe radiator assembly and thermal performance experimental validation.

Keywords: Bi-porous screen; Screen-groove hybrid wick; Titanium water heat pipe; Kilopower system.

[371] –HP6_3

Application of Li/TZM heat pipe for hypersonic vehicles

Qin Lu[1], Longfei Hu[1*], Haitao Han[1] , Siyuan Chen[1], Bangcheng Ai[1], Weiqu[1]
[1]*China Academy of Aerospace Aerodynamics, Beijing, Yungang West Road 100074, China*

Abstract
Thermal protection system (TPS) which are correlated to the safety of hypersonic vehicles, will encounter severe challenges when exposed to the extreme heating during long-time hypersonic flight in the atmosphere. Stagnation regions, such as wing and tailing leading edges and nose caps, are critical design areas of hypersonic vehicles due to heat flux distribution varying sharply from leading edge to the big acreage. Refractory metal - TZM (Titanium-Zirconium-Molybdenum Alloy) hightemperature heat pipe is being considered for hypersonic vehicles due to its good high temperature performance. In this paper a kind of Thumbnail-Zirconium-Molybdenum Alloy heat pipe with a lithium working fluid has been put forward. Fabrication and testing of TZM heat pipe has been perform in high-frequency induction heater of furnace. The temperature of heat pipes reached to about 1300K radiation heating in the air chamber. Analysis on heat transfer of high temperature heat pipes are studied, and the results indicated TZM heat pipe can transport heat quickly.

Keywords: hypersonic vehicles; TZM; High temperature; Design of heat pipes.

[12] –HP6_4

Parametric study on the permeability of micro-pillar wick with dual-height configuration

Daehun Lee[1] and Chan Byon[1*]
[1]*School of Mechanical Engineering and Nuclear engineering Ulsan National Institute of Science and Technology (UNIST), Ulsan 44919, Republic of Korea*

Abstract
In this study, a parametric study on the permeability of micro-pillar-wick with dual-height configuration, is performed. The effect of the primary and secondary pillar height on the nondimensional permeability is investigated. This work shows that the permeability of the micro-pillar wick can be significantly improved by applying the dual-height configuration. The permeability of the dual-height micro pillar array can be optimally designed by tailoring the geometric parameters. In this study, a mathematical-correlation for predicting the permeability is proposed as a design guideline of the micro-pillar wick.

Keywords: Micro-pillar wick, Dual-height-configuration, Permeability, Meniscus.

[264] –HP6_5

Performance evaluation of an additively manufactured freeform wick for heat pipe applications

Davoud Jafari[1], Wessel W. Wits[1*], Bernard J. Geurts[2,3]
[1]*Faculty of Engineering Technology, Department of Design, Production and Management, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands*
[2]*Faculty of Electrical Engineering, Mathematics and Computer Science, Multiscale Modeling and Simulation, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands*
[3]*Center for Computational Energy Research, Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands*

Abstract
Evaporation rates of working fluid from porous structures are of great importance to heat pipe applications. This study presents the evaluation of the evaporation/boiling process of water from a stainless steel 316L wick structure fabricated through 3D-printing technology. The fabrication process that is employed to provide the test sample, yields relatively high repeatability within the wick structure. An experimental facility was developed to observe the characteristic processes of flat heat pipe operating conditions. The internal volume of the test cell is 40 × 20 × 6 mm[3]. A uniform heat

flux was applied to the base plate near one end, while the other end was cooled by means of a cooling water jacket. The thermal performance of the 3D-printed wick, filled with water as working fluid, is tested for different heat inputs 0.75–82.5 kW/m2. Evaporation thermal resistances were determined for different heat loads and filing ratios. Additionally, the wick surface was visualized during evaporation and boiling, which allows for correlating the thermal performance with the observed regime. It is found that nucleate boiling from the wick substrate leads to a substantially increased thermal performance compared to evaporation from the liquid-free surface at the top of the wick. The 3D-printed wick features a minimum evaporator resistance of 0.086 K/W. Experimental results are combined into an evaporation/boiling curve specifically for 3D-printed wicks. The transition between the evaporation and boiling regimes is found to be dependent on the heat flux and filling ratio, and is reasonably well predicted by the bubble-nucleation criterion available in the literature. Altogether, the experimental results verify that 3D printing is a promising technology to fabricate freeform porous structures for heat pipe applications. Compared to flat heat pipes with a screen mesh, grooved wick or composite wick, a 3D-printed wick yields a higher thermal performance.

Keywords: Porous structure; Evaporation; Boiling; Visualization; Additive manufacturing; 3D printing.

[419] – HP6_6

An experimental investigation into thermal performance of multi-wick structure vapour chamber heat spreader

Jason Velardo[1*], Randeep Singh[2], Masataka Mochizuki[3], Phan Thanh Long[3], Makoto Takahashi[3], Abhijit Date[1] and Aliakbar Akbarzadeh[1]

[1] *School of Engineering, RMIT University, Bundoora, Victoria, 3083, Australia*
[2] *Fujikura Automotive Europe GmbH, Albin-Koebis Strasse 6, D-51147 Koeln, Germany*
[3] *Fujikura Ltd., 1-5-1, Kiba, Koto-Ku, Tokyo 135-8512, Japan*

Abstract
The thermal demands of high heat flux systems have generally been a challenging task for thermal designers. The vapour chamber has been introduced to assist in heat removal from high heat flux devices such as electronic devices. They operate on the principles of two phase heat transfer. This paper presents an experimental study into heat spreaders. A vapour chamber with multiple wick structures and a copper plate were explored in this work. Both were of the same exterior dimensions. The vapour chamber had both sintered powder wick and wire mesh wick in the evaporator and a wire mesh wick in the condenser section. An exploration of the temperature drops and distributions within the vapour chamber and copper heat spreaders was carried out. These were broken up into axial and lateral aspects of performance. It was found that the vapour chamber far outperformed the copper spreader in regards to lateral performance. It was also found that the copper spreader performed slightly better than the vapour chamber in regards to axial performance. A discussion of these aspects has been provided. Overall, the performance of the vapour chamber exceeded that of the copper spreader for all heat inputs; with approximately 4^{o}C lower heat source temperatures within the tested range of heat inputs.

Keywords: Thermal management; Vapour chamber; Heat spreader; Hybrid wick; Spreading resistance.

Room A: Session #8: [PHP3] – Pulsating Heat Pipes #3

[63] –PHP3_1

Heat transfer performance of the open-loop micro pulsating heat pipe with Self-rewetting Fluids

Misaki Sasa[1], Koji Fumoto[2*], Takahiro Okabe[1], Raffaele SAVINO[3], Takao Inamura[1], Minori Shirota[1]

[1]*Department of Intelligent and Machines, Hirosaki University, 3 Bunkyo-cho, Hirosaki 036-8561, Japan*

[2]*Department of Mechanical Engineering, Aoyama Gakuin University, 5-10-1 Fuchinobe, Chuo-ku Sagamihara 252-5258, Japan*

[3]*Department of Industrial Engineering, University of Naples Federico II, Naples, Italy*

Abstract

We experimentally investigate the heat transfer characteristic of a micro pulsating heat pipe (MPHP). The MPHP consists of 20 parallel channels made of copper tubes with an internal diameter of 0.8 mm. Water, ethanol, and the aqueous solution

1-butanol are used as the working fluids. This aqueous solution is known as a self-rewetting fluid. A self-rewetting fluid is a dilute aqueous solution of alcohols with more than four carbon atoms (such as butanol and pentanol). Self-rewetting fluids have the special property of surface tension. The surface tension of self-rewetting fluids decreases gradually with an increase in temperature, reaching a minimum at approximately 60 ℃, and subsequently increases gradually at higher temperatures. Therefore, the self-rewetting fluid flows to the higher temperature area because of the Marangoni effect. This flow should improve the boiling phenomenon. The boiling phenomenon is an important factor in the heat transfer mechanism of a PHP. Hence, using a self-rewetting fluid as a working fluid is expected to improve the heat transfer performance of an MPHP. The experimental results indicate that a stable oscillating motion of working fluid is generated in a PHP with the self-rewetting fluid in a heat load regime lower than that of water. In addition, the effective thermal conductivity of a PHP with a high concentration self-rewetting fluid is higher than that of other fluids in the high heat-load regime. Moreover, the heat transfer enhancement of an MPHP with a self-rewetting fluid is highly significant at a low fill-ratio condition.

Keywords: Heat transfer performance evaluation; Pulsating heat pipe; Self-rewetting fluid; Marangoni effect.

[289] –PHP3_2

Experimental Study of Start-up in a Closed Loop Pulsating Heat Pipe with Alternating Superhydrophobic Channels

Luis Betancur[1*], Daniele Mangini[2], Arthur Facin[1], Marcia Mantelli[1], Kleber Paiva[1], Bruna Coutinho[1] and Marco Marengo[2]
[1]*Department of Mechanical Engineering, Federal University of Santa Catarina, Florianopolis 88040-900, Brazil*
[2]*School of Computing, Engineering and Mathematics, University of Brighton, Brighton, United Kingdom*

Abstract
A Pulsating Heat Pipe has been designed with alternating hydrophilic/superhydrophobic channels and tested at different heat power inputs. The device consists in a copper tube (internal/external diameters of 3.18/4.76 mm), bent into a planar serpentine of ten channels and five U-turns in the heated zone. The tube is partially functionalized with a superhydrophobic coating, in such a way to create an alternation of hydrophilic and superhydrophobic tubes along the loop. The aim is to investigate how the wettability affects the start-up, the fluid motion along tubes with different wettabilities and the overall performance of the device. Then, the overall behavior is compared to another PHP, having the same geometry and under the same working conditions, but completely hydrophilic. The PHP is evacuated and then filled with distilled water, with a filling ratio of 50%. The heating section is equipped with two heating elements that supply up to 350W. A cold plate, directly connected to a thermal bath, keeps the condenser at a constant temperature of 20°C. 16 T-type thermocouples are located on the external tube wall at the evaporator and at the condenser zones, while the fluid pressure is measured at the cooled region by a pressure transducer directly mounted in contact with the flow. Input power has been increased from 20W up to 350W in 10 steps, and then decreased following the same heating steps. Temperature evolution recorded both at the condenser and at the evaporator zones allows to obtain the overall PHP thermal performance for all the tests performed. It is found that the alternating wettability of tube sections strongly affects the flow motion, the start-up and the overall performance. Comparing the results obtained with such a functionalized pulsating heat pipe to a completely hydrophilic pulsating heat pipe, the thermal resistance of the functionalized pulsating heat pipe is all the times higher than the hydrophilic one. Moreover, the start-up is achieved for higher heating power levels for the functionalized pulsating heat pipe. Local temperature measurements at the hydrophilic sections are lower than the temperature recorded on the superhydrophobic tubes. In addition, temperature fluctuations are more noticeable at the hydrophilic inserts, synonym of a pulsating flow able to dissipate heat in those regions. On the contrary, the temperature measurements at superhydrophobic surfaces exhibit a flat trend, as if the flow is blocked within the functionalized inserts. The superhydrophobic coating, hindering the liquid film formation, decreases locally the flow motion. Enhancing the inner wettability, the flow motion is improved, since the liquid film can cover the inner surface, acting as a sort of lubricant that facilitates the liquid plugs and vapor bubbles passage. These experiments point out the importance of the wettability wall for pulsating heat pipes.

Keywords: Closed Loop Pulsating Heat Pipes; Alternating Channels; Wettability; Hydrophobicity.

[407] –PHP3_3

Evaluation of the effect of flow oscillations on the heat transfer coefficient and the liquid film instabilities, for isolated vapour slugs within mini-channels, utilising advanced VOF simulations

Manolia Andredaki[1], Anastasios Georgoulas[1*], Nicolas Miche[1] and Marco Marengo[1]

[1]*Advanced Engineering Centre, School of Computing Engineering and Mathematics, University of Brighton, Lewes Road, Brighton BN2 4GJ, East Sussex, UK.*

Abstract

In the present investigation, an enhanced Volume Of Fluid (VOF) based numerical simulation framework that accounts for conjugate heat transfer between a solid region and a two-phase flow region with phase-change due to evaporation and/or condensation, is applied for the conduction of parametric numerical simulations, aiming to investigate the effect of oscillation frequency and amplitude in the heat transfer coefficient and the liquid film instabilities, for isolated vapour slugs within a mini-channel. For this purpose, different series of parametric numerical experiments were performed, investigating the effect of oscillation amplitude and frequency on the heat transfer coefficient within the considered mini-channel, for moderate applied heat fluxes and for two different working fluids (FC-72 and Ethanol). It is shown that the local heat transfer coefficient is directly affected by both the oscillation amplitude and frequency. Furthermore, the generation of capillary ridges at the liquid film surrounding the considered vapour slugs is identified and quantified. It is shown that the generation frequency as well as the height of the proposed ridges are directly related to the corresponding frequency and amplitude of the pressure oscillations at the inlet of the considered mini-channel.

Keywords: Volume of Fluid, Conjugate Heat Transfer, oscillating slug flow, mini-channel.

[384] –PHP3_4

Experimental Investigation of a Pulsating Heat Pipe Fabricated by a 3-D Printer

Fumihiko Hideyama[1], Masahiro Kawaji[2], Yasushi Koito[1] and Toshio Tomimura[1]

[1] *Department of Advanced Mechanical Systems, Kumamoto University, 2-39-1 Kurokami, Chuo-ku, Kumamoto 860-8555 Japan*

[2] *Mechanical Engineering Department, The City College of New York, 160 Convent Avenue, New York, New York 10031 USA*

Abstract

A pulsating heat pipe (PHP) is a passive two-phase heat transport device and has a serpentine channel between an evaporator and a condenser section. An appropriate amount of a working fluid is enclosed, and liquid slugs and vapor plugs form and move in a serpentine channel. In the present study, the PHP was fabricated by a 3-D printer. Fourteen parallel channels having the cross section of 1.3 mm × 1.3 mm and the length of 150 mm were connected to form a single serpentine channel. The evaporator and the condenser section were both 25 mm in length. For fluid-flow visualization, a transparent ABS (Acrylonitrile Butadiene Styrene) filament was employed as a 3-D printing material. HFE-7000 was used as a working fluid and its filling ratio was 50 % of a total volume of the serpentine channel. In experiments, the evaporator section of the PHP was heated by a heater and the condenser section was water-cooled using a cooling jacket. The heat input was changed from 4 W to 7 W while the cooling water temperature and its flow rate were kept at 4.0 ºC and 200 mL/min, respectively. Transient temperature distributions of the PHP were measured by K-type thermocouples and pulsating two-phase fluid-flow phenomena in the serpentine channel were captured by a high-speed video camera. From the experimental results, the pulsating phenomena of liquid slugs and vapor plugs in the serpentine channel and the heat transfer characteristics of the PHP were clarified. Furthermore, the thermal resistance of the present PHP was compared with that of the previous 3-D printed PHP.

Keywords: Pulsating heat pipe; 3-D printing; Visualization; Two-phase heat transport.

[364] –PHP3_5

Pulsating heat pipe simulations: impact of PHP orientation

Iaroslav Nekrashevych, Vadim S. Nikolayev_

Service de Physique de l'Etat Condens_e, CEA, CNRS, Universit_e Paris-Saclay, CEA Saclay, 91191 Gif-sur-Yvette Cedex, France

Abstract
In this communication, we discuss simulation results of a 10-turn copper-water pulsating heat pipe (PHP) at di_erent orientation with respect to the gravity. The phase distribution of the phases inside the PHP, in particular, the liquid _lm distribution, is inuenced by gravity. This a_ects the overall PHP performance. We show that, independently of the PHP orientation, the contribution of the latent heat transfer is large with respect to the sensible heat transfer. We discuss the PHP startup, two stable regimes observed in the simulation (intermittent regime and chaotic oscillations) and the transition between them.

Keywords: Pulsating heat pipe, Oscillation, Liquid _lms, Phase change, Simulation.

[302] –PHP3_6

The phenomenon of unidirectional circulating flow in an oscillating heat pipe

Chunrong Yu[1], Yulong Ji[1*], Lilin Chu[1], Zongyu Wang[1], Zhenting Wu[1], Hongbin Ma[2]
[1]*Marine Engineering College, Dalian Maritime University, Dalian, Liaoning, 116026, China*
[2] *Department of Mechanical & Aerospace Engineering, University of Missouri, Columbia, MO 65211, USA*

Abstract
The phenomena of two different types of unidirectional circulating flow pattern in a copper oscillating heat pipe (OHP) were firstly discovered and investigated. The OHP has six turns and three sections: evaporator, condenser and adiabatic sections with lengths of 40 mm, 64 mm, and 51 mm, respectively. R152a was used as the working fluid, the effects of the tilt angle from 0 ° to 90 ° and the heat input on the flow and heat transfer of the working fluid in OHP was studied. The experimental results showed that (1) the OHP charged with R152a can form a unidirectional circulating flow at any tilt angle under certain heat input, and the unidirectional circulating flow become steady as the heat input increases; (2) another type of circulating flow was found in the same OHP as the heat input increased to a relative high level, the difference between the two types of circulating flow is that the liquid slugs move forward with or without back forward oscillating movement; (3) the unidirectional circulating flow of the working fluid in the OHP significantly enhance the heat transfer of OHP.

Keywords: Oscillating heat pipe; Unidirectional circulating flow; Heat transfer enhancement; Oscillating movement.

Room B: Session #8: [TS3] – Thermosyphons #3

[44] –TS3_1

Experimental Investigation on a Loop Thermosyphon with Dual Evaporators of Different Heating Distributions and Filling Ratios

Hainan Zhang[1], Shuangquan Shao[1] and Changqing Tian[1,2*]
[1] *Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China*
[2]*University of Chinese Academy of Sciences, Beijing 100049, China*

Abstract
Loop thermosyphon with multiple evaporators can transfer heat from several heat sources to a single cold source with no energy consumption, therefore it is ideal device in multi-source heat transfer. Existing studies mainly focus on its heat transfer and flow distribution at the steady state while the transient performance is lack of investigation. In this paper, the effects of heating power distribution and filling ratio on the startup process and operation fluctuation of a loop thermosyphon with dual evaporators are investigated experimentally. The results the transition time and thermal resistance both decrease and then increase with the increase of filling ratio and the optimal filling ratio is 69%. Under equal total heating power, the transition time is shorter when the heating distribution is more uneven. The thermal resistance of one evaporator is smaller when the heating power on itself is higher, no matter what the heating power of other evaporator is. Heating on one evaporator with the same heating power with the other brings a longer transition time of the loop and a larger thermal resistance of the other evaporator, compared with the condition when only the other evaporator has heating power input. The operation fluctuation is more significant when the heating power and

filling ratio are higher, which is due to the conflict between the outlet flow of the two evaporators. This paper will help the understanding of the transient performance of loop thermosyphon with multiple evaporators.

Keywords: Multi-source heat transfer; Loop thermosyphon; Dual evaporators; Startup; Fluctuation.

[258] –TS3_2

Theoretical and experimental analyses of the thermal resistance of a loop thermosyphon for passive solar heating of buildings

Pedro Bellani[1*], Fernando Milanez[2], Marcia Mantelli[1], Sauro Filippeschi[3], Mauro Mameli[3], Fabio Fantozzi[3]

[1]*Department of Mechanical Engineering, Federal University of Santa Catarina, Florianopolis 88040-900, Brazil*

[2]*Department of Energy Engineering, Federal University of Santa Catarina, Ararangua 88900-000, Brazil*

[3]*Department of Energy, Systems, Land and Construction Engineering, University of Pisa, Italy*

Abstract

This study presents experimental and theoretical analyses of the thermal performance of a two-phase copper-R141b loop-thermosyphon, which was developed for solar heating of buildings. A prototype of the so-called wall-thermosyphon was built and tested at the Heat Pipe Laboratory of the Federal University of Santa Catarina (Labtucal-UFSC). During the tests, three parameters were varied: purge method, power input levels and inside wall evaporator roughness. The results show that recent boiling heat transfer coefficient literature correlations is in good agreement with the experimental data for the thermal resistance of the device under study. However, the condensation thermal resistance calculated with the literature correlations do not represent the same trend found in the experiments. The total thermal resistance of the wall-thermosyphon varies between 0.22 and 0.011 °C/W.

Keywords: Two-phase loop-thermosyphon; thermal resistance; Wall-thermosyphon.

[269] –TS3_3

Characterization of boiling regimes in a flat confined two-phase thermosyphon

Antoine Voirand[1*], Marine Narcy[1], Stéphane Lips[1] and Valérie Sartre[1]
[1]*Univ. Lyon, CNRS, INSA-LYON, CETHIL UMR 5008, F-69621, Villeurbanne, France*

Abstract
A transparent flat confined two-phase thermosyphon is experimentally investigated in order to visualize the boiling flow pattern variations when inclining the system and link this information to the thermal performance of the system. The device is constituted of a copper plate on which the heat sink and heat source are located, and of a transparent polycarbonate plate to enable the visualization of the boiling pattern. The inner thickness of the flat two-phase thermosyphon is close to the capillary length of the fluid, and induces confined boiling in the evaporator section, which leads to an enhancement of the heat transfer and a corresponding decrease of the thermal resistance of the system compared to non-confined thermosyphons. Two fluids are tested, water and pentane. The confinement difference between the two fluids enables to assess the influence of confinement on the boiling regime and heat transfer capacity, particularly its dependence on inclination. It appears that the thermal performance of the two-phase thermosyphon is not affected by the inclination angle in the range 10°-170° (90° being the vertical position) by confining the boiling process in only one direction. Less confinement (for pentane) shows a reduction of this unaffected range of inclination angle.

Keywords: Thermosyphon; Confined boiling; Two-phase heat spreader; Boiling regime.

[352] –TS3_4

Study of a loop thermosyphon evaporator for thermal control of aircrafts

Gabriela C. V. Simas[1], Marcia B. H. Mantelli[1] and Juan Pablo Flórez M.[1]

[1]*Heat Pipe Laboratory, Department of Mechanical Engineering, Federal University of Santa Catarina, Florianópolis, Brazil*

Abstract
This work presents experimental studies of a two-phase loop thermosyphon, designed to use the aircrafts fuselage low temperatures at high altitude to promote passive thermal management of electronics components in avionics. The main purpose of this work is to develop the evaporator of a loop thermosyphon composed by one evaporator coupled to two condensers presented in literature. The proposed evaporator comprises ten square stacked copper plates bonded by diffusion. Channels were manufactured in the inner plates so that internal grooves are obtained after the stack is bonded. Studies with concentrated and distributed heat sources over the evaporator external surface are under performance. Parameters such as start-up and operation temperatures will be compared, according to the condition submitted.

Keywords: Loop thermosyphon; Evaporator; Concentrated heat source; Thermal spreading.

[352] –TS3_5

Validation of AC² for calculation of passive residual heat removal with heat pipes

Anne-Kathrin Krüssenberg*, Fabian Weyermann, Arun Ramachandran, Andreas Wielenberg, Andreas Schaffrath
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Boltzmannstr. 14, 85748 Garching near Munich, Germany

Abstract
GRS develops and validates computer codes like AC² mainly in order to simulate all relevant phenomena within a nuclear power plant during normal operation, incidents, accidents and severe accidents. Currently, Small Modular Reactor (SMR) concepts are developed and discussed in almost all countries using nuclear energy worldwide. There are certain SMR concepts under consideration that use heat pipes for passive heat removal. That is one of the reasons GRS decided to improve the models of AC² for becoming able to calculate passive residual heat removal with heat pipes and thermosiphons. Starting with the module ATHLET (Analysis of Thermalhydraulics of Leaks and Transients) the applicability of its existing models has been checked for modeling long thermosiphons and calculating their operational behavior. Identified model gaps and code weaknesses like properties of fluids and materials or heat transfer correlations are being closed to the extent possible. The main model improvements are validated against heat pipes experiments performed by IKE, University of Stuttgart. These improvements will be applied to simulate the passive residual heat removal with heat pipes from spent fuel storage pools and wet storages within the above mentioned cooperation.

Keywords: Calculation of Operation of long Thermosiphons; Operation Behavior of Passive (Safety) Systems.

[450] –TS3_6

A study on the condensation heat transfer performance of condensers with internal fins and plate fins of loop type two-phase thermosyphon

Dong-Hyun Cho[1]*, Jong-Un Park[2]
[1]*Department of Computer aided Mechanical Design Engineering, Daejin University, 1007, Hogukro, Pocheonsi, Gyeinggodo, 11159, Rep. of Korea*
[2]*Pukyong National University, 599-1, Daeyoen3-Dong, Nam-Gu, Busan, 48513, Rep. of Korea*

Abstract
Flexible two-phase thermosyphons are devices that can transfer large amounts of heat flux with the boiling and condensation of the working fluid resulting from small temperature differences. A flexible two-phase thermosyphon consists of the evaporators with metal with foams, an insulation unit, and the condensers with internal fins and plate fins. The working fluid inside the evaporator with metal foam is evaporated by the heating of the evaporator in the lower part of the flexible two-phase thermosyphon and the evaporated steam rises to the condenser with internal fins and plate fins in the upper part to transfer heat in response to the cooling fluid outside the tube. The resultant condensed working fluid flows downward along the inside surface of the tube due to gravity. These processes form a cycle. In the present study, a flexible two-phase thermosyphon heat exchanger which is 480mm wide, 68mm long, and 1,000mm high was used. The heat transfer pipes in the heat exchanger were 15mm in diameter and 1,000mm in length and 98 heat transfer pipes were installed in the heat exchanger. The inside of the condenser was composed of heat transfer pipes installed with high efficiency internal fins to increase the heat transfer surface area of the heating media in the heat transfer pipes and low fin shapes were engraved with rolling to increase the heat transfer surface area for the fluid

inside the cylinder. Using refrigerant R134a as a working fluid for the loop type flexible two-phase thermosyphon heat exchanger to conduct heat transfer performance experiments for changes in the temperature of the cooling air outside the condenser and changes in the mass flow rate. According to the results of the present experiments, as the spaces between internal discontinuous pins decreased, pressure drops increased. Changes in the temperatures at the outlet of the condenser were shown to be a little smaller. Therefore, it can be seen that as the spaces between internal discontinuous pins decreased, the heat transfer performance increased. As the temperature of the air flowing in the condenser the condensers with internal fins and plate fins increased, the condensation heat transfer rate of the thermosyphon heat exchanger increased. As the condenser refrigerant inflow temperature increased, the condensation heat transfer rate of the condensers with internal fins and plate fins of the thermosyphon heat exchanger increased.

Keyword s loop type flexible two-phase thermosyphon, condenser section, internal fins, plate fins, performance of heat transfer.

DAY #5: Thursday, June 14, 2018

Room A: Session #9: [PHP4] – Pulsating Heat Pipes

[363] –PHP4_1

Intensive Evaporation in Thin Liquid Film with Dry Spots and Dynamic Contact Lines

Oleg A. Kabov[1,2*], Dmitry V. Zaitsev[1,2], Egor M. Tkachenko[2]

[1]*Kutateladze Institute of Thermophysics SB RAS, Novosibirsk 630090, Russia*

[2]*Novosibirsk State University, Novosibirsk 630090, Russia*

Abstract

Systematic experimental studies of the flow and destruction of a water film, shear-driven in the channel, under heating from a local heat source with size of 1x1 cm^2 has been performed. The influence of liquid and gas flow rates and the channel height (0.2–2.0 mm) on heat transfer and CHF have been investigated. With the help of high-speed imaging it was found that the maximum intensity of heat removal from the heater is achieved in the mode, when the film flow continuity is broken, and the heater is covered with small (about 100 microns) dry spots with the lifetime about 1/100 – 1/1000 s; at that the number of spots that exist simultaneously on one square centimeter of the surface can reach several hundreds. Experiments have resulted in the values of heat flux and heat transfer coefficient, which are a record for a thin liquid film (1200 W/cm^2 and 350 000 W/m^2K). The values of the critical heat flux are several times higher than CHF for flow boiling in the same channel. 3D nonstationary model of co-current flow of liquid-vapor system has been developed.

Keywords: Heat transfer enhancement; Critical heat flux; Film rupture; Theory and experiment.

[232] –PHP4_2

Experimental study of a flat PHP for the temperature homogenisation of two symmetric plates

Aline Dell'innocenti[1], Stéphane Lips[2], Valérie Sartre[2], Nicolas Blet[2‡], Jérôme Coulloux[1], Jocelyn Bonjour[2]
[1]*Atherm, 1 rue Charles Morel, F-38420, Domène, France*
[2]*Univ Lyon, CNRS, INSA-Lyon, CETHIL UMR5008, F-69621, Villeurbanne, France*

Abstract
A copper-water closed flat Pulsating Heat Pipe (PHP), 3.4 m long and of inner diameter 4 mm, was manufactured and tested. This PHP aims both at homogenising the temperature of a large aluminium plate, of surface area 150 × 420 mm^2, and at lowering its mean temperature by transferring the heat to an adjacent heat sink of same dimensions. The PHP thermal resistance is measured at various heat transfer rates, condenser temperatures and inclination angles. It decreases when the heat transfer rate increases or when the PHP is progressively tilted from the vertical unfavourable orientation to a favourable one. Resistance values as low as 0.04 K/W are measured. Whatever the conditions, a minimum heat input of 300 W is necessary for the correct start-up of the PHP. A map of the operating regimes – no-flow, oscillating,

intermittent and stable behaviour - is proposed. Non-reproducibility effects are highlighted in tilted position, leading to different operating regimes at increasing and decreasing heat loads, but also more broadly depending on the history of the working operating conditions of the PHP. However, the concept proposed in the present work is very promising for applications involving large heat source and heat sink.

Keywords: Pulsating heat pipe; Thermal resistance; Inclination angle; Operating regimes; Start-up; Hysteresis

[160] –PHP4_3

Modelling of a hydrogen based pulsating heat pipe considering Taylor bubble generation

Xiao Sun[1], Dongyang Han[1], Sizhuo Li[1], Zhihua Gan[1,2,3*], Bo Jiao[4] and John Pfotenhauer[5]

[1]*Institute of Refrigeration and Cryogenics, Zhejiang University, Hangzhou 310027, China*

[2]*Key Laboratory of Refrigeration and Cryogenic Technology of Zhejiang Province, Hangzhou 310027, China*
[3]*National Center for Quality Supervision and Test of Refrigerating appliances (Henan), Minquan 476800, China*

[4] *Department of Mechanical Engineering, Harbin University of Science and Technology (Rongcheng Campus), Rongcheng 264316, China*

[5] *Department of Mechanical Engineering, University of Wisconsin Madison, Madison 53706, USA*

Abstract

Cryocoolers can be used to cool MgB_2 superconductor at 20 K temperature region, and pulsating heat pipes (PHP) are regarded as a solution to distribute cooling power for cryocoolers. The experiments on PHPs with hydrogen have been carried out, indicating their efficient performances at 20 K temperature region. There are large differences in physical properties between the fluids at room temperature and the fluids at cryogenic temperature, resulting in their different heat transfer and oscillation characteristics. Up to now, the numerical investigations on the hydrogen PHP have rarely been carried out. In this study, a model of the closed-loop PHP with multiple liquid slugs and vapor bubbles is performed with hydrogen as working fluid. Taylor bubble generation is included in the model. Similarly to the phenomenon observed in room temperature PHP, oscillation and one-way flow are obtained by the model. Separation and combination of liquid slugs are observed as well. The effective thermal conductivity calculated by the model agrees well with experimental results, which indicates the effectiveness of the model.

Keywords: Pulsating heat pipes; Taylor bubble; Cryogenic fluids; Effective thermal conductivity

Room B: Session #9: [SP2] – Special Two-phase Devices #2

[167] –SP2_1

Capillary Jet Loop

Vincent Dupont[1*], Basile Paran[1], Stéphane Van Oost[2] and Cyrille Billet[1]
[1]*Calyos SA, Allée centrale, Zoning de Jumet 52, 6040 Charleroi, Belgium.*
[2]Euro Heat Pipes *SA, Rue de L'Industrie 24, 1400 Nivelles, Belgium.*

Abstract
In this study an innovative two-phase closed loop concept is proposed. This hybrid system is a combination of one or more local capillary loops with a two-phase ring (TPR). The ring provides the liquid to the capillary structure and each evaporator induces a vapor jet thanks to an injector element. The momentum exchange between the high velocity vapor flow and the low velocity single-phase, or two-phase, flow inside the ring insures the transport function. The paper discusses the governing equations of such a system and the experimental performances of a demonstrator able to transfer 470W from a 40 x 40 mm² footprint heater i.e. 29 W/cm².

Keywords: capillary loop, thermal bus, multiple heating sources, electronics cooling, dielectric fluid, jet pump efficiency.

[125] –SP2_2

Optimum and design on separate heat pipe equipment by theory

Qu Wei [1], Tian Ye [2], Deng Junxiang [2] and Xue Zhihu [1]
[1]*China Academy of Aerospace Aerodynamics, Beijing 100074, China*
[2]*Shenyang Institute of Special Equipment Inspection & Research, Shenyang 110035, China*

Abstract
Evaporator is the most important part of one Separate Heat Pipe (SHP). The evaporating heat transfer and two-phase flow in one tube of an evaporator is modeled. After SHP works, the bubbles flow faster than that of the liquid in an evaporator. By the differential method of one evaporator tube, the flow field of the evaporator, density of each cross-section etc. are introduced and derived. By the calculation of the whole SHP, the performance is obtained. For the operating evaporator, the density of the vapor-liquid mixture at the exit is not that of the vapor. The vapor velocity curve of different heat flux is identical, the maximum bubble velocity is 2.68m/s. And the liquid velocity is three orders quantity less than that of the vapor, the liquid flow velocity is very small and can nearly be neglected. The equivalent driving position difference of liquid is acquired. The optimized structure of one evaporator is designed. The vapor tube and the liquid tube are all connected from the top of the evaporator, the returned liquid flow to the bottom of the evaporator more uniformly.

Keywords: Separate heat pipe; Evaporator; Density of vapor-liquid mixture; Bubble velocity; Equivalent driving position difference of liquid.

[173] –SP2_3

Performance tests on 0.4mm-thick novel ultra-thin vapor chambers

Kuo-Chun Hsieh and Shwin-Chung Wong *
[1]*Department of Power Mechanical Engineering, National Tsing Hua University, Hsin-Chu 300, Taiwan, R.O.C.*

Abstract
This work presents the performance test results for 0.4mm- and 0.5mm-thick ultra-thin vapor chambers fabricated using a novel design. This novel vapor chamber (VC) consists simply of a grooved upper plate as the condenser and a mesh-wicked lower plate as the evaporator and liquid path. The inner surface of the upper plate is etched with parallel grooves and inter-groove openings as the vapor path. The groove walls provide strong structural support, an enlarged condensation area, and a direct shortcut for the condensed liquid on the groove surface to return to the evaporator. In contrast to traditional VCs, the novel design has the advantages of simpler structure, easier manufacturing process, lower cost, superior anti-compression ability, and better thermal performance. The novel VC keeps excellent structural integrity with thin walls at a total thickness of 0.4 mm or 0.5 mm and a footprint of 140 mm × 80 mm. When cooled by combined natural convection and thermal radiation, the minimum thermal resistance is less than 0.3 ºC/W at 11 W without reaching the dryout limit. Under water-cooled forced convection, the maximum heat loads of the 0.4 mm and 0.5 mm VCs reach 102 W before the dryout limit. The thermal resistances of both VCs are superior to a 0.5 mm copper sheet. Under the low heat loads with natural convection, the thermal resistances of both VCs are similar. Under the high heat loads with water cooling, the thermal resistances of the 0.4 mm VC appear larger than those of the 0.5 mm VC, because of the higher pressure and temperature drops through the narrower vapor ducts in the thinner VC.

Keywords: Vapor chamber; Heat pipe; Ultra-thin vapor chamber; Ultra-thin heat pipe.

Room A: Session #10: [PHP5] – Pulsating Heat Pipes #5

[358] –PHP5_1

An original look into Pulsating Heat Pipes: Inverse heat conduction approach for assessing the thermal behavior

Luca Cattani[1], Daniele Mangini[2], Fabio Bozzoli[1,3*], Luca Pietrasanta[2], Nicolas Miche'[2], Mauro Mameli[4], Sauro Filippeschi[4], Sara Rainieri[3]. Marco Marengo[2]
1 SITEIA.PARMA Interdepartmental Centre, University of Parma, Parco Area delle Scienze 181/A, Parma, Italy
2 *School of Computing, Engineering and Mathematics, University of Brighton, Lewes Road, BN2 4GJ Brighton, UK*
3 *Department of Engineering and Architecture, University of Parma, Parco Area delle Scienze 181/A, Parma, Italy*
4Department of Energy, Systems Land and Construction Engineering, University of Pisa, Largo L. Lazzarino, Pisa, Italy

Abstract
A promising solution in the field of passive two-phase heat transfer devices is represented by Pulsating Heat Pipes (PHPs). These relatively new devices, which achieves resounding interest in terms of high heat transfer capability, efficient thermal control, flexibility and low cost, have been extensively studied in the last years by many researchers. Several studies have been carried out to deeply characterize the thermal behavior of Pulsating Heat Pipes. Although many authors have investigated the heat flux values for these devices, almost all of them have presented the results only in terms of the mean values at the evaporator and the condenser area. High-speed and high-resolution infrared imaging is performed on a single loop PHP designed with sapphire inserts. Sapphire, being almost transparent in the IR-spectrum, allows to measure the temperature of the fluid inside the pipe by means of IR analysis. The sapphire tube is partially coated with a highly emissive paint, allowing in this way to determine at the same time the external wall temperature and the fluid temperature. In this work a novel approach to investigate the local heat flux in PHPs is presented and tested: the temperature distributions on the external wall of the PHP were used as input data for the inverse heat conduction problem in the wall under a solution approach based on the Tikhonov regularization method. Heat is released from the fluid to the sapphire wall when a two-phase flow is pushed with a high temperature from the evaporator; increasing the wall tube temperature. On the contrary, when a cold flow is pushed back from the condenser, the tube releases the heat previously accumulated; thereby decreasing its temperature. This approach allows to analyze the thermal behavior of the device by investigating the direct interconnection between the thermo-fluid dynamic phenomena within the PHP and the local heat flux measurements. The results proposed in this work could be a breakthrough for developing and validating advanced lumped parameter models and emerging CFD simulations of PHPs.

Keywords: Pulsating Heat Pipe, Infrared Analysis, Inverse heat conduction.

[121] –PHP5_2

Influence of channel geometry on diffusion bonded flat plat pulsating heat pipes

Arthur Facin[1,*], Luis Betancur[1], Marcia Mantelli[1], Juan Pablo Florez[1], Bruna H. Coutinho[1]
[1]*Department of Mechanical Engineering, Federal University of Santa Catarina, Florianopolis 88040-900, Brazil*

Abstract
Pulsating Heat Pipes (PHP) are efficient heat transfer devices, which work due to the oscillating motion of a working fluid that changes phase within narrow channels. The design geometry aspects play a major role in the thermal performance of PHP. The present study shows the influence of two cross section channel geometries (square and circular) on the heat transfer performance of two flat-plate pulsating heat pipes, with identical overall dimensions of 210 mm x 150 mm. Both flat plate pulsating heat pipes are fabricated using the diffusion bonding process, a novel union process that avoids the use of conventional soldering processes. The PHPs tested contain ten parallel channels and hydraulic diameter of 3.18 mm. Distilled water was used as the working fluid. The design of experiment (DOE) technique was applied, aiming the statistical analysis of the following parameters and their combinations: filling ratio, inclination angle and condenser temperature, on the thermal performance of both PHPs. The PHP with square cross section showed to be quite more efficient than the circular one. It is believed that the capillarity effect exerted by the corners of the square geometry channels on the working fluid helped the liquid to be better distributed over the channels, increasing the evaporation processes and improving the system start-up.

Keywords: Flat plate pulsating heat pipes; diffusion bonding; square and circular channel cross sections

[332] –PHP5_3

Thermal and Mechanical Performance Evaluation of small satellite with networked Variable Conductance Oscillating Heat Pipe

Naoko Iwata[1], Yoshiro Miyazaki[2] and Hiroyuki Ogawa[3*]

[1]*Research and Development Directorate, Japan Aerospace Exploration Agency, 2-1-1, Sengen, Tsukuba, 305-8505, Japan*

[2]*Thermal Control Laboratory Inc., 6-13-608 Bunkyo, Fukui 910-0017, Japan*

[3]*Institute of Space and Aeronautical Science, Japan Aerospace Exploration Agency, 3-1-1, Yoshinodai, Sagamihara, 252-5210, Japan*

Abstract

The time and costs for development of satellite can be diminished if no thermal design iteration is necessary and instruments can be mounted without consideration of the thermal design. Such an innovative concept is realized by spreading variable conductance oscillating heat pipes on every structure panel. The temperatures of the panels where components are mounted are maintained are kept constant even if the locations of the instruments or their heat dissipation characteristics change by the function of variable conductance oscillating heat pipes. Our research has been progressed step by step toward application to real spacecraft. In this study, a prototype of a cubic small satellite is manufactured and its thermal and structural performance is tested. The prototype consists of 6 aluminum honeycomb panels with an area of 0.025 m2 or less and two variable conductance oscillating heat pipes. Stainless steel pipes with a diameter of 1 mm or less of the oscillating heat pipes are embedded in the skin on one side of the honeycomb panels. The thermal and structural dummies which simulate the thermal and structural properties mounted on the panels. The vibration test results and thermal balance test results will be reported.

Keywords: Oscillating heat pipe; Variable conductance; Satellite; Thermal performance test.

[253] –PHP5_4

Space structures with embedded Flat Plate Pulsating Heat Pipe built by Additive Manufacturing technology: development, test and performance analysis.

Federico Belfi*[1], Filomena Iorizzo[1], Claudio Galbiati[1], Fabio Lepore[1]

[1]*Argotec s.r.l., Turin, 10155, Italy*

Abstract

In this paper is described the development and the experimental study of a Flat Plate Pulsating Heat Pipe (FPPHP) built by means of metal additive manufacturing. In the recent years, small/medium aerospace companies have gained interest in the development of small satellites. The small dimensions, coupled with the need of high power devices for science and communications, increase the interest in thermally functional structures. The space business is characterized by a very small production lot, and custom designs from project to project. The Additive Manufacturing (AM) exactly fits these needs and, in the past years, the use of this technology in aerospace projects has grown significantly. This paper, after a brief review of the Pulsating Heat Pipe (PHP), focuses on the development and testing of a panel with an embedded closed loop Flat Plate Pulsating Heat Pipe built by means of metal AM technique. The article presents a trade-off analysis between the metal AM technologies available on the market; by means of the trade-off analysis a design strategy is proposed by the authors. A comparison between available FPPHP results in literature and the 3D printed structure will show the differences between the common subtractive technology and the innovative AM technique.

Keywords: Additive manufacturing; Pulsating heat pipe; Flat plate pulsating heat pipe; Direct metal laser melting.

[409] –PHP5_5

Infrared analysis and pressure measurements on a single loop pulsating heat pipe at different gravity levels

D. Mangini[1], M. Pozzoni[2], M. Mameli[3], L. Pietrasanta[1], M. Bernagozzi[1], D. Fioriti[3], N. Miché[1], L. Araneo[4], S. Filippeschi[3], M. Marengo[1].

[1]*School of Computing, Engineering and Mathematics, University of Brighton, Lewes Road, BN2 4GJ Brighton, UK*
[2]*University of Bergamo, Via Galvani, 2, 24044 Dalmine BG, Italy*
[3]*DESTEC, University of Pisa, Largo Lucio Lazzarino 2, 56122 Pisa, Italy*
[4]*Polytechnic of Milan, Via Lambruschini 4A, Milan, Italy*

Abstract

A Single Loop Pulsating Heat Pipe (SLPHP) with an inner diameter of 2 mm is tested in hyper/micro gravity conditions during the 68th ESA Parabolic Flight Campaign. The system is designed with two sapphire tubes that connect the heated and the cooled section, allowing simultaneous fluid flow high-speed visualization, and a direct to fluid IR analysis by using respectively a high-speed camera and a Medium-Wave Infrared Camera (MWIR). Three independent heaters are positioned at the evaporator in order to vary the power distribution and to promote different flow motions with specific heating configurations. Furthermore, two highly accurate pressure transducers measure the pressure drop between the condenser and the evaporator. Additionally, twelve thermocouples mounted on the external tube wall record local temperatures during parabolic flight tests. Such a complete thermo-fluid dynamic analysis at different gravity levels, coupled with the acquisition of high-speed and infrared images in the transparent section of the SLPHP, has the main objective of providing a better understanding on the relationship between the fluid flow motion and the thermal response of the device. Infrared Time-space temperature maps of the flow are correlated with pressure measurements, the external wall tube temperatures, the liquid slug velocity and the local void fraction; providing an exhaustive overview of such a PHP transparent tube both in microgravity and hyper-gravity conditions. Additionally, for the first time in microgravity, the effect of the condenser temperature on PHPs is explored. When the condenser temperature is set at a higher value than the environment, results highlight that the possibility to invert the flow motion direction by means of non-symmetrical heating configurations is hindered. These experimental data could assist the development of improved numerical models of Pulsating Heat Pipes at different gravity levels.

Keywords: Pulsating Heat Pipe; Infrared analysis; Microgravity experiments.

[76] –PHP5_6

Thermal performance of pulsating heat stripes (PHS) built with plastic materials

Oguzhan Der[1], Marco Marengo[2] and Volfango Bertola[1*]
[1]*Laboratory of Technical Physics, School of Engineering, University of Liverpool, Liverpool L69 3GH, United Kingdom*
[2]*School of Computing, Engineering and Mathematics, University of Brighton, Brighton BN2 4GJ, United Kingdom*

Abstract
A low-cost, flexible pulsating heat pipe (PHP) was built in a composite polypropylene sheet consisting of three layers joint together by selective laser welding, to address the demand of heat transfer devices characterized by low weight, small unit thickness, low cost, and high mechanical flexibility. A thin, flexible and lightweight heat pipe is advantageous for various aerospace, aircraft and portable electronic applications where the device weight and its mechanical flexibility are essential. The concept is to sandwich a serpentine channel, cut out in a polypropylene sheet and containing a self-propelled mixture of a working fluid with its vapour, between two transparent sheets of the same material; this results into a thin, flat enclosure with parallel channels hence the name “pulsating heat stripes” (PHS). The transient and steady-state thermal response of the device was characterised for different heat input levels and different configurations, either straight or bent at different angles. The equivalent thermal resistance was estimated by measuring the wall temperatures at both the evaporator and the condenser, showing a multi-fold increase of the equivalent thermal conductance with respect to solid polypropylene.

Keywords: Pulsating heat stripes; Plastic heat pipe; Selective laser welding.

Room B: Session #10: [SP3] – Special Two-phase Devices #3

[13] –SP3_1

Two-Phase Cooling Technology Comparison for Power Electronic

Daniele Torresin[1*], Daniele Kane, Bruno Agostini and Matteo Bortolato

[1]*ABB Switzerland Ltd., Corporate Research, Segelhofstrasse 1K, Baden-Dättwil 5405, Switzerland*

Abstract

The experimental results of a pulsating heat pipe (PHP) and a novel thermosiphon coolers with the same overall dimensions are presented. These designs use numerous aluminium Multiport Extruded (MPE) tubes disposed in parallel to achieve the desired compactness. The sub-channels of the MPEs for the PHPs are connected in a serpentine manner by means of fluid distribution elements integrated in the two manifolds. This configuration enables the oscillation of liquid slugs and elongated

bubbles between the evaporator and the condenser areas. The thermosiphon connects all MPEs via collection chambers in both manifolds. Tests were performed with the fluids R245fa, R1234ze and R1233zd and the influence of different parameters such as heat load, fluid filling ratio and orientation are investigated. The results show that the novel thermosiphon design in which cooling fins were brazed also to the condenser section of the vapor riser channels offers at 1.6 kW a 14% performance improvement in vertical orientation compared to the PHP design with R245fa. Whereas the novel thermosiphon only worked vertically, the PHP was showing orientation free behavior for heat loads greater than 1.4 kW.

Keywords: Pulsating heat pipe; Thermosiphon; Heat transfer; Power electronic.

[92] –SP3_2

Thermal performance of a large closed multi-loop heat pipe using HFC-23 and HFC-410A as the working fluid

Shun Okazaki[1], Hideyuki Fuke[1], Katsumasa Takahashi[2], Manami Kondo[3], Akiko Kawachi[3], Noboru Yamada[2] and Hiroyuki Ogawa[1]
[1] *Japan Aerospace Exploration Agency (JAXA), Kanagawa 252-5210, Japan*
[2] *Nagaoka University of Technology, Niigata, 940-2188, Japan*
[3] *Tokai University, Kanagawa, 259-1292, Japan*

Abstract
We have investigated the basic thermal performance of a large closed multi-loop two-phase heat-pipe system being developed for a space-science project on the General Anti-Particle Spectrometer. This heat pipe is designed to operate in a balloon-borne environment with a requirement for cooling detectors in the spectrometer instrument to be lower than -35°C. The thermal performance of the heat pipe was measured for two working-fluid materials, HFC-410A and HFC-23. In the case of HFC-410A, apparent overheating could be observed locally in the heating section; this was not the case with HFC-23. The excess overheating with HFC-410A must be caused by high wall superheating required for incipient boiling. In addition, HFC- 23 produced higher maximum heat-transport capability of the heat pipe as compared to HFC-410A. We have also developed a simulation code in which the superheating phenomenon is considered. The simulated temperature distributions along the heat pipe as well as the predicted maximum heat-transport capability showed good agreement with the experimental results. From these investigations, we concluded that HFC-23 is preferred as the working fluid for this heat pipe system.

Keywords: Meter-scale multi-loop heat pipe; Super heating; HFC23; HFC410A.

[194] –SP3_3

Experimental investigation of a capillary-assisted high performance evaporator

Alexandre Marie[1,2], Pascal Lavieille[1], Marc Miscevic[1], Laurent Lachassagne[2], Vincent Dupont[2]
[1]*LAPLACE, Université de Toulouse, CNRS, INPT, UPS, France*
[2] *IRT St Exupéry, Toulouse, France*

Abstract
A particular architecture for a miniaturized evaporator is proposed in which liquid is spread on the heat source using a thin capillary structure connected to two manifolds. The vapor produced by the heat source is extracted from the device using a separate outlet. A prototype has been designed, manufactured and integrated in a mechanically pumped loop in order to evaluate the evaporator efficiency in terms of heat transfer coefficient and induced pressure drop. In this paper, a capillary structure consisting in parallel rectangular micro-grooves is investigated with HFE7000 used as the working fluid. Results show that the evaporator is able to extract heat flux of the order of 10 $W.cm^{-2}$ with heat transfer coefficients close to 10^4 $W.m^{-2}.K^{-1}$ while inducing pressure losses below a few hundred Pascal. Direct visualizations of the flow in the capillary structure allowed a precise characterization of the evaporator functioning mode, in particular the existence of two distinct two-phase flow regimes depending on the flooding of the capillary structure: nucleate boiling and liquid films evaporation. In order to predict the occurrence of these operating modes, a hydraulic model of the evaporator assembly has been developed and validated thanks to dedicated experimental campaigns. In particular, this model is able to predict the separation between the nucleate boiling and evaporation mode and highlights the fact that the capillary limit is not the main restricting factor in terms of the device maximum manageable heat flux.

Keywords: Miniaturized evaporator; Capillary pumping; Heat transfer intensification; Capillary structure; Experiments.

[339] –SP3_4

Development of a Cooling System for the IR Detectors

Savchenkova Natalia

Department of the Heat and Mass Transfer Process and Devices, National Research University

"Moscow Power Engineering Institute", 111250, Moscow, Krasnokazarmennaya str., 14, Russia

Abstract

The article describes the development of the design of a radiation cooler that should provide the temperature of photodetector devices in the range 70-80 K. For this, an overview of existing cryogenic cooling systems, the possibilities of using radiation coolers, coolers on heat pipes, throttling, absorption and other cryogenic refrigerators are made. Attention is paid to the choice of the working fluid of the heat pipes. The influence of the optical properties of coatings on working surfaces and radiation shield is estimated.

Keywords: Cryogenic system; Radiation refrigerator; Heat pipe; Radiation shields.

[389] –SP3_5

Experimental investigation of a novel heat sink with temperature uniformity

Hao Chen, Qiang Li*
MIIT Key Laboratory of Thermal Control of Electronic Equipment, School of Energy and Power Engineering, Nanjing University of Science & Technology, Nanjing 210094, China

Abstract
A novel heat sink with phase transition in the circulation loop was designed and fabricated to solve the heat dissipation of large size and high power electronic equipment and increase the temperature uniformity between electronic components with different power. The heat sink was composed of evaporation substrate, condensation substrate, capillary pump, reservoir and aluminum fins. The thermal performance of the heat sink under natural convection was tested and analyzed for R245fa under different working conditions. Experimental results indicated that the heat sink has an excellent temperature uniformity and outstanding heat dissipation capacity. The thermal performance of heat sink was influenced by the filling ratio, heat input and inclination angle. The response of heat sink to variable heat input is fast and the operation stability of heat sink is great. The temperature difference can be decreased to 2.9℃ at the heat input of 250W and the thermal resistance can be as small as 0.0082K/W. In addition, the behavior of two-phase flow in the heat sink was observed and identified.

Keywords: Phase transition, Natural convection, Temperature uniformity, Heat dissipation.

[385] –SP3_6

Transient Numerical Simulation of Mechanically Pumped Two-phase Loop System: Comparison between Simulation and Test Results

Meng Qingliang* Zhao Zhenming and Zhang Huandong

Beijing Institute of Space Mechanics & Electricity, Beijing 100094, China

Abstract

Mechanically pumped two-phase loop (MPTL) system used for accurate and stable thermal control of orbital heat sources can show excellent characteristics. In order to study the dynamic behaviors of heat and mass transfer of MPTL system,

particularly in response to the heat load variations, a transient numerical model is developed by using the time-dependent Navier-Stokes equations. The model is used to study operating state, flow and heat characteristics based upon the analyses of variations of massflow, temperature, and quality under different operating conditions. Above all, the complex transient behaviors in response to heat load variations in the MPTL system are studied in this model, such as the mass transfer between accumulator and the loop. By comparison between the test data and simulated results, it is found the correspondence is very good. The model can be used to design MPTL system and to predict the behavior before a system has been built.

Keywords: Mechanically pumped two-phase loop (MPTL); Transient numerical simulation; Heat and mass transfer; Accumulator

POSTER SESSIONS

Poster Session #1

[7] –PS1_1

Cooling of electronic components on LTCC module with embedded flat heat pipe

Denis A. Nesterov[1], Valery A. Derevyanko[1], Sergey B. Suntsov[2]

[1]*KSC SB RAS, Institute of Computational Modelling of Siberian Branch of the Russian Academy of Sciences, 660036, Krasnoyarsk, Russia*

[2]*Joint Stock Company "Academician M.F. Reshetnev's "Information Satellite Systems", Krasnoyarsky Krai, Zheleznogorsk, Russia*

Abstract

The results of experimental investigations of a ceramic circuit board sample with an embedded flat heat pipe are presented. The sample was made on the technology of low temperature co-fired ceramic (LTCC). The flat heat pipe is formed at the bottom side of the ceramic substrate by means of using a copper porous tape with vapor channels as a capillary structure. The developed prototype of LTCC module was used for investigation of removing and spreading of the high heat fluxes from high power electronic elements mounted on the module. The embedded flat heat pipe with acetone as working fluid provides 40 W/cm^2 of heat flux removal from the heat source with heat dissipation area of 1 cm^2. The measured value of thermal resistance between the heat source and the cooler surface under the module is 0.8 °C/W.

Keywords: Flat heat pipe; Heat spreader; Electronic cooling; Low temperature co-fired ceramic (LTCC).

[30] –PS1_2

Investigation the effect of electro discharge machining on the heat transport performance of extruded heat pipes

Cem Ömür[1*], Ahmet Bilge Uygur[1], Hasan Gürgüç IŞIK[1], İlhami HORUZ[2], Sadık Ayan[3], Murat Konar[3]
[1]*Turkish Aerospace Industries, Ankara 06980, Turkey*
[2]*Gazi University, Eng. Faculty, Mech. Eng. Dept., Ankara, 06570, Turkey*
[3]*ASAŞ Alüminyum Sanayi ve Ticaret A.Ş, İstanbul, Turkey*

Abstract
In this study, the effect of electro discharge machining (EDM) on the heat transport performance of extruded heat pipes is investigated. Firstly, the wire EDM limitations on the groove geometry is demonstrated. It is seen that due to the wire EDM process, the internal corners of the rims of die insert can only be manufactured with a curvature instead of sharp edges. This necessitates a modification on the vapor core diameter of the HP to prevent a performance reduction due to the increase in the entrance width of the grooves. Secondly, the effect of the EDM wire diameter on the number of grooves that can be machined on a specific heat pipe diameter is investigated. It is shown with thinner the wires, thinner groove fins can be machined which yields higher number of grooves that can be manufactured. Moreover, it is seen that when the wire diameter is increased, the number of grooves that can be manufactured is higher for trapezoidal grooved HP. This is due to the fact that the widest zone of the trapezoidal grooves corresponds to outer layer of the HP diameter.

Keywords: Electro discharge machining; EDM wire diameter; groove geometry; number of grooves.

[37] –PS1_3

A phase transition model based on a sharp interface model

Haiyu Wang[1,3], J. G. M. Kuerten[1,2] and B. P. M. van Esch[1]

[1]*Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, 5600MB, the Netherlands*

[2]*Faculty EEMCS, University of Twente, the Netherlands*

[3]*Research Center of Fluid Machinery Engineering and Technology, Jiangsu University, Zhenjiang, 212013, China*

Abstract

A Phase transition model based on the Volume of Fluid (VOF) method and Piecewise-Linear Interface Calculation (PLIC) is developed for the purpose of calculating evaporation and condensation in heat pipes. In order to handle the complex geometry in heat pipes, which is caused by the use of porous media or a fiber wick, a new PLIC algorithm is proposed. The new PLIC is able to calculate the interface position on an unstructured mesh with quadrilateral cells. The interface provided by PLIC is supposed to be sharp, which means that the interface should only exist in one cell, so that the distribution of the heat and mass source terms in a diffuse interface can be avoided. The idea of implementing the heat and mass source terms is simple and physical. It is based on several assumptions: 1) the interfacial temperature is the saturation temperature; 2) phase transition happens at the interface; 3) thermal conduction is the only way of transporting heat to the interface. The temperature difference between the interface and its surroundings drives the interfacial phase transition, and the amount of heat transferred is used to calculate the mass source term.

Keywords: Evaporation; Condensation; Volume of Fluid; Piecewise-linear interface calculation; Pore scale simulation;

[38] –PS1_4

Development of thinned aluminum flat heat pipe through inclined wall and press process

Seok-Hwan Moon*, Su-Hyen Hong, Hyun-Tak Kim
Materials & Components Basic Research Division, ETRI, Korea
*218 Gajeong-ro, Yuseong-gu, Daejeon, 305-700 Korea, Phone: +82-10-3459-8543, e-mail: shmoon@etri.re.kr**

Abstract
As a means of heat dissipation and thermal management in small electronic and communication devices, heat pipes are increasingly positioned as a good solution. To be applied to the module and system-level heat dissipation package, the heat pipe needs to be in surface contact rather than line contact. In order to do so, a round copper heat pipe is transformed into a plate-like shape through a secondary pressing process. In this study, the extrusion structure is designed to be sloped to solve the problem that it is difficult to be relatively thin compared to the large area of the plate structure. That is, a plurality of partitions separating the working fluid flow space in the plate-type heat pipe are designed to be inclined at 45 degree, and the extruded envelope is developed to obtain the desired total thickness through the second addition process of press. The capillary structure is inserted and positioned within the envelope prior to the secondary press process. Through this study, an aluminum flat heat pipe(AFHP) with a total thickness of 0.95 mm and a total length of 150 mm, which has a capillary structure with braided wire bundles or carbon wire bundles added thereto, was designed and manufactured. Through the performance test, it was found that the heat transfer performance of the AFHP with inclined wall did not show any deterioration characteristic compared with the AFHP having the normal vertical wall. The isothermal and heat transfer rate of the AFHP with Cu braid wick was superior to that of AFHP with simple rectangular groove wick. On the other hand, when the carbon wire bundle is added in the Cu braid, the isothermal characteristic was enhanced two times and the heat transfer rate was 15.5 W by improving about 42 % in the conditions that inclination angle is -90 degree and the evaporator temperature is not exceed 110 °C.

Keywords: Aluminum flat heat pipe, Inclined wall, Pressing, Braid, Carbon wire bundle

[47] –PS1_5

Visualization study of an ultra-thin thermal ground plane

Lucang Lyu[1], Ji Li[1*]
[1]*School of Engineering Sciences, University of Chinese Academy of Sciences, 19A Yu-quan-lu Road, Shijingshan District, Beijing 100049, China*

Abstract
This work presented a thermal ground plane with 0.5 mm interior height for visualization to study the phase-change process and two-phase flow characteristics in an ultra-thin thermal ground plane, in which novel wick structure was employed to regulate the two-phase flow direction. To fully interpret the heat transfer mechanism, effects of cooling conditions and operation modes were investigated carefully. It is found that the quasi-loop-type vapor-liquid circulation was observed under natural convection cooling condition, alleviating the vapor-liquid counterflow. Moreover, the nucleate boiling process was clearly observed before the steady state was reached. When positioned in the horizontal direction and cooled by forced water circulation, only evaporation process was visualized at steady state. In addition, the gravity force had impact on the two-phase flow characteristics and heat transfer performance. Nevertheless, the proposed thermal ground plane could functionally dissipate 56.3 W in the anti-gravity direction, while in the gravity favorable mode, a minimum thermal resistance of 0.35 ^{o}C/W was achieved at 75.5 W (75.5 W/cm^2).

Keywords: Ultra-thin thermal ground plane; Visualization study; Wick structure; Two-phase flow; Thermal performance.

[165] –PS1_6

Modeling of a screen mesh wick heat pipe using Al2O3

Bernardo Herrera[1,2*], Farid Chejne[2], Marcia B. H. Mantelli[3], Juan Mejía[2] and Karen Cacua[1]
[1]*Faculty of Engineering, Instituto Tecnológico Metropolitano, Medellín, Colombia*
[2]*Faculty of Mines, Universidad Nacional de Colombia, Medellín, Colombia*
[3]*Faculty of Mechanical Engineering, Universidade Federal de Santa Catarina, Florianópolis, Brazil*

Abstract
In this work, a phenomenological model that considers the interaction of nanoparticles of a nanofluid Al_2O_3/water within a cylindrical mesh wick heat pipe has been developed. The model is based on Navier-Stokes equations and it uses the balance of population as a method to account for the interaction of nanoparticles. The model predicted values of capillary limits with nanofluids up to 10% higher than the capillary limit of the heat pipe working with DI water. Those values were in agreement with the values expected to occur experimentally. Although the better performance of the capillary limit in the model was due to the reduction of the effective pore radius which increases the capillary pressure, that was not the main cause for improvement of the capillary limit in experimental conditions at lower nanofluid concentrations. On the other hand, it was found that exists and optimum concentration of nanoparticles which decreases the effective thermal resistance of the heat pipes. In this work, that concentration was 0.5% w/w.

Keywords: Mesh wick heat pipe, Nanofluid, Capillary pressure, Population balance, Modeling.

[210] –PS1_7

Development of Heat Pipe Heat Exchanger

Wei-Jie Hung, Chen-Yu Lu, Cheng-Wei Wang, Shung-Wen Kang*
Department of Mechanical and Electro-Mechanical Engineering, Tamkang University 151,Taipei 25137, Taiwan, ROC

Abstract
In this study, the gas-to-liquid heat pipe heat exchanger was fabricated and tested, and the thermal recovery capability and thermal performance of heat pipe heat exchangers were investigated. The device consists of 19 stainless steel-water heat pipes with an outside diameter of 6.2 mm, a wall thickness of 0.5 mm and a length of 300 mm. The condition for experiment was conducted where, hot gas and cooling waters enter at temperatures of 150-250 ºC and 30ºC, respectively. The flow rate of gas through the evaporator is 0.114-0.270 kg/min, while the flow rate of water through the condenser is 0.940 kg/min. The results showed that the maximum heat transfer rate was 445.5 W, and the maximum effectiveness was 0.609. The present research also compare between experimental and theoretical investigation with reference to the correlation in the literature.

Keywords: Heat pipe heat exchanger; Heat pipe; Thermal network.

[267] –PS1_8

Performance Divergences of Axially Grooved Heat Pipes with Narrow Channels during Inclination Ground Testing

Nadjara dos Santos, Valeri Vlassov*, Jorge Bertoldo Junior and Olga Kchoukina

National Institute for Space Research, S.J.Campos-SP, Brazil

Abstract

Heat pipes are extensively used in space applications for spreading the heat of electronic equipment along the satellite structural panels. For such utilization, the ammonia-filled axial aluminum grooved heat pipes are commonly used by embedding them into the honeycomb panels. Two-core heat pipes provide the redundancy and appropriate fitting between two face sheets of the panel. For typical panel thickness of ~20mm, the diameter of vapor core is relatively small, about 6 mm. During satellite thermal vacuum tests, the entire satellite shall be precisely leveled in order to keep the conditions for horizontal heat pipes working ability. In large thermal-vacuum chambers, such high precision horizontal pre-leveling may be lost when the chamber is under vacuum: bottom shroud may slightly be deformed under atmospheric pressure. Therefore, it is important to know the possible heat pipe performance divergences under small angles in both favorable and unfavorable inclinations. The present study releases experimental data of the inclination tests of a two-core ammonia heat pipe in wide range of negative and positive inclinations under different heat loads. Both, steady state and transient start-up performance were assessed. It was found that under some small favorable inclinations the heat pipe presents some unexpected anomalies in the total thermal resistance, while under small unfavorable the heat pipe works well. At start up, some anomalies were observed under small inclinations. The temperature overshoots may be of two different types: due to dry-out or due to eventual over-flooding of the evaporator section. The initial transient behaviors are very similar however the consequences may be very different for the case of ground satellite testing.

Keywords: two-core heat pipe; ground testing; inclination tests; satellite thermal control

[313] –PS1_9

Black box modelling of a latent heat thermal energy storage system coupled with heat pipes

Alessia Arteconi[1], Francesco Ferracuti[2], Roberto Tascioni[3,1], Khamid Mahkamov[4], Murat Kenisarin[4], Carolina Costa[4], Luisa F. Cabeza[5], Alvaro de Gracia[5,6], Elvedin Halimic[7], David Mullen[7], Kevin Lynn[7], Luca Cioccolanti[1]

[1]*Università eCampus, via Isimbardi 10, Novedrate 22060, Italy*

[2]*Università Politecnica delle Marche, via Brecce Bianche 1, Ancona 60131, Italy*

[3]*DIAEE, Sapienza Università di Roma, via Eudossiana 18, Rome 00184, Italy*

[4]*Department of Mechanical Engineering and Construction, Northumbria University, Newcastle upon Tyne NE1 8ST, UK*

[5]*GREiA Research Group, INSPIRES Research Centre, University of Lleida, Pere de Cabrera s/n, Lleida 25001, Spain*

[6]*CIRIAF – Interuniversity Research Centre on Pollution and Environment "Mauro Felli", Via Duranti 63, 06125-Perugia, Italy*

[7]*Aavid Thermacore, Wansbeck Business Park 12, Ashington, Northumberland NE63 8QW, UK*

Abstract

This paper presents black box models to represent a LHTESS (Latent Heat Thermal Energy Storage System) coupled with heat pipes, aimed at increasing the storage performance and at decreasing the time of charging/discharging. The presented storage system is part of a micro solar CHP plant and the developed model is intended to be used in the simulation tool of

the overall system, thus it has to be accurate but also fast computing. Black box data driven models are considered, trained by means of numerical data obtained from a white box detailed model of the LHTESS and heat pipes system. A year round simulation of the system during its normal operation within the micro solar CHP plant is used as dataset. Then the black box models are trained and finally validated on these data. Results show the need for a black box model that can take into account the different seasonal performance of the LHTESS. In this analysis the best fit was achieved by means of Random Forest models with an accuracy higher than 90%.

Keywords: PCM, Heat pipes, black box models, ARX, NARX, Random Forest.

[318] –PS1_10

Performance Evaluation of a Cooling System with Intergrade Heat Pipes and Thermoelectric Devices

Youn Cheol Park[1] and Gang-Soo Ko[2]

[1]*Department of Mechanical Engineering, Jeju National University, Jeju 63243, Korea*

[2]*Graduate School of Mechanical Engineering, Jeju National University, Jeju 63243, Korea*

Abstract

A combined thermoelectric device and heat pipe cooling module were combined together as one packaged module and an experimental investigation was conducted to get a heat exchange method when the heat sink temperature is larger than the heat source. The developed cooling module was installed as serial connection and parallel connection based on the air direction. The developed module was installed at controlled environmental chamber to determine the heat transfer characteristics. In the experiment, the air volume flow rate was varies from 1m^3/min to 3 m^3/min and air flow direction was changed with respect to the heat exchanger allocations. As results, the heat extraction performance of the cooling module shows 283.2W in serial connection and 76.7W in parallel connection. Moreover, it shows that the heat absorption rate of the module is 66.2W in serial connection and 54.1W in parallel connection. As the result, it is found that the developed heat exchange module could be used in extreme condition since the heat transfer direction is opposite to the conventional heat transfer mechanism which hot air flows to cold air.

Keywords: Thermoelectric device; Integrated design; Heat pipe; Heat sink and source.

[351] –PS1_11

Modeling of Multidimensional Heat Transfer in a Flat Grooved Heat Pipe

Cem Kurt[1], Gülnihal Odabaşı[2], Yiğit Akkuş[3,4], Barbaros Çetin[1], Zafer Dursunkaya[2*]

[1]*Microfluidics and lab-on-a-chip Research Group, Mechanical Eng. Dpt., İ.D. Bilkent University 06800 Ankara, Turkey*

[2]*Mechanical Engineering Department, Middle East Technical University, 06800 Ankara, Turkey*

[3]*ASELSAN A.Ş, 06172 Yenimahalle, Ankara, Turkey*

[4]*Mechanical Engineering Department, Southern Methodist University, Dallas 75205 TX, USA*

Abstract

Heat pipes, using phase change heat transfer mechanism, have wide application areas from outer space to thermal management of electronic components due to their reliability and effectiveness in transferring heat. Large amounts of thermal energy can be transferred from a heat source to a sink with small temperature differences. In this study, a computational model is presented to analyze the performance of flat grooved heat pipes. In the in-house developed code, a finite difference scheme is implemented to couple the multidimensional heat transfer in the solid and liquid domain to a quasi 1-D axial fluid flow together with the evaporation and condensation phase change models, for rectangular grooved heat pipes. The same computational methodology is also implemented in COMSOL Multi-physics *via* MATLAB interface, this

time including 3D effects on the fluid flow inside the groove which further extents the applicability of the proposed computational model for different groove geometries.

Keywords: Heat pipe; Multidimensional heat transfer; Modeling.

[396] –PS1_12

Performance of Small Diameter Heat Pipes for Low Power Applications

Kate Smith[1*], Tim Persoons[1], Jane Cornett[2], Marc Dunham[3], Baoxing Chen[2]

[1]*Department of Mechanical and Manufacturing Engineering, Trinity College Dublin, Dublin 2, Ireland*

[2]*Analog Devices Inc., Wilmington, MA, USA*

[3]*Analog Devices Inc., San Jose, CA, USA*

Abstract

This study investigates the performance of heat pipes of small dimension (diameter ~ 3 mm) in bending particularly for applications involving low power and low temperature difference between the heat source and heat sink. Typically, commercial heat pipes can withstand a bend radius of six times the heat pipe outer diameter and maintain heat transfer performance. In most applications heat pipes are used for their capability to transfer large thermal loads, however this study focuses on applications where low input heating power is transported over long distances, as is the case for thermoelectric energy harvesters. The aim is to assess the performance of small diameter heat pipes at low levels of input power (~ 1 W) in bent geometries. Performance of the heat pipes is characterized in terms of the thermal resistance of the heat pipe network from heat input to output. Commercially available heat pipes are assessed in orientations where the influence of gravity does not assist the liquid return from the condenser to evaporator. It was found that performance of the heat pipe was limited compared to the manufacturers specifications, showing a 66% reduction in the maximum thermal transport capability. However, the heat pipe showed adequate results for the required low temperature, low heat flux application.

Keywords: Bending Radius; Low thermal load Performance; Commercial Heat Pipe; Two-Phase Electronic Cooling.

[398] –PS1_13

Soil Heat Stabilizers with Powder Capillary Structure

Victor V. Maziuk[1], Alexandr F. Ilyushchenko[1], Pavel S. Ancheuski[1], Alexandr A. Antuh[1], Georgiy V. Koloskov[2], Enver V. Ibragimov[2]

[1]*Powder Metallurgy Institute, Minsk, Belarus* [2]*SPA "North", Moscow, Russia*

Abstract

The use of powder capillary structure on inside surface of evaporator of soil heat stabilizers greatly intensifies heat transfer process. This is achieved by enlargement of the area of heat transfer at evaporation and increasing the heat transfer coefficient on the inner surface of the evaporator. A technology has been developed for molding and sintering a thin (thickness about 0.2 mm) iron powder porous layer on the inner surface of the iron pipe outer diameter of 76 mm, wall thickness of 4 mm and length of 3 m. The eventual goal of the work was an experimental study of the effect of the powder capillary structure on the heat transfer performance and efficiency of the heat stabilizer. As a result of the experiments it was established that the internal thermal resistance of such heat stabilizer is 3.4 times lower than that of the heat stabilizer having smooth tube surfaces. Therefore, on the condenser and vaporizer the heat energy transfer will be three times as much as in the conventional thermal stabilizer.

Keywords: Heat pipe; Cryolithozone; Frozen soil; Powder porous layer.

[399] –PS1_14

A Practical method for operating and durability tests of Heat Pipe based on using vacuum chamber

Isar Dashti[1*], Saeed Asghari[2], Mohsen Abedi[3] and Mojtaba Sheida[4]
[1, 2]*Materials and Energy Research Institute, Iranian Space Research Center, Iran*
[3]*Sattelite Research Institute, Iranian Space Research Center, Iran*
[4]*Iranian Space Research Center, Iran*

Abstract
The measurement of the physical characteristics of a heat pipe along with its durability test is the basis of this study. Two types of heat pipes are made with different wicks and their thermal resistances are measured by a specially developed test setup. In the proposed test setup, a vacuum chamber is used. The advantage of using a vacuum chamber is the absence of heat transfer by convection, which causes the entire amount of power in the evaporator flow through the heat pipe (although there is heat transfer by radiation, but its amount is negligible). Subsequently, with the help of this chamber, a heat pipe durability test is presented and no failure in performance of heat pipes was observed in 12 cycles. Temperature difference acquire at each sample time during the test. The average of data and their variance is calculated after the test. The variance could be a proper criteria for durability and lifetime of heat pipes. Other result of this study is application of acetone as working fluid at below 0°C.
.
Keywords: Operating test; durability; heat pipe; vacuum chamber.

[417] –PS1_15

Heat Pipe experiences in ENEA: a review

Andrea Mariani* and Luca Saraceno

Energy Department, Production, Conversion and Use of Energy Division, Laboratory of Development of Chemical Processes and Thermofluidynamic, ENEA, Rome, 00123, Italy

Abstract

In the past the Thermal Fluid-Dynamics Lab of ENEA performed some test on different kind of Heat Pipe; this paper presents a comprehensive review of these activities. We studied the influence of the main geometric and thermal fluid-dynamics parameters on the behavior of a Wickless Heat Pipe (two-phase thermosyphon) used in solar panel. The thermal behavior of a new type of flat solar collector that integrates the fluid storage tank was investigated; this new apparatus works as a thermosyphon. Heat Pipe with a capillary structure was also studied in the past. We used a Loop Heat Pipe in which the presence of the capillary structure is necessary only in the evaporator. The capillary was a porous structure of steel. In another activity the capillary pressure influence on open channels pressure drop was investigated. The measured values of viscous liquid pressure drop in a small square section open channel showed that as in certain conditions the capillary pressure can influence affects the pressure drop evaluation. The same test section was used to perform some tests in evaporation conditions aiming to analyze the resulting evolution of the liquid meniscus. A thermal analysis and study of dryout and capillary limit was also performed.

Keywords: Review, Two-phase thermosyphon, Loop Heat Pipe, Meniscus

[422] –PS1_16

Hydrogen Permeation Management for High Temperature Heat Pipes in Energy Conversions Systems

John H. Rosenfeld[1] and Mark T. North[2]
[1]*Aavid / Thermacore, 780 Eden Road, Lancaster, PA 17601 USA*
[2]*Aavid / Thermacore, 780 Eden Road, Lancaster, PA 17601 USA*

Abstract

Heat pipes are a favorable approach for integrating energy conversion components into future power-generation systems. In such applications, hydrogen can be present as a by-product of a nuclear power heat source, a byproduct of combustion, or in high-temperature metal hydride thermal energy storage vessels. Hydrogen permeation can affect high-temperature alkali metal heat pipes negatively if allowed to accumulate inside the closed vapor space volume in sufficient amount to block vapor flow. Considerable study has been given to develop solutions to this challenge, and concepts have been evaluated to suppress hydrogen permeation into alkali metal heat pipes. Additional methods have been identified to mitigate the problem by designing features into the structures to allow the hydrogen to also permeate out of the heat pipes to reach an acceptable low equilibrium blockage. An overview is presented that describes the potential sources of hydrogen in high-temperature energy conversion systems, the basic principles of hydrogen permeation, and the methods of mitigating its effects. Moreover, analytical approaches are presented to enable systems designers to evaluate hydrogen permeation on a quantitative basis for specific designs. Hydrogen effects on heat pipe operation can be managed successfully if steps are taken to prevent it from accumulating inside the heat pipe.

Keywords: Hydrogen, permeation, heat pipe, high temperature.

[470] –PS1_17

Effect of flattening thickness on the thermal performance of ultra-thin heat pipe with sintered copper mesh

Heng Tang *, Jie Li, Gong Chen and Guisheng Zhong

School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510640, PR China

Abstract

This study proposes a sintered copper mesh wick structure fabricated by weaving and sintering for ultra-thin heat pipes (UTHPs). Three UTHPs with the thickness of 1.2, 1.0 and 0.8 mm were fabricated by flattening cylindrical copper pipes of 6 mm diameter. The manufacturing process of UTHP was studied and the thermal performance of UTHP samples were investigated experimentally. The effects of various heat inputs and flattening thickness on the thermal performance of the heat pipe were analysed. The results indicate that the flattening thickness has a great influence on the thermal performance of UTHPs, the maximum heat transfer capability of UTHPs decreased quickly with a decrease in the flattening thickness. The maximum heat transport capability of the UTHP with flattening thickness of 1.2 mm and 1.0 mm was 23 W and 17 W, respectively. And the UTHP completely lose its heat transfer capacity under the flattening thickness of 0.8 mm. Moreover, the UTHP with flattening thickness of 1.2 mm and 1.0 mm can become operational in a short while, and the temperature of each section can attain a new steady value without any abrupt variation in the temperature even under high and variable input power.

Keywords: Ultra-thin heat pipe; Copper mesh wick structure; Flattening thickness; Thermal management

[126] –PS1_18

A method of fast quality control inspection of loop heat pipe

Bin-Juine Huang[1*], H.H.Huang[1], and T.L.Liang[1]

[1] *Department of Mechanical Engineering, National Taiwan University, Taipei, Taiwan 106*

Abstract

The dynamic behavior of loop heat pipe (LHP) is a variable structure system which changes with heat load and attitude of LHP. The startup phenomena of a LHP can be classified into four modes, according to the heat load Q_{in}: (1) failure mode: $Q_{in} < Q_{min}$, (2) oscillating mode: $Q_{min} < Q_{in} < Q_{crit}$, (3) overshoot mode: $Q_{crit} < Q_{in} < Q_s$, and (4) normal mode: $Q_s < Q_{in}$ [4]. The startup of the 100W prototype made in the present study is normal in the range of heat load 50W-120W. For heat load <50W, oscillating and unstable properties are observed in which the dynamic behavior is in second-order linear system. Based on the system dynamics behavior of a LHP, the steady-state performance of LHP can be predicted from a short transient test. It is shown in the present study that, the steady-state performance of a LHP can be accurately predicted using a short transient test for about 80s from a step heat load, which reduces the time of the test from 1,800 s

in steady-state test to 80 s. This test method has been applied in the fast quality control inspection of commercial loop heat pipe in mass production. No LHP failure occurs so far for about 30,000 sets installed in LED luminaires in about 10 years operation [5].

Keywords: Loop heat pipe; Heat pipe; Commercial loop heat pipe; Quality inspection of loop heat pipe.

[152] –PS1_19

Numerical simulation of a new-type loop heat pipe

Kai Zhu[1], Xueqiang Li[1, 2, 3], Hailong Li[1, 3*], Xiaoqing Chen[1], Yabo Wang[1]

[1]*Key Laboratory of Refrigeration Technology of Tianjin, Tianjin University of Commerce, Tianjin, 300134, China*

[2]*School of Environmental Science and Engineering, Tianjin University, Tianjin, 300072, China*

[3]*School of Sustainable Development of Society and Technology, Malardalen University, SE 721 23 Västrås, Sweden*

Abstract

It has been proved that the driving force of the working fluid in loop heat pipes (LHP) comes from not only the capillary head, but also the pressure head due to evaporation. To effectively use the pressure head of evaporation, a new type of loop heat pipe (LHP), with the wick separated from the heating surface by a chamber, was proposed and studied. Experiments have shown that the novel LHP can operate successfully. In order to deeply understand the characteristics of operation and further explore the role of the pressure head of evaporation, it is essential to do modeling. A mathematical model has been established based on energy and mass balance. However, the operational mechanism, especially the evaporation and the flow characters of liquid and vapor, still remains unclear. Therefore, the objective of this work is to develop a CFD model to simulate the new LHP, which will be further validated by experimental data.

Keywords: Loop heat pipe; CFD simulation; FLUENT; Evaporation mechanism; Vapor-liquid flow.

[157] –PS1_20

Experimental study on a cryogenic loop heat pipe with a flat evaporator

Chang Zhang[12], Rongjian Xie[1]and Yinong Wu[1]

[1] *Shanghai Institute of Technical Physics of the Chinese Academy of Sciences, Shanghai 200083, China*

[2] *University of Chinese Academy of Sciences, Beijing 100049, China*

Abstract

The cryogenic loop heat pipe is a two-phase heat transfer featuring high efficiency. It can be applied in cryogenic thermal control systems in the programs of deep-space exploration. The disadvantage of the traditional design of the evaporator in the cryogenic loop heat pipe, which refers to the cylindrical form unfavorable to the contact to the plane heat source, increases the heat transfer temperature difference. On account of this problem, a new design, cryogenic loop heat pipe with a flat evaporator, was discussed in this paper, in which its super-critical starting characteristic, heat-transfer capability was studied and its heat-transfer capability ranging from 70k—100k tested. It was proved that the cryogenic loop heat pipe with a flat evaporator can finish the super-critical starting process smoothly. Besides, the temperature in its primary evaporator decreases fast. The primary evaporator can operate independently with the heat-transfer power as much as 15W. On this basis, the heat-transfer capacity of the loop heat pipe was tested with different filling rates at the working temperature of 80K. The lowest heat-transfer resistance is achieved with the 70% filling rate at the working temperature of 80K.

Keywords: Cryogenic loop heat pipe; Flat evaporator; Heat transfer; Start-up; Filling rate.

[262] –PS1_21

Design of a High Temperature Loop Heat Pipe for Solar-Dish Systems

Sonia Fereres[1*], Mikael Mohaupt[2], Benjamin Lagier[3], Raphael Mari[3], Emmanuel Dehombreux[2], Cristina Guraya[4], Cristina Jimenez[4], Xabier Azpiroz[4], Bastien Bonnafous[5], and Sonia De la Rosa[1]

[1]Abengoa Innovación, Energia Solar 1, Campus Palmas Altas, Sevilla 41014, Spain

[2]Euro Heat Pipes, Rue de l'Industrie 24, B-1400 Nivelles, Belgium

[3]Airbus Defence and Space SAS,31 Rue des Cosmonautes, 31400 Toulouse France

[4]Tecnalia, Mikeletegi Pasealekua 2. 20009 San Sebastian, Spain

[5] ESA/ESTEC, Noordwijk, The Netherlands

Abstract

Extending the electricity production of solar thermal dish-Stirling systems beyond daylight hours by incorporating thermal energy storage can increase its competitiveness and its ability to compete in distributed energy generation with photovoltaics in certain scenarios. To achieve this, the concentrated solar radiation at the receiver must be decoupled from its power conversion unit located at the parabolic dish's focal point. Here the design of a high temperature loop heat pipe (LHP) is investigated to effectively transport this concentrated radiation to alternative locations. The system would bring additional benefits such as lighten structural loads when the power conversion unit is mounted on the rear structure of the dish or on the ground, reducing costs and allowing other multi-dish system configurations. However, the large power transport (> 10 kW) and high temperature (> 600ºC) requirements are above current state-of-the-art LHP, making this a challenge in terms of material, fluid, and overall design. Here, we analyze the system requirements, evaluate the system technology trade-offs and develop a numerical model to determine the most promising solution to build and test a future prototype.

Keywords: High temperature; Loop heat pipe; Solar dish-Stirling; Liquid metal loop heat pipe.

[298] –PS1_22

Loop Heat Pipe Wick Fabrication via Additive Manufacturing

Bradley Richard[1*], Devin Pellicone[1] and William G. Anderson[1]
[1]*Advanced Cooling Technologies, Inc., Lancaster, PA, USA*

Abstract
CubeSats and SmallSats are increasing in popularity and capability, but also are requiring improved thermal management to keep up with increasing heat loads and fluxes. Loop heat pipes (LHPs) offer a passive and proven solution, but are currently too expensive for many cost sensitive small satellite projects. By developing 3D printed LHPs using a direct metal laser sintering (DMLS) process the fabrication costs can significantly be reduced while offering increased reliability with the elimination of the knife-edge seal. An optimization study was completed on DMLS parameters for 316LSS to minimize the pore size of 3D printed primary wicks. A minimum pore radius of 5.6µm was achieved. A proof of concept LHP prototype was built with a 3D printed primary wick. Experimental testing was completed. A maximum power of 125W at steady state was achieved. Additionally, low power startup, adverse elevation, and power cycle tests were completed to verify performance over a wide range of conditions. Based on the success of the proof of concept prototype more development is underway for optimization of 3D printed primary wicks, and parameters for secondary wick fabrication.

Keywords: Loop heat pipe; Primary wick; Additive manufacturing; CubeSats

[263] –PS1_23

Thermal modeling for the transient performance of a micro heat pipe using liquid thin-film theory

Eui Guk Jung[1], Joon Hong Boo[2*]
[1]*Dept. of Fire & Disaster Prevention Engineering, Changshin University, 262 Palyong-ro, Masanhoewon-gu Changwon-city, Gyeongsangnam-do, Korea*
[2]*School of Aerospace and Mechanical Engineering, Korea Aerospace University, Goyang, Gyeonggi-do 10540, Korea*

Abstract
Transient analytical model is presented for prediction of heat and mass transfer in a micro heat pipe. Mass, momentum, and energy equations for the vapor and liquid phases were modified for more accurate prediction of transient response. In particular, the liquid-vapor interface profile was obtained with the liquid thin-film theory through augmented Young-Laplace equation. Consequently, the interface areas for heat and mass transfer were predicted and incorporated into the governing equations of each phases. As a result, the axial distributions of mass flow, pressure, and temperature were obtained for vapor and liquid in the micro heat pipe. The analytical model was validated by comparison of its solutions with experimental results. The discrepancy between the experimental and numerical results for the temperature difference between the evaporator and condenser was less than 0.5°C, which manifested improved accuracy.

Keywords: Micro heat pipe, Transient analytical model, Phase-change interface, Thin-film theory, Film thickness, Augmented Young-Laplace equation.

Poster Session #2

[34] –PS2_1

Effect of Fluid Loading on the Performance of Low Temperature T Thermosyphons

Saber Mohamed[1], Daniel Ewing[1], Chan Y. Ching[1], Ahmed Zaghlol[2]
[1] *Department of Mechanical Engineering, McMaster University, Hamilton, ON, CANADA*
[2]*MERSEN Canada, Mississauga, ON, CANADA*

Abstract
Experiments were performed to characterize the effect of fluid loading on the boiling instabilities of copper-water T-type thermosyphons. The thermosyphons consisted of square cross-section horizontal evaporators (the cross in the T) and round condenser tubes oriented either vertically or at 8 degrees from the horizontal. The evaporator was embedded into an aluminum heat spreading plate. Heat was added using heaters in the plate and removed using a water jacket on the condenser tube. The unsteady heat transfer out of the condenser was compared to temperature fluctuations in the heat spreading plate, on the thermosyphon, and in the cooling water jacket flows for different fluid loadings. Measurements for a nominal heat transfer of 70W (for a saturation pressure of approximately 2 kPa) showed evidence of stable film evaporation, stable boiling, and an unsteady variation between the two modes in the evaporator section. The first occurred at low filling ratios for the inclined condenser, the last at large filling ratios (100% and 130% of the evaporator volume), with oscillations between the modes for moderate filling ratios.

Keywords: Heat pipe; Boiling instability; Thermosyphons

[129] –PS2_2

Experimental Behaviors of Closed Loop Flat Plate Pulsating Heat Pipes: a Parametric Study

Filippo Pagnoni[1,2*], Vincent Ayel[2], Cyril Romestant[2] and Yves Bertin[2]
[1] *Department of Aerospace Engineering, Politecnico di Milano, Milan, 20158, Italy*
[2] *Pprime Institut CNRS – ENSMA – Université de Poitiers, UPR 3346, Futuroscope-Chasseneuil, France*

Abstract
Two closed loop Flat-Plate Pulsating Heat Pipes (FPPHPs) have been tested under various operating conditions, working fluids and different evaporator – condenser distances. The devices have the same geometrical features;

nevertheless, on one FPPHP plate external grooves between adjacent channels have been engraved to minimize the transversal thermal conductive spreading whilst the other is a simple smooth plate. Both FPPHPs have shown better performances when tilted in favorable vertical position. It has been found that higher secondary fluid temperatures within the condenser provide better thermal performances. The working fluids are ethanol and FC72. Their different thermophysical properties and critical diameters have remarkable effects on FPPHPs behavior. Moving the condenser towards evaporator increases the heat transfer capabilities, reducing the influence of gravity. Finally, the higher thermal insulation between adjacent channels, provided by the external grooves, seems to degrade the thermal performance, especially in horizontal position and on the edge.

Keywords: Flat plate pulsating heat pipe; Parametric analysis; Heat transport capability; Thermal performance.

[146] –PS2_3

Study on the working fluid selection for a pulsating heat pipe

Juno Kim[1] and Sung Jin Kim[1]
[1]*Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea*

Abstract
The objective of this study is to suggest a guideline for selecting the working fluid of the micro pulsating heat pipe (MPHP) depending on the operating temperature. Using MEMS techniques, silicon-based MPHP with 10 turns and a hydraulic diameter of 667 μm is fabricated. Five working fluids with different boiling points are used as working fluid of the MPHP. The thermal performance of the MPHPs is evaluated by changing the operating temperature from -20℃ up to 80℃ in increments of 10℃. Flow characteristics of the MPHPs are also investigated through high-speed photography. Experimental results show that the thermal resistance of the MPHP increases and startup input power decreases as the operating temperature increases. The MPHP have an optimum operating temperature for which the evaporator temperature is the lowest depending on the working fluid. The flow visualization results show that the stopover phenomenon is observed when the thermal performance of the MPHP decreases. Finally, the figure of merit for selecting the proper working fluid for the MPHP is derived and validated by using experimental results. The limitations and prospects of the proposed figure of merit are discussed in detail.

Keywords: working fluid; operating temperature; flow visualization; micro pulsating heat pipe

[307] –PS2_4

Numerical Study for Improvement of Startup Characteristics of Oscillating Heat Pipe

Nao Inoue[1*], Koji Fujita[2] and Hiroki Nagai[2]
[1]*Department of Aerospace Engineering, Tohoku University, Sendai 980-8577, Japan*
[2]*Institute of Fluid Science, Tohoku University, Sendai 980-8577, Japan*

Abstract
This paper presents a numerical study for improving the startup characteristics of oscillating heat pipes (OHPs). Our previous study suggested that OHPs have difficulty starting up when the liquid phase localizes in the cooling section. Here, we performed a numerical study by changing the surface roughness in the pipe to prevent startup failure and unstable temperature oscillations caused by the uneven distribution of liquid in the cooling section. The calculations showed that changing the surface roughness makes nucleate boiling more likely to cause uneven pressure distribution at each turn, thus inducing flow in the OHP and improving the startup characteristics. We also showed the possibility of improving startup at a low heat load by placing the rough surface in the adiabatic and heating sections.

Keywords: Oscillating Heat Pipe; Startup; Check Valve; Numerical Analysis.

[367] –PS2_5

Experimental study of oscillating heat pipes with periodic expansion-constriction cross-sections

Tingting Hao, Nan Li, Xuehu Ma*, Zhong Lan and Tao Bai

Institute of Chemical Engineering, Dalian University of Technology, Dalian, Liaoning Province, 116024, China

Abstract

Slug oscillation and heat transfer performance of oscillating heat pipes (OHPs) with periodic expansion and constriction cross-sections were investigated experimentally. Turn number of the OHP was 4. Uniform cross section OHP had 8 parallel square channels with the cross section of 2 × 2 mm^2. Periodic expansion OHP had channels with the expansion and constriction cross section of 3 × 2 mm^2 and 2 × 2 mm^2, and periodic constriction OHP had channels with the expansion and constriction cross section of 2 × 2 mm^2 and 1 × 2 mm^2. OHPs were operated in vertical orientation. The working fluid was deionized water. High speed camera was used to record the liquid slug movements and liquid-vapor interface profiles. Due to the surface tension effect, the liquid-vapor interface length increased, leading to the improvement performance of OHP with periodic expansion structure. Experimental results showed that the liquid-vapor interface was symmetric for the uniform cross-section OHP, and the non-uniform cross-section caused the asymmetric liquid-vapor interface. Furthermore, the liquid-vapor interface length in the periodic expansion OHP was higher than that in the uniform cross-section OHP which resulted in the increased heat transfer area of the condensation and evaporation sections. The liquid slug movement became stronger in the periodic expansion. Compared to the uniform cross-section OHP, the average amplitude and velocity of the liquid slug in the periodic expansion OHPs were increased by 0%~16% and 9%~70%, respectively. The heat transfer performance of periodic expansion OHP was higher than the uniform cross section OHP and the heat transfer performance of periodic constriction OHP was lower than the uniform cross section OHP.

Keywords: Oscillating heat pipe; Periodic expansion–constriction; Liquid-vapor interface; slug oscillation.

[409] –PS2_6

Infrared analysis and pressure measurements on a single loop pulsating heat pipe at different gravity levels

D. Mangini[1], M. Pozzoni[2], M. Mameli[3], L. Pietrasanta[1], M. Bernagozzi[1], D. Fioriti[3], N. Miché[1], L. Araneo[4], S. Filippeschi[3], M. Marengo[1].

[1]School of Computing, Engineering and Mathematics, University of Brighton, Lewes Road, BN2 4GJ Brighton, UK
[2]University of Bergamo, Via Galvani, 2, 24044 Dalmine BG, Italy
[3]DESTEC, University of Pisa, Largo Lucio Lazzarino 2, 56122 Pisa, Italy
[4]Polytechnic of Milan, Via Lambruschini 4A, Milan, Italy

Abstract

A Single Loop Pulsating Heat Pipe (SLPHP) with an inner diameter of 2 mm is tested in hyper/micro gravity conditions during the 68th ESA Parabolic Flight Campaign. The system is designed with two sapphire tubes that connect the heated and the cooled section, allowing simultaneous fluid flow high-speed visualization, and a direct to fluid IR analysis by using respectively a high-speed camera and a Medium-Wave Infrared Camera (MWIR). Three independent heaters are positioned at the evaporator in order to vary the power distribution and to promote different flow motions with specific heating configurations. Furthermore, two highly accurate pressure transducers measure the pressure drop between the condenser and the evaporator. Additionally, twelve thermocouples mounted on the external tube wall record local temperatures during parabolic flight tests. Such a complete thermo-fluid dynamic analysis at different gravity levels, coupled with the acquisition of high-speed and infrared images in the transparent section of the SLPHP, has the main objective of providing a better understanding on the relationship between the fluid flow motion and the thermal response of the device. Infrared Time-space temperature maps of the flow are correlated with pressure measurements, the external wall tube temperatures, the liquid slug velocity and the local void fraction; providing an exhaustive overview of such a PHP transparent tube both in microgravity and hyper-gravity conditions. Additionally, for the first time in microgravity, the effect of the condenser temperature on PHPs is explored. When the condenser temperature is set at a higher value than the environment, results highlight that the possibility to invert the flow motion direction by means of non-symmetrical heating configurations is hindered. These experimental data could assist the development of improved numerical models of Pulsating Heat Pipes at different gravity levels.

Keywords: Pulsating Heat Pipe; Infrared analysis; Microgravity experiments.

[412] –PS2_7

Start-up of a large diameter Pulsating Heat Pipe on ground and on board a sounding rocket

Stefano Piacquadio[1], Andrea Catarsi[1], Pietro Nannipieri[1], Martina Anichini[1], Lorenzo Barsocchi[1], Giulia Becatti[1], Luca Buoni[1], Federico Celi[1], Paolo Di Giorgio[1], Paolo Fattibene[1], Eugenio Ferrato[1], Pietro Guardati[1], Edoardo Mancini[1], Gabriele Meoni[1], Federico Nesti[1], Edoardo Pratelli[1], Lorenzo Quadrelli[1], Alessandro Simone Viglione[1], Francesco Zanaboni[1], Mauro Mameli[1], Federico Baronti[1], Luca Fanucci[1], Salvo Marcuccio[1], Carlo Bartoli[1], Paolo Di Marco[1], Sauro Filippeschi[1], Marco La Foresta[2], Lorenzo Caporale[2], Nicola Bianco[3], Marco Marengo[4]
[1]*University of Pisa, Largo Lucio Lazzarino 2, 56122 Pisa, Italy*
[2]AAVID Thermalloy, Via del Fonditore, 4, 40138, Bologna, Italy
[3]University of Naples Federico II, P.le Tecchio, 840, 80125, Naples, Italy
[4]*School of Computing, Engineering and Mathematics, University of Brighton, Lewes Rd, Brighton BN2 4AT, United Kingdom*

Abstract
This work presents the results obtained by a large diameter Pulsating Heat Pipe tested both on board a sounding rocket in March 2017 and on ground. During the flight, the PHP is tested exclusively at 200 W, while on ground several combinations of heat power input and inclination are tried. Since no steady state occurred on board the rocket, the comparison between flight and ground data focuses on the startup phenomenon, whereas the thorough ground test campaign describes the limits and performances of the device working in thermosyphon mode. The expected outcome of the Space PHP behavior is between that of a purely conductive tube and that of a gravity assisted thermosiphon. The obtained results, instead, evidence a favorable difference in the Space PHP thermal response with respect to any kind of ground test. Important innovations, as the employment of Fiber Bragg Grating sensors, allowed an easier integration of a high number of sensors for the temperature data acquisition with respect to conventional thermocouples.

Keywords: Pulsating Heat Pipe; Space; Sounding rocket; Start-up.

[426] –PS2_8

Effect of Water Based CuO nanofluid on Startup Mechanism and Thermal Performance of a Closed Loop Pulsating Heat Pipe

Vipul M. Patel[1*], Telli Srinivasa Rao[2] and Hemantkumar B. Mehta[3]
[1*]*Research Scholar,* [2]*Research Student,* [3]*Assistant Professor*
Mechanical Department, Sardar Vallabhbhai National Institute of Technology,
Surat-395007, Gujarat, India.

Abstract
Efficient working fluid is a significant parameter for the effective performance of pulsating heat pipe. Nanofluids can be a potential substitution for conventional fluids in heat transfer field because of improved thermal conductivity. The paper presents the effect of water-based CuO nanofluid on a 3-turn closed loop pulsating heat pipe (CLPHP) with 2 mm diameter at different %vol/vol concentrations and heat input. The start-up mechanism and thermal performance were investigated. The commercially available CuO nanoparticles (spherical 30-50 nm size) were used and DI water based CuO nanofluids were prepared in the laboratory using Sodium Dodecyl Sulphate (SDS, NaC12H25SO4) as a surfactant. Filling ratio (FR) of 50% with bottom heating mode was kept constant throughout the experiment. Heat input of 10W-70W was applied in gradual steps of 10 W. Clogging of the capillary was observed at 1% concentration of CuO-water nanofluid. Hence, present study was carried out for 0.05%, 0.07%, 0.1%, 0.3% and 0.5% concentration nanofluids only. The CLPHP with nanofluids of 0.05%, 0.07% and 0.1% concentrations showed better start-up mechanism and thermal performance as compared to DI water due to improved heat transfer characteristics. The CLPHP with nanofluids of 0.3% and 0.5% concentrations showed delayed start-up mechanism and poor performance as compared to DI water due to higher viscosity.

Keywords: Pulsating heat pipe; Startup mechanism; Thermal performance; Clogging problem; Water based CuO nanofluid;

[50] –PS2_9

Experimental investigation of horizontal and slightly inclined closed two-phase thermosyphons and heat pipes for solar façade integration

Katharina Morawietz*, Theresa Paul and Lena Schnabel

Fraunhofer Institute of Solar Energy Systems ISE, 79110 Freiburg, Germany

Abstract

The reliable and efficient operation of closed two-phase thermosyphons and heat pipes under various inclination angles is a key factor for the broad solar thermal activation of building façades. However, state-of-the-art standard heat pipe collectors only operate successfully at a certain minimum inclination. Therefore, one major challenge of solar façade integration is the investigation and development of closed two-phase thermosyphons and heat pipes for flexible, also horizontal orientation. In this work, three different types of heat pipes and tow-phase thermosyphons are investigated regarding their heat transfer limits under horizontal orientation or slight inclination: two commercial standard solar two-phase thermosyphons comprising low fill rates, a commercial mesh heat pipe and two two-phase thermosyphons comprising high fill rates (30 and 50 vol-%). Results indicate that for the commercial standard solar two-phase thermosyphons and the commercial mesh heat pipe solar power can only be gained by elevating the operating temperature or the inclination angle clearly above horizontal. The results for the two-phase thermosyphons comprising high fill rates indicate a good potential at horizontal orientation. However, due to high degrees of non-condensable gases (fabrication defects and leakage problems) the repetition of tests is required to make a clear statement.

Keywords: Two-phase thermosyphon; Heat pipe; Heat transfer limit; Horizontal operation; Solar façade integration.

[166] –PS2_10

Impact of graphene oxide addition to the working fluid on thermal behavior of the thermosyphon

Agnieszka Wlaźlak[1], Bartosz Zajączkowski[1*], Michał Woluntarski[2] and Matthias H. Buschmann[3]
[1]*Wrocław University of Science and Technology, Wroclaw, 50-370, Poland*
[2]*Institute of Electronics Materials Technology, Warsaw 01-919, Poland*
[3]*Institut für Luft- und Kältetechnik, Dresden 01309, Germany*

Abstract
In recent years, graphene has gained increasing interest due to its reported unique properties, but its application in heat transfer area is still in an initial stage. Graphene oxide used in the presented research was synthesized from graphite using a modified Hummers method. GO-water nanofluids with and without surfactant addition (sodium dodecyl sulfate) were experimentally tested as working fluid in the thermosyphon. Their influence on thermal parameters of the device and how their deposition into layer affects the results were described and compared with water and surfactant solution. As the high-resolution measurement system was employed, the so-called geyser boiling phenomenon was investigated. This is a kind of instantaneous boiling where the working fluid assembled above an appearing bubble is pushed to the condenser section without previous evaporation. Finally, particles remained in the working fluid after the experiment were examined with a scanning electron microscope. In a brief summary, nanofluids have potential to become reliable high-efficient heat transfer fluids. However, many parameters such as the type of nanoparticles, their concentration, and the type of surfactant must be considered with regards to the particular application.

Keywords: Nanofluids; Thermosyphon; Graphene oxide; Surfactant; Heat transfer fluid; Thermal resistance.

[196] –PS2_11

Quick Estimation of the Maximum Filling Ratio of Closed Two-Phase Thermosyphons

How Ming Lee[1*], Pei-Chen Li[2], Kuo-Chao Liang[2] and Heng-Yi Li[1]

1 *Physics Division, Institute, Nuclear Energy Research, Longtan District, Taoyuan City 32546, Taiwan*
2 *Chemical Engineering Division, Institute, Nuclear Energy Research, Longtan District, Taoyuan City 32546, Taiwan*

Abstract
The initial filling ratio of the working fluid is one of important factor in design and operation for a closed two-phase thermosyphon (CTPT). CTPTs have been extensively studied experimentally and numerically. However, most models involving tens variables and dozens equations, are too complicated to quickly find a solution. A fast estimation of the initial filling ratio is helpful in focusing the studying target and narrowing the testing range, which can shorten the R&D time. This study hence tried to find a simple and quick calculation for rough estimation of the maximum initial filling ratio. The method was simply based on the mass balance. Two cases were studied for Cu/H_2O CTPT with various sizes. The maximum initial filling ratios calculated generally ranged from 0.5 to 0.6. Although the maximum initial filling ratio estimated in this study were not all agreed with literatures' data. Authors think that the simple mass balance approach could be used for fast estimation of an initial filling ratio. Further experimental tests are still needed to determine the exact initial filling ratio.

Keywords: Filling ratio; Closed two-phase thermosyphons; Maximum heat capacity; Heat pipes; Mass and energy balance

[287] –PS2_12

Heat transfer characteristics of thermosyphon heat exchanger for cooling electrical cabinet

Feng Zhou[1,2], Guoyuan Ma[1,2*], Zhongliang Liu[1,2], Fuping Li[3] and Xianghui Yan[1,2]

[1]*College of Environmental and Energy Engineering, Beijing University of Technology, Beijing 100124, China*

[2]*The Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Ministry of Education of China, China*

[3]*College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing 100124, China*

Abstract

A thermosyphon heat exchanger was applied to an electrical cabinet for its unique characteristics. An experiment was conducted to investigate heat dissipation performance under various working fluids heat transfer rates, and ambient temperatures. The results indicate that Merit Number decreases with the increase of ambient temperature and that R152a performs the best out of three working fluids. The steady-state temperatures of working fluids are sorted from low to high: R22, R152a, R134a. The steady-state temperature increases by about 5℃ while ambient temperature rises by 5℃. In general, R152a and R22 show better performance than R134a. In particular, R152a has a wider temperature range because of its Merit Number adjusts smoothly with ambient temperature and its highest average level. Lastly, the Energy Efficiency Ratio (EER) of the thermosyphon heat exchanger is 2-3 times greater than air conditioner and the cost is only a third to half the price of air conditioner.

Keywords: Thermosyphon heat exchanger; Heat transfer characteristic; Electrical cabinet; Working fluid

[288] –PS2_13

Effect of filling ratios on thermal performance of two-phase closed thermosyphon at different inclination angles

Yeong Hwan Kim[1,2], Dong Hwan Shin[1], Jin Sub Kim[1], Seung M. You[3] and Jungho Lee[1*]

[1]*Department of Energy Conservation Systems, Korea Institute of Machinery and Materials, Daejeon, 34103, Republic of Korea*

[2]*Department of Mechanical, Engineering, Graduate School, Inje University, Gimhae, 50834, Republic of Korea*

[3]*Mechanical Engineering Department, University of Texas at Dallas, 800 W. Campbell Rd., Richardson, TX75080, USA*

Abstract

The effects of filling ratio on thermal performance of two-phase closed thermosyphon are experimentally investigated at the different inclination angles. The thermosyphon consists of evaporator, adiabatic and condenser sections which are 300, 300, 325 mm long, respectively. Distilled water is used as working fluid after degassed process. The amount of working fluid based on the volume of evaporator section, and the degree of inclination angles were used as major experimental parameters. The thermal performance was measured at the heat flux ranging from 10 to 300 kW/m^2. The wall temperature and internal temperatures at nine different points of the thermosyphon were measured to determine the overall thermal resistance. In this study, the thermosyphon with the filling ratio of 0.5 showed the best thermal performance. It is observed that partial dry out and decrease of condensation area occurred at the filling ratios of 0.25 and 0.75, respectively. Both boiling and condensation heat transfer are affected by the flow behavior which is originated at the evaporator section and the liquid fluctuation is associated with the thermal performance of the two-phase closed thermosyphon.

Keywords: Two-phase closed thermosyphon; Heat transfer coefficient; Filling ratio; Inclination angle

[317] –PS2_14

Numerical Investigation on Thermal Performance of Two Phase Closed Thermosyphon

Sachin B. Shinde, Vishal G. Trambadia, Manish K. Rathod

Mechanical Engineer Department of Mechanical Engineering, S.V. National Institute of Technology, Surat 395 007, India

Abstract

In the present work, the performance of thermosyphon in terms of temperature distribution and thermal resistance is investigated for different inclination angle, heat input and fill ratio (FR) with water as working fluid. Computational Fluid Dynamic (CFD) analysis of a two phase close thermosyphon in 2D considering mass transfer time relaxation parameter based on density ratio is carried out. The volume of the fluid (VOF) model in ANSYS FLUENT is used for the simulation. The CFD predicted temperature profile and thermal resistance in the thermosyphon is compared with experimental results. The effect of different heat input varies from 200W to 400W on thermal performance of thermosyphon at different fill ratio (50%, 70%, 83.5% and 95%) and at different inclined position (10°, 30°, 45°, 60° and 90°) of heat pipe is established. The results show that at low fill ratio and low inclination angle, there is a significant increase in the evaporator temperature. Further, higher fill ratio and vertical orientation produces the lowest thermal resistance for all the given heat input. As heat input increases, the effect of the fill ratio and inclination angle becomes more significant.

Keywords: Two phase close thermosyphon; Heat pipe; Fill Ratio; Inclination Angle.

[365] –PS2_15

Surfactant effect in the thermal performance of a two-phase thermosyphon using Al_2O_3 nanofluid

Karen Cacua[1,2], Robison Buitrago-Sierra[1] , Bernardo Herrera[1,2], Anderson Gallego[1] and Elizabeth Pabón[2]
[1] *Faculty of Engineering, Instituto Tecnológico Metropolitano, Calle 54 A No. 30-01, Medellín, Colombia*
[2] *Faculty of Sciences, Universidad Nacional de Colombia, Calle 59A 63-20, Medellín, Colombia*
[2] *Faculty of Mines, Universidad Nacional de Colombia, Calle 80 No. 65-223, Medellín, Colombia*

Abstract
An experimental study was carried out to evaluate the effect of surfactant addition on the nanoparticles dispersion during nanofluids preparation, on the thermal performance of a two-phase closed thermosyphon (TPCT) after operation cycles. Al_2O_3 (0.1 wt.%) based nanofluids with different concentrations of SDBS (0.032 wt.% and 0.064 wt.%) were prepared via two-step method. Stability after nanofluids preparation was evaluated using visual inspection, UV-spectroscopy and dynamic light scattering (DLS). Nanofluids with and without surfactant were used as working fluid in a glass TPCT. Results show that the TPCT thermal efficiency was increased up to 10% respect to water by the presence

of nanoparticles and surfactant. A dried limit with water as working fluid was observed and fluid expansion was identified with surfactant presence. Differences in thermal efficiency and temperature profiles using nanofluids with and without surfactant and only surfactant-water as working fluids in TPCT were not significative. However, in evaporator zone, a slight increase of the thermal resistance was identified when surfactant was added. After TPCT operation with nanofluids, nanoparticles agglomeration and sedimentation were observed and a porous layer in the evaporator surface was identified.

Keywords: Thermosyphon; Nanofluid stability; Thermal performance; Porous layer.

[375] –PS2_16

Concentric Annular Thermosyphon for Passive Cooling System of Spent Fuel Pool

Jongsoo Kim

Dept. of Refrigeration and Air Conditioning, Pukyoung National University, 365 Sinseonro, Namgu, Busan, Korea

Tel: +82-51-629-6176, E-mail: jskim@pknu.ac.kr

Abstract

Since the Fukushima accident, safety issues about spent fuel pool (SFP) have been raised. The current cooling systems of SFP cannot be used to an accident such as a blackout. Hence, lots of attempts to develop passive cooling systems of SFP have been made, and heat pipes can be used effectively to develop a new passive cooling system of SFP. There are lots of previous studies to apply heat pipe to passive cooling systems of SFP. An annular thermosyphon is similar to a conventional thermosyphon except that the cross section of the pipe is annular instead of circular. Its heat transfer area of evaporator section can be increased significantly without increasing the outer diameter of a pipe. Also, it has enhanced heat transfer coefficients. Hence, applying an annular thermosyphon to the SFP passive cooling system is more efficient. In this study a new passive cooling system of SFP with annular thermosiphon was designed, and experiments were conducted to optimize the thermal performance of the thermosyphon. Using R-134a as working fluid, we measured the temperatures of the evaporator section and the condenser section of the thermosyphon by changing the charging ratio and the air velocity of condenser side. And the measured heat transfer rate of thermosyphon at temperatures of 60℃ and 82℃ in case of an emergency. The result of experiments show that the optimal charging ratio is 65%, and that heat transfer rate increases as air velocity increases. Furthermore, heat transfer rate increases as water temperature increases.

Keywords: Spent fuel pool, Passive cooling system, Concentric annular thermosyphon

[421] –PS2_17

Advances in the use of Gas-Controlled Heat Pipes in metrology

Andrea Merlone[1*], Graziano Coppa[1], Chiara Musacchio[1], Fabio Bertiglia[1], Luigi Iacomini[1], Helen McEvoy[2], Graham Machin[2], Jonathan Pearce[2], Stephan Krenek[3], Steffen Rudtsch[3], Eric Georgin[4], Jacques-O. Favreau[4]

[1]*Istituto Nazionale di ricerca Metrologica (INRiM), Torino, 10135, Italy*

[2]*National Physical Laboratory, Teddington, TW11 0LW, United Kingdom*

[3]*Physikalisch-Technische Bundesanstalt (PTB, Berlin, 10587, Germany*

[4]*Centre Technique des Industries Aérauliques et Thermiques, Villeurbanne, 69603, France*

** Corresponding author*

Abstract

Gas-Controlled Heat Pipes (GCHPs) are studied, designed, manufactured and used in metrology, for thermodynamics studies and for sensor calibrations. Several different models of GCHPs have been made in different materials, filled with different working fluids and optimized for different temperature ranges. The wide scientific and technical applications cover different aspects such as vapour/pressure curves studies for pure elements and substances, innovative temperature standards, temperature sensors, calibration facilities, accurate pressure controllers, availability of stable and uniform enclosures, black bodies. Since the first models of GCHP made by JRC at Ispra their capabilities have been constantly improved during the years, in terms of temperature stability and uniformity, heat and pressure control, variety of fluids used. GCHPs filled with different working fluids, thus operating at different temperature ranges, have been connected to the same pressure line in the so called "Temperature Amplifier" configuration. Others have been used to link contact thermometry to radiation thermometry while others are constantly used for calibration of platinum thermometers and thermocouples between -30 °C and 1000 °C. This paper reports on the advances in various use of heat pipes in metrology, from several different National Institutes of Metrology who have adopted this technology for primary and secondary laboratories.

Keywords: Temperature Metrology, Gas-Controlled Heat Pipes, Temperature Amplifier, Calibrations

[29] –PS2_18

Experimental assessment of pump-assisted loop heat pipes

Salvatore Vasta[1], Valeria Palomba[1] and Davide La Rosa[1]

[1]*CNR Institute for Advanced Energy Technologies (ITAE), Messina, 98126, Italy*

Abstract

In the present work, a test set-up for the experimental assessment of heat pipes operating in a loop configuration is presented. Key feature of the system is the use of a pump for liquids for the transport of the condensate, thus distinguishing from the vast majority of commercial or research-grade heat pipes, which employ gravity or capillary action for liquid transport. The set-up is equipped with high-accuracy sensors and allows continuous operation. Results of an experimental campaign realised with R600 as refrigerant inside the heat pipes are reported as well, highlighting the possibility of transferring heat even without the pump when a threshold pressure difference between condenser and evaporator is reached. The examined system was able to transfer up to 2 kW under the selected boundary conditions. At the same time, the flexibility of the presented set-up was successfully proved.

Keywords: Butane; R600; Design of heat pipes; Two-Phases Loop; Pump-assisted heat pipes; loop heat pipes;

[88] –PS2_19

Experimental investigation on start-up and heat transfer performance of gravity-actuated separate heat pipe

Qiao Yan[1,2], Li Jia[1,2*]

[1] *Institute of Thermal Engineering, School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, China*

[2] *Beijing Key Laboratory of Flow and Heat Transfer of Phase Changing in Micro and Small Scale, Beijing 100044, China*

Abstract

In this paper, the startup and heat transfer characteristics of a gravity-actuated separate heat pipe (GASHP) system were experimentally investigated, including its evaporator section. Two aluminum microchannel evaporators with different channel length were studied and the charging ratio involved in this paper was mainly 60%. The results showed that the heat load on evaporator, the air temperature and air velocity flowing over condenser had significant influences

on the startup characteristics, stability of operation and heat transfer performance. According to the features of startup process, it was divided into three stages. It found that there existed entrainment phenomenon at lower heat loads, which led to a temporary fluctuation of pressure difference between evaporator and condenser, and this effect would be weakened at higher heat loads. The comparison of the two evaporators indicated that the channel length had an important effect on heat transfer, which was mainly caused by the different vapor quality within the channels.

Keywords: GASHP; Microchannel evaporator; Startup characteristic; Pressure fluctuation; Heat transfer; Vapor quality

[162] –PS2_20

Frozen start-up performance of a novel flat plate heat pipe receiver used in solar power tower plant

Ruiwen Zhou[1], Xiang Ling[1*] , Wenyu Li[1] and Lin Yang[1]
[1]*School of Mechanical and Power Engineering, Nanjing Tech University, No.30 Puzhu South Road, Nanjing, 211816, China*

Abstract
A novel flat plate heat pipe receiver (FPHPR) is proposed for solar power tower plant which is run under the condition of non-uniform, non-steady sate and high density of heat flux. The structure of the receiver was designed and the experimental system used to simulate the actual solar radiation was constructed. The start-up characteristics of the novel FPHPR were test and analyzed. In addition, the heat transfer limits such as entrainment and sonic limit usually encountered during start-up process were discussed. The comparisons of thermal performance between initial and successive frozen start up process were conducted. The results show that the novel FPHPR could start up normally by one side heating and the non-heated surface has good isothermal performance. Heat transfer limits are not encountered during start-up process. FPHPR could successively succeed to start-up from frozen state and rapidly reach the working state. Based on these studies, guidelines of the utilization of the novel FPHPR in solar power tower plant are provided.
Keywords: Solar energy; Flat plate heat pipe receiver; Start-up performance; Heat transfer limits.

[220] –PS2_21

A theoretical investigation of a controlled hybrid mechanical/capillary pumped loop

Marie Levêque[12*], Sébastien Dutour[1], Marc Miscevic[1], Pascal Lavieille[1], Yves Bertin[3], Raphaël Mari[24]
[1]*University of Toulouse, UPS, LAPLACE, 31062, Toulouse cedex 9, France*
[2]*IRT-saint Exupéry, 3 rue Tarfaya - CS 34436, 31405 Toulouse cedex 4, France*
[3]*Institut PPRIME (UPR CNRS 3346), ISAE-ENSMA, 1 av. Clément Ader-BP40109, 86961 Futuroscope-Chasseneuil, France*
[4]*Airbus Defence and space, 31 rue des Cosmonautes, 31400 Toulouse, France*

Abstract
A series hybrid mechanical/CPL system is a way to improve the performance characteristics over a plain CPL system, as demonstrated by Schweickart et al [1]. However, few hybrid loops actually operate because the control of the system remains difficult. An investigation of a controlled hybrid CPL is proposed based on a dynamic model, consisting of the coupling of a CPL model and a mechanical pump whose speed is controlled by a PID. We first theoretically determined the controller parameters versus the CPL characteristics in order to optimize the command for a given CPL. In a second part, some simulations of two different architectures were performed and analyzed. These results have confirmed that the hybrid system is very attractive to greatly improve the CPL performance.

Keywords: Hybrid Capillary Pumped Loop; Mechanical pumping; Non-linear modelling and control.

[333] –PS2_22

Effect of sink temperature on the stability of the pressure-controlled loop heat pipe

Wukchul Joung[1] and Joohyun Lee[1]
[1] *Korea Research Institute of Standards and Science, 267 Gajeong-ro, Yuseong-gu, Daejeon 34113, Korea*

Abstract

Recently, a novel temperature control technique utilizing the unique thermo-hydraulic operating principles of the pressure-controlled loop heat pipes (PCLHPs) was proposed and proved its effectiveness, by which a faster and more stable temperature control was possible by means of the pressure control. However, due to its recent emergence, the proposed hydraulic temperature control technique has not been fully characterized in terms of the various operating parameters including the sink temperature. In this work, the effect of the sink temperature on the LHP-based hydraulic temperature control was investigated to improve the stability of the proposed technique. Start-up characteristics and transient responses of the operating temperatures to different pressure steps and sink temperatures were examined.

Keywords: Pressure-controlled loop heat pipe; Hydraulic temperature control technique; Sink temperature; Stability; Control gas pressure control.

[420] –PS2_23

Water desalination and power cogeneration utilizing heat pipe heat exchanger

Jason Velardo[1*], Jayden Searle[1], Jack Nihill[1], Abhijit Date[1], Aliakbar Akbarzadeh[1]
[1]*School of Engineering, RMIT University, Bundoora, Victoria, 3083, Australia*

Abstract
Energy production in Australia is predominantly achieved with non-renewable sources such as coal and natural gas, with up to 86% of national energy being produced by these processes. Further, access to fresh water is fast becoming an issue in the harsh Australian climate. This paper proposes a novel design capable of producing electrical energy and desalinating water using only waste heat from industrial processes. A finned heat pipe heat exchanger plays an integral role in this process, extracting heat from a low-medium temperature waste heat stream and passing it through a thermoelectric generator and evaporative water desalination unit. Preliminary experimentation on this system showed that different desalination loop configurations played a large role in the desalination ability of the system, however had negligible effect on the thermal to electrical conversion efficiency of the system. When a closed loop system was used, the recovery ratio of the desalination unit reached 4% at the highest waste heat temperature. In the open loop configuration, the recovery ratio was below 1% for all tested inputs. The thermal to electrical conversion efficiency of this system was also measured and a value of about 1.2% was determined for most cases. Thus the ability of this novel system to both produce useful electrical energy and desalinate water was proven.

Keywords: Heat pipe heat exchanger; Heat recovery; Thermoelectric generator; Desalination

[39] –PS2_24

Oscillating Heat Pipe Cooling Technology for Li-Ion Batteries of Future Electric Vehicles

Won-Sik Chung[1], Riguang Chi[1], Seok-Ho Rhi[1*] and Young-Soo Lee[2]
[1]*School of Mechanical Engineering, Chungbuk National University, 1-Chungdae-ro, Seowon-gu, Cheongju, Chungbuk, Korea*
[2]*Thermal Energy System Laboratory, Korea Institute of Energy Research, 152 Gajeong-ro, Yuseong-gu, Daejeon 305-343, KOREA, 82-42-860-3161, Korea*

Abstract
Novel concept design incorporated with oscillating heat pipe (OHP) for Li-ion battery cooling of future electric vehicles (EVs) has been proposed in this paper. The purpose of the present study is to investigate experimentally to design optimum cooling system to remove the heat generated from the 18650 Li-ion batteries using OHP. The OHP used in the present experimental work was made of a copper pipe with an inner diameter of 1 mm and an outer diameter of 2 mm. The temperatures of four points placed in different positions of the OHP and 1 point of the heater were measured. Various variables affect the performance of OHP. Five important variables have been studied such as the effect of tube turns, working fluid, coolant temperature, condenser length, and rotational angle experimentally. The heat supplied was set to 5 W and 10 W for the experiment.
As a result of the experiment, it is confirmed that it has an optimum number of turns for operation. The OHP with 8 to 9 turns showed smooth oscillatory flow behavior with enough cooling performance. Methanol was the most suitable for

the working fluid. The effect on the length of the condenser was minor in terms of the performance, and the temperature variation showed the best performance at 20 °C. At the heat input of 10 W and filling ratio is 15%, the temperature difference between the source and the sink was 31.6 °C and thermal resistance at this condition is 3.16 °C/W.
Keywords: Oscillating heat pipe, Electric Vehicle, Li-ion battery, Heat transfer, Cooling