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Advanced Transport Technologies for NASA Thermal Management/Control Systems

Science Principal Investigator:
Miles Greiner, Professor and Interim Chair, Mechanical Engineering Department
University of Nevada, Reno, 89557, (775) 784-4873, greiner@unr.edu

Submitted by: Dr. Lynn Fenstermaker
Director of Nevada NASA EPSCoR
lynn.fenstermaker@dri.edu
Desert Research Institute
755 E. Flamingo Road
Las Vegas, NV 89119

Nevada System of Higher Education
2601 Enterprise Rd.
Reno, NV 89512
EIN: 88-6000024

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Annual Report
For period: July 1, 2015 to June 30, 2015

Lynn Fenstermaker

Signature: ______________________________________
Dr. Lynn Fenstermaker

Progress Summary

Project Goal and Objectives

The objective of this project is to develop technologies that can be used to design mechanically-pumped two-phase cooling loop in microgravity for NASA Space systems. Specifically, design a system with a ~1-m^2-flat coolant plate whose temperature can be controlled to better than 1 K isothermality with discrete and time-varying heat loads of ~5W/cm^2.

Task Objectives

1. University of Nevada, Reno (UNR), Co-PI and Science-Lead: Miles Greiner, Ph.D.

   Develop a pumped two-phase coolant loop systems to meet these objectives, with specific emphasis on evaporator design (This is a change from the originally-proposed objective which employed single-phase heat transfer).

2. University of Nevada Las Vegas (UNLV), Co-PI: Kwang Kim, Ph.D.

   Dropwise condensation: The objective of this task is to develop a scalable and performance-effective technique for enhancing steam condensation heat transfer rate. In this task, a technique based upon wet chemistry, for promoting dropwise condensation will be studied.

   High-critical-heat flux boiling surfaces: The objective of the research is to establish an experimental framework to utilize porous layers as high-critical-heat flux boiling surfaces.

3. Truckee Meadows Community College (TMCC), Co-PI: Ted Plaggemeyer.

   Develop STEM educational modules bringing NASA challenges and Nevada research solutions to college students.

4. Desert Research Institute (DRI), Co-PI: Curtis Robbins.

   Perform proof of concept experiments that demonstrate the applicability of Nevada research-based solutions for NASA space systems. Mr. Robbins is no longer with DRI, so this objective may change

Accomplishments under these Goals

Work accomplished at UNR includes:

- Two Ph.D. students, Md Shujan Ali and Nishan Pandey were hired and began work in January 2016. In November 2015, Science-Lead Miles Greiner traveled to the Jet Propulsion Laboratory (JPL) to meet and begin collaborations with Eric Sunada and Ben Furst. The originally-proposed work focused on single-phase heat transfer augmentation. As a result of discussions about NASA needs, the focus of the UNR work was changed to pumped two-phase loops. This will allow the lead technical principal investigator and students to develop expertise in a new area of heat transfer. The UNR research group is conducting an extensive literature survey on boiling heat transfer in microgravity. They are also becoming familiar with passive (un-pumped) loop heat pipes, capillary-pumped loops, and their evaporator designs. Finally, they are finding papers on pumped two-phase loops.

- The UNR group is currently reproducing a low-order computational model of a loop heat pipe system published by Siedel *et al.* [1] (Figures 1 and 2). This allows the group to learn about engineering-level models of each component, and how the performance of the system is affected by the performance of each component.
- The students presented their research goal, objectives and current results in a poster that was intended for training undergraduate students. They presented the poster to Mr. Ted Plaggemeyer from TMCC, to support his undergraduate educational module development efforts.
- Mr. Curtis Robbins, who was a co-principal investigator from the Desert Research Institute (DRI), left his position. The UNR PI is working with DRI to identify an appropriate replacement.

Work accomplished at UNLV includes:

- Dropwise condensation: Design and fabrication of the condensation experimental apparatus was conducted. The current state of the design is shown in Figure 3 of the research summary section. The high-visibility flange window seen is currently being constructed. Also, the sensor flange will allow internal ambient temperature and pressure measurements. A vacuum port with valve has also been machined into the flange. An OMEGA PX309-030AV pressure transducer and two TJ36-CPIN-18U-6 thermocouples will be implanted in to obtain pressure and temperature in the chamber. A National Instruments DAQ modular system will be used to measure sensor data.

- High-critical-heat flux boiling surfaces: Based upon our previous boiling research, design and fabrication of the pool boiling apparatus was conducted. The current state of the design is shown in Figure 4 of the research summary section. All necessary material for the boiling chamber has arrived at the lab. Minor machining still needs to be completed and then the parts will be cleaned and assembled.

Work accomplished at TMCC:

- Based on the information provided by UNR, additional literature review is being conducted at TMCC in order to develop introductory modules for members of the Introduction to Engineering (ENGR100) course. This course serves approximately 110 students in five sections each semester. For spring semester 2016, a brief introduction video to heat pipes will be given to 3 of the 5 ENGR sections. As the project progresses, the modules will be refined and expanded to cover more applications.

FUTURE WORK

At UNR

- Complete the loop heat pipe system model, and apply it to a mechanically-pumped two-phase loop.
- Work with Ben Furst and Eric Sunada at JPL, Jentung Ku from NASA Goddard, and Mojib Hasan from NASA Glenn to identify critical technology needs for pumped two phase loops, which will likely involve evaporator design.
- Perform computational fluid dynamics simulations of evaporator operation.
- Design and construct experiments to develop advanced evaporators and other systems.

At UNLV

- Continue to build the experimental setups.
- Study surface-modification techniques for both dropwise condensation and high critical heat flux boiling surfaces.

Research Summary

Introduction

Thermal control of life-support, power electronics, and other systems is a key enabler for a variety of NASA space, air-flight, and monitoring technologies and is the topic of this research. An example system requiring advanced thermal control is the Surface Water Ocean Topography (SWOT) project, which is designed to acquire precise measurements of land hydrology and ocean circulation. The resulting data will help generate a global assessment of surface water resources and detailed ocean process mapping that will ultimately be used for climate modeling. SWOT's instruments have relatively high electronic heat-dissipation (~1 kW) and must be co-located with other components. However, the instrument temperatures must be extremely stable, with a rate of change below 0.05 K/minute. Furthermore this must be accomplished in low-Earth orbit, where the variations of solar insolation and Earth reflectance and emission are large. To put this challenge in perspective, typical spacecraft instruments have temperature stability requirements on the order of 1 K/min, usually achieved by isolating components. Lightweight, compact, low-power and reliable thermal control technologies must be developed and proven to meet these requirements.

NASA thermal control systems typically employ liquid coolant loops that remove heat from heat-generating components and transport it to cooler modules, which either utilize the heat or reject it to space. While NASA currently relies on single-phase coolant loops (in which the liquid does not evaporate as it absorbs heat), phase-change systems (in which the coolant boils as it absorbs heat and condenses when it delivers it) can reduce the size, weight, temperature variations, and pumping power requirements of thermal control systems, without loss of reliability.

Heat pipes, loop heat pipes, and capillary pumped loops are passive phase-change thermal management systems. In each, heat is removed from high temperature external components by the device's evaporator section (that contains a porous wick to deliver cooling liquid to surfaces where it is vaporized). The vapor is transported to a condenser section where heat is absorbed by a cooler component or rejected to space. This condenses the vapor and the resulting liquid returns to the evaporator. Capillary pressure that develops in the evaporator's wick drives the liquid and vapor flows, and no external pumping power is required.

To increase the controllability and reliability of thermal management systems, NASA is considering systems in which a pump is placed in the liquid line. Pumped two-phased loops are currently used in some military, aerospace, and electronics cooling applications. One of the objectives of the current work is to apply them to low-gravity space applications. In some terrestrial applications, as the liquid boils at a surface, the vapor is removed by buoyancy forces and replaced by fresh liquid. However, in low-gravity space environments, buoyancy is not effective. As a result, vapor can build up, insulating the surface from the liquid coolant. At a critically-high surface heat flux, this insulating layer can be sufficiently thick to cause the heated surface to fail or even melt. In pumped two-phase loops, there is some liquid flow over the heated surfaces even when buoyancy is not effective. However, little experimental or computational data exist to characterize flow boiling in low gravity environments, especially within the porous wick structures that are contained in evaporators.

Current UNR Work

Graduate Students: Md Shujan Ali and Nishan Pandey
Faculty: Dr. Miles Greiner, Dr. Hassan Masoud and Dr. Mustafa Hadj-Nacer

Administration

Funding for this work became spendable at UNR on September 23, 2015. Graduate student recruitment began immediately, and two Ph.D. students, Md Shujan Ali and Nishan Pandey were hired in January 2016. During the Fall 2015 Semester, the Principal Investigator (PI) traveled to the Jet Propulsion Laboratory (JPL) to meet with Eric Sunada and Ben Furst. The primary goals of this meeting were to review the proposed work, consider NASA needs, and begin collaboration on the project. The originally-proposed work focused on single phase heat transfer augmentation, with which the PI has extensive experience. However, based on NASA needs, the focus of the UNR work will be changed to pumped two-phase loops. This will allow the principal investigator and students to develop expertise in a new area of heat transfer.

Shortly after the arrival of the Ph.D. students, Professor Hassan Masoud, who is a new UNR assistant professor in the ME Department with expertise in fluid mechanics and transport processes, became a co-principal investigator on the project. Mr. Curtis Robbins, who was a co-principal investigator from the Desert Research Institute (DRI), left his position. The UNR PI is working with DRI to find a replacement.

Technical Work

The graduate students are currently conducting an extensive literature survey on boiling heat transfer in microgravity, loop heat pipes, capillary pumped loops, and evaporator design. They are also constructing a computational model of a loop heat pipe that predicts system performance for a range of heat loads and component designs. These tasks are describe in the next two sections.

Literature Review

Many studies have been conducted in the literature on capillary pumped loop heat pipes (LHPs) [1–7]. Most of these studies were focused on miniature LHPs for electronic applications [1-5, 7]. Fewer investigations have been performed on large scale LHPs or in microgravity condition [8] that can be useful for spacecraft application, and even fewer on mechanically pumped two-phase LHPs.

The evaporator is the most important and critical component of a LHP. Tsai *et al*. [2] constructed a flat plate LHP evaporator for electronics cooling. They used comb-grooves structure in the evaporator and they introduced diversion slug prior to vapor line to sooth the streamlines of vapor and increase the vapor chamber volume. They showed that these modifications have decreased the start action temperature. Crepinsek *et al.* [3] conducted experiments using single and dual flat plate evaporators. For a single evaporator, the temperatures were not affected greatly under stepwise heat load. For dual evaporators, there was a strong interaction between the individual evaporators under asymmetric heat loads that would provide the potential for one evaporator to change another evaporator's boiling conditions. Also, they found that the parallel configuration of the evaporator would be able to handle higher heat load than the series configuration.

The porous wick provides the capillary driving force to circulate the working fluid and to keep the liquid and vapor phases separated. During steady-state operation of a LHP, the sum of pressure drops due to frictional, inertial, and body forces must not exceed maximum capillary pressure of the wick. Choi *et al.* [4] investigated the role of porous wick on the performance of the entire LHP. Their study presented the fabrication and characterization of sintered porous wicks to be employed in LHPs. Their target application was the thermal management of high power density desktop computers, workstations, and servers. The authors showed that the wick function is critical to overall system performance and its characteristic properties, such as effective pore radii, permeability, and effective thermal conductivity should be chosen in an optimized way. The authors also presented several ways to experimentally assess the wick properties. Weibel *et al.* [5] designed integrated nanostructured wicks using carbon nanotube arrays for their relatively small height and high axial conduction characteristics. They found that even if this structure would result in low thermal resistance across the evaporator section, it would suffer from dry-out quicker than the conventional wick structures due to their low permeability. They concluded that interspersing high permeability wicks throughout the nanotube arrays would help to overcome the dry-out problem.

Loop Heat Pipes are complex systems to model due to presence of coupled phenomena at different scales. Launay *et al.* [6] presented an analytical model to predict the steady-state behavior of a LHP by linking its operating temperatures to various fluidic and geometrical parameters. Their approach enables the identification of the physical mechanisms that influence the LHP operating behavior. Seidel *et al.* [1] developed an analytical model to characterize the LHP with a flat plate evaporator. They modelled the system by using energy balance equations in each component of the system with two-dimensional (2D) temperature field in the evaporator. They also conducted sensitivity analysis and concluded that the major parameters influencing the LHP are independent. The results from their model were in a good agreement with the experimental results. Crepinsek *et al.* [7] conducted finite element analysis for different evaporator body materials and found that the use of lower thermal conductivity material will result in less heat leakage to the liquid chamber/reservoir through the body. Thus, the system would be able to handle higher heat fluxes in comparison to the use of higher thermal conductivity materials.

Mizerak *et al.* [8] presented a large-scale (230 cm^2) evaporator design that uses capillary action from a wick to keep the boiling surface wetted. Their objective was to achieve less than 1°C isothermality for discrete 5W/cm heat loads located arbitrarily on the evaporator and to construct a robust and extensive platform for payload cooling under microgravity condition to be used in spacecraft applications. The design that the authors presented was largely theoretical and uncertain. The performance of their design needs to be tested in microgravity condition to validate the design.

Some of studies consider the presence of non-condensable gases (NCGs) as a detrimental factor of the LHP operation [1, 7]. They suggested to use high purity liquids as well as the wick and evaporator body made of high purity materials to reduce the amount of NCGs in the system.

Loop Heat Pipe System Model

This section presents a steady-state analytical model of a capillary-driven LHP, based on the analysis by Siedel *et al.*, 2015 [1]. It models the thermohydraulic behavior of a 2D flat circular evaporator using a Fourier series expansion. Heat transfer in the evaporator wick includes parasitic heat loses to the reservoir and non-condensable gases. This model can be used to determine the relevant system temperatures and mass flow rates for a range of system heat transfer rates and pressures.

Figure 1 shows a schematic of the LHP and its thermal resistance network model. The LHP consists of an evaporator and condenser, as well as vapor and liquid lines. The evaporator consists of an enclosure, a porous wick and a reservoir. Liquid enters the evaporator on its left side at temperature $T_{r,i}$, and flows into the reservoir, which contains both liquid and vapor at temperature T_r. Liquid seeps into the wick, which is assumed to be fully saturated, where it is heated by a source below the evaporator. The liquid reaches its saturation temperature T_v near the lower surface of the wick. Grooves cut into the evaporator body provide open passages for vapor to flow out of the evaporator and into the vapor line. The vapor flows into the right side of a condenser of length L_c, which is in contact with a low temperature sink of temperature T_{sink}. The vapor condenses and after a distance $L_{2\varphi}$ it is saturated. Subcooled liquid leaves the condenser at temperature $T_{c,o}$. It then flows back to the evaporator though the liquid line, where it loosen heat to the surroundings at temperature T_{ext}.

Heat to the evaporator Q_{in} flows to either the wick Q_w or the reservoir body Q_b, so that

$$Q_{in} = Q_w + Q_b \ . \tag{1}$$

A fraction Q_{ev} of Q_w evaporates liquid at the wick-groove interfaces, while the rest is conducted through the wick and liquid to the reservoir, which is known as parasitic heat flux. Q_{ev} is calculated as

$$Q_{ev} = \dot{m} h_{lv} \quad , \tag{2}$$

where h_{lv} is the heat of vaporization and $\dot{m}$ is the liquid mass flow rate. The heat flux Q_b is conducted through the evaporator wall to the reservoir and part of that flux, $Q_{ext,e}$, is transferred by convection to the ambient. The heat transfer rates Q_w, Q_b, Q_{ev}, and $Q_{ext,e}$ are all functions of the reservoir, groove, wick, and evaporator temperatures, T_r, T_v, T_{we}, and T_e, respectively.

There is a contact resistance between the evaporator body and the wick defined as

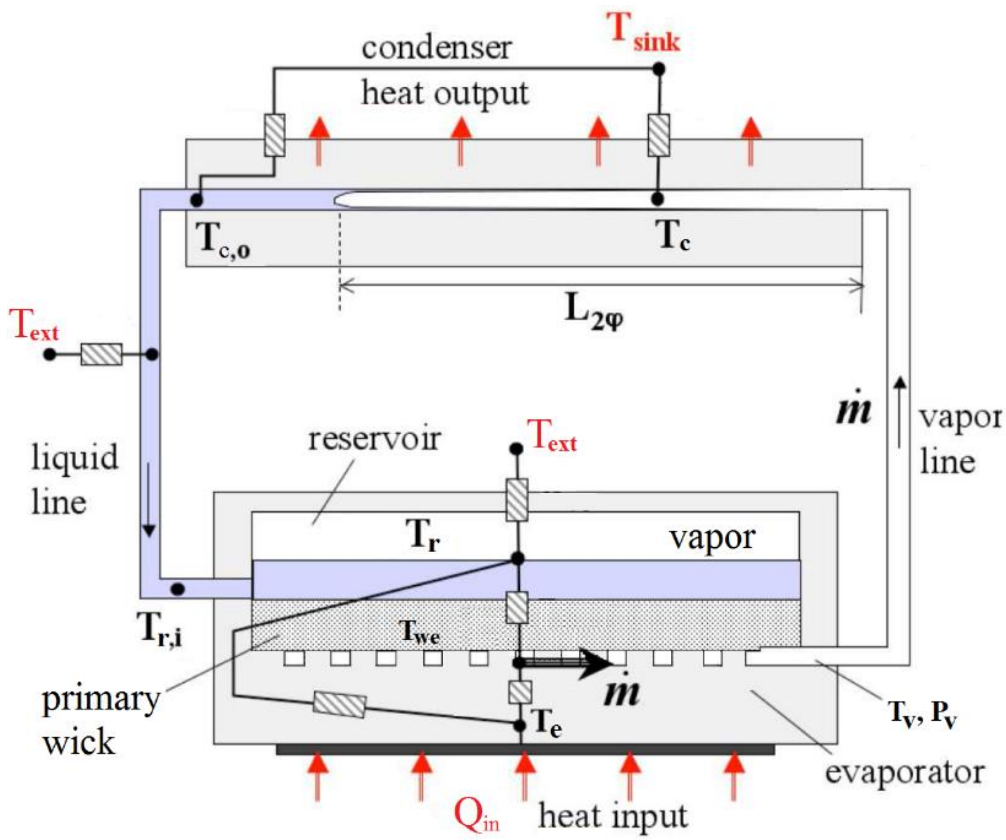

Fig. 1: Schematic of the LHP model [1] and its thermal resistance network [9].

$$R_c = S_c \frac{T_e - T_{we}}{Q_w} \tag{3}$$

where S_c is the contact area between the evaporator envelop and the wick.

That heat input (Q_{in}) to the evaporator may be divided into five components,

$$Q_{in} = Q_{ev} + Q_{sen} + Q_{sub} + Q_{ext,e} + Q_{ext,r} \tag{4}$$

where Q_{sen} is the sensible heat given to the liquid, Q_{sub} is the subcooling due the liquid entering the reservoir, and $Q_{ext,r}$ is the heat flux transferred to the ambient from the reservoir. The expressions for Q_{sen} and Q_{sub} are given as

$$Q_{sen} = \dot{m} c_{pl} (T_v - T_r) \tag{5}$$

$$Q_{sub} = \dot{m} c_{pl} (T_r - T_{r,i}) \tag{6}$$

where $T_{r,i}$ is the temperature of the water entering the reservoir from the condenser and c_{pl} is the specific heat of the liquid. The heat transfer from the reservoir to the ambient is approximated as

$$Q_{ext,r} = h_{ext} S_r (T_r - T_{ext}) \ , \tag{7}$$

assuming the reservoir temperature T_r is uniform. In this expression, h_{ext} is the heat transfer coefficient to the ambient, S_r is the reservoir external area, and T_{ext} is the ambient temperature.

Using a thermodynamic relationship between the saturation temperature inside the grooves and the one at the liquid-vapor interface in the reservoir [6], the difference between the vapor and reservoir temperature is

$$\Delta T = T_v - T_r = \left(\frac{\partial T}{\partial P}\right)(\Delta P_v + \Delta P_l - \rho_l g \Delta H + P^*_{NCG}) \tag{8}$$

where ρ_l is the liquid density, g is the gravity, and ΔH is the elevation of the condenser relative to the evaporator. ΔP_v and ΔP_l are the pressure drops in the liquid and vapor lines, respectively, and P^*_{NCG} is the pressure caused by the non-condensable gases (NCG). The saturation-temperature variation on pressure is obtained from the Clausius-Clapeyron equation

$$\frac{\partial T}{\partial P} = \frac{T_v(1/\rho_v - 1/\rho_l)}{h_{lv}} \tag{9}$$

where ρ_v is the vapor density. The vapor line is considered adiabatic, therefore, the vapor enters the condenser at temperature T_v. The pressure drop due to the elevation of the condenser is small, which allows us to assume that condensation occurs at temperature T_v ($T_c \approx T_v$).

The temperature of the liquid at the outlet of the condenser $T_{c,o}$ is calculated considering a convective heat transfer h_{sink} and h_{ext} as

$$T_{c,o} = T_{sink} + \ (T_v - T_{sink})\ exp\left(\frac{-\pi\big(L_c - L_{2\varphi}\big)}{\dot{m}c_{pl}\big(1/(h_l D_{c,i}) + 1/(h_{sink} D_{c,o})\big)}\right) \tag{10}$$

where T_{sink} is the sink temperature and L_c and $L_{2\varphi}$ are the condenser and the two-phase lengths, respectively. $D_{c,i}$ and $D_{c,o}$ are the inner and outer diameters of the condenser tube and h_l is the heat transfer coefficient between the liquid and the tube wall. Similarly, the heat balance in the liquid line is given by

$$T_{r,i} = T_{ext} + \ \big(T_{c,o} - T_{ext}\big)\ exp\left(\frac{-\pi L_l}{\dot{m}c_{pl}\big(1/(h_l D_{l,i}) + 1/(h_{ext} D_{l,o})\big)}\right) \tag{11}$$

where L_l is the liquid line length and $D_{l,i}$ and $D_{l,o}$ are the inner and outer diameters of the liquid line tube, respectively. The heat exchange with the heat sink in the two-phase zone can be expressed as

$$\dot{m}h_{lv} = \frac{1}{\frac{1}{h_{cond} D_{c,i}} + \frac{1}{h_{sink} D_{c,o}}} \pi L_{2\phi}(T_v - T_{sink}) \tag{12}$$

Table 1. Summary of the constant values used in the calculation of the thermohydraulic behavior of the LHP

Ambient temperature, T_{ext}	*22 °C*
Heat sink temperature, T_{sink}	*22 °C*
Condenser and transport lines i/o diameters	*2/2.4 mm*
Transport line length, L_l	*200 mm*
Condenser length, L_c	*100 mm*
Heat transfer coefficient with the heat sink, h_{sink}	$2000\ W\ m^{-2}\ K^{-1}$
Heat transfer coefficient with the ambient, h_{ext}	$5\ W\ m^{-2}\ K^{-1}$
Heat transfer coefficient with the transport lines, h_l	$1500\ W\ m^{-2}\ K^{-1}$

where h_{cond} is the heat of condensation.

Equations (1-4), (8), and (10-12) represents a set of eight non-linear independent equations with eight unknowns T_{we}, T_e, T_r, $T_{r,in}$, $T_{c,o}$, T_v, m_l, and $L_{2\varphi}$. Solving these equations will lead to the determination of the complete thermal state of the LHP. In the current work, we evaluate the LHP performance assuming the working fluid is water.

Figure 2 shows a plot of temperatures T_e, T_{we}, T_v, T_r, $T_{c,o}$, $T_{r,in}$ as functions of the heat input Q_{in}. These results were generated by solving the set of the non-linear independent equations using MatLab for a range of Q_{in}. Table 1 summarize the values of the different constants used in the calculations.

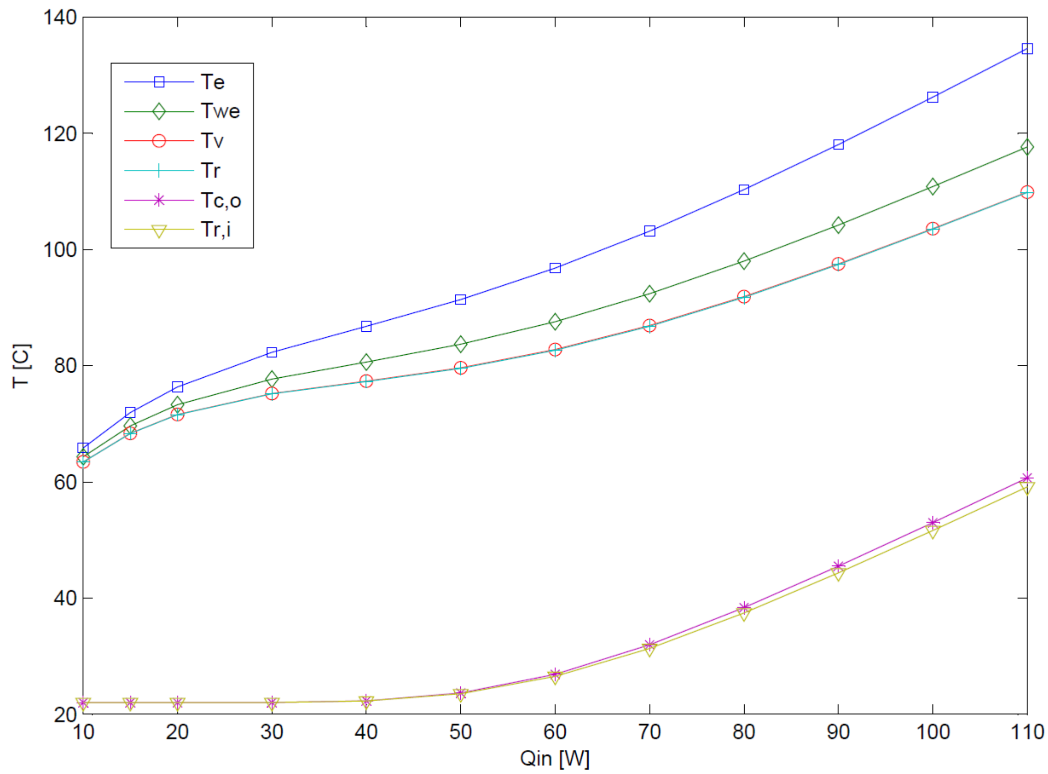

Fig. 2: LHP Temperatures of interest as function of the heat input.

Figure 2 shows that the evaporator temperature increases with Q_{in}. However, the slope is relatively low for Q_{in} < 50, then increases for higher heat inputs. The difference between the evaporator and wick temperatures, T_e and T_{we}, respectively, shows the impact of the thermal resistance (Eq. 3) at the interface between the wick and evaporator envelop. The saturation temperatures in the reservoir and vapor grooves, T_r and T_v are almost equal because of the small pressure drop in the loop (see Eq. 8). Also, the temperature $T_{c,o}$ and $T_{r,i}$ are very close due to very low heat transfer to the ambient.

The analytical model represents a simple solution that can be used to design the LHP without the need of large computational resources. It will allow us also to better understand the thermal behavior of the LHP and the effect of the different parameters.

Current UNLV Work

Introduction

Dropwise condensation occurs when condensate forms in droplets on a surface, as opposed to filmwise condensation when the condensate forms a thermally insulated film. Treating a surface to promote dropwise condensation can improve heat transfer significantly. Khandkar [10] presents a useful review of the state-of-the-art in dropwise condensation research. This work is a continuation of previous research performed at UNLV's Active Materials and Smart Living (AMSL) lab [11]. While previous research focused on quantifying heat transfer coefficients on these surfaces, this work focuses on the visualization of dropwise condensation using high-speed photography. The process will be quantified with image processing and analysis. The results will permit a better understanding of the mechanisms of dropwise condensation, and will give insight into how such mechanisms improve heat transfer when compared to filmwise condensation. The project entails the design and fabrication of an experimental apparatus, preparation of samples with varying hydrophobicity, high-speed footage collection, and an eventual thesis write-up and defense.

Experimental Design

High-speed visualization has been tested in the existing experimental setup outlined in the previous research [11]. In this experiment, dropwise condensation is promoted on a horizontal tube mounted in a condenser chamber. An array of small sight glasses are mounted perpendicular to the sample tube orientation. Light is introduced through one of these sights, while a high-speed camera is mounted outside of another. The condensation characteristic on the tube can be captured at up to 1,000 frames-per-second using this method. However, the small size of the sight-glasses limits both sample illumination and the observable surface area of the sample. It is also desirable to observe condensation characteristics on a flat plate rather than a cylinder.

A separate experimental apparatus has been designed to accomplish high-speed visualization of condensation on a flat plate (Figure 3). Tests on the existing apparatus have informed design decisions that should achieve sufficient illumination and observable surface area of the sample. The apparatus will be supported by a channel strut frame. The chamber is a stainless steel cross-type pipe fitting with 114 mm inner diameter at each of four inlets. Four custom flanges are to be mounted at each inlet to the chamber. One inlet flange is designed to accept a 75 mm copper plug. A 40 mm square plate will be mounted to one side of the plug, while the other side will be cooled by a jet impingement apparatus outside of the chamber. The inlet flange opposite the sample contains a 100 mm custom sight glass. This allows for lighting and high-speed capture. A third inlet flange has vacuum hose and sensor fittings for removing non-condensable gases and measuring ambient conditions. The final inlet flange will be connected to a steam supply line and condensate trap.

There has been significant progress in the fabrication of this design. The channel strut frame and cross-type pipe fitting has been assembled. The design allows for the chamber to be locked at different angles. This has been done so that observations can be made with the sample oriented at different angles with respect to gravity. The flange containing a sight glass is completed and ready for mounting. The flange containing sensor and vacuum hose fittings is currently being machined. The requisite mass flow rates of water for jet impingement and steam supply designs have been modeled. Final adjustments of the sample flange and jet impingement design are underway. Some 40 mm square plate samples have already been prepared using methods outlined by Zhang [12]. Samples of varying hydrophobicity will be prepared and their condensation characteristics compared in the resulting high-speed footage. Image analysis will be applied frame-by-frame, and aspects of droplet growth, coalescence, and drop-off will be analyzed.

Fig. 3: Design (left) and flow-visualization experimental set up (right) for dropwise condensation

High-critical-heat flux boiling surfaces

Introduction

Nucleate pool boiling is an efficient method of transferring heat and is widely used in engineering devices. One of the largest issues occurs when dry spots start to form on the boiling surfaces. This phenomena occurs when the heat flux starts to approach the critical heat flux (CHF). In the beginning, the dry spots are rewetted by surrounding liquids, and this process continues as the heat flux reaches the CHF. Boiling crisis occurs when these localized dry spots start to spread irreversibly – this is a sign that the heat flux has surpassed the CHF. [13] This is an issue because it leads to heat failure and is directly related to safe operation of thermal energy conversion systems [14]. One important perspective of this research is to delay the formation of dry spots to delay the occurrence of boiling crisis by using modified surface structures – specifically through the use of porous layers.

Experimental Design

The design for this research is based on an experimental set up that was used for similar previous research that was conducted. The nucleate pool boiling experimental apparatus (Figure 4) is rectangular in shape and has a stainless steel housing that is 101.6 mm in width, 101.6 mm in height, and 177.8 mm in length. The two ends consist of Teflon PTFE plates that are 152.4 mm in height and length and 12.7 mm in thickness; O-rings are used to seal the boiling chamber. The Teflon plates each have four 9.5 mm holes that are 12.7 mm away from the width and height edges. These holes were machined so that four aluminum rods can be placed through these holes. Eight aluminum hex nuts are used to keep the Teflon plates tight to the stainless steel housing. The top of the stainless steel housing has a hole for a fitting to attach the reflux condenser – the reflux condenser will have be attached to a constant temperature controller. The reflux condenser will be used to condense the vapor formed from boiling. Two stainless steel through-wall sights are used to give the capability to view the sample surface as boiling occurs. One sight glass is attached along the length of the housing, and the second sight glass is attached to the Teflon plate that is on the opposite side of where the sample will be located. The other Teflon plate has a spot for a PTFE fitting that will be used to attach an aluminum alloy test section (specifically, Al 6061) and a thermocouple. [15]

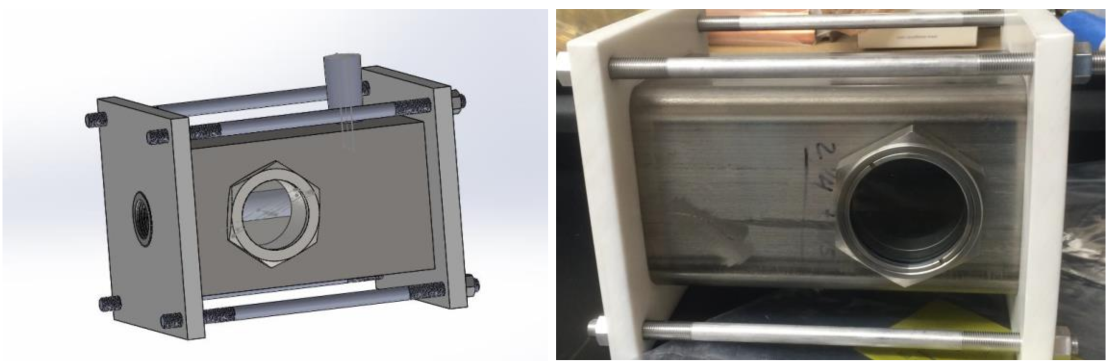

Figure 4: Design (left) and flow-visualization experiment (right) for pool boiling

Additionally, the Al 6061 samples still need to be fabricated for experimentation. A 9.6 mm hole is fabricated in the center for the cartridge heater, and four 2.2 mm holes are fabricated on the top, bottom, left, and right of the sample centered between the inner and outer radii. The four holes are made to fit T-type thermocouples purchased from OMEGA Engineering, INC (Stamford, CT). All of the holes are 63.5 mm deep. The cartridge heater is a 120 V, 400 W high-temperature cartridge heater from McMaster-Carr (Elmhurst, IL). Thermal paste will be used when inserting the thermocouples and cartridge heaters into the Al 6061 sample. [15]

An AC power source will be used to control the amount of power to the cartridge heater and a digital multi-meter will be used to measure the output voltage and current going into the heater.

Furthermore, temperature data will be taken from the T-type thermocouples and a data acquisition system (the specific system is still being determined) will be used to ensure proper data collection. [15]

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Education Office Supporting Information

List of Participants & Collaborations Details

1. Miles Greiner, University of Nevada, Reno, Professor of Mechanical Engineering, Science Principal Investigator
2. Kwang Kim, University of Nevada, Las Vegas, Professor of Mechanical Engineering, Topic Principal Investigator
3. Ted Plaggemeyer, Truckee Meadows Community College, Professor of Engineering, Educational Specialist
4. Hassan Masoud, University of Nevada, Reno, Assistant Professor of Mechanical Engineering, Participant
5. Mustafa Hadj-Nacer, University of Nevada, Reno, Research Scientist, Participant
6. Eric Sunada, Jet Propulsion Laboratory (JPL), Pumped two-phase loop researcher
7. Ben Furst, Jet Propulsion Laboratory (JPL), Pumped two-phase loop researcher
8. Jentung Ku, Goddard Space Flight Center, Pumped two-phase loop researcher

Systemic Jurisdiction Improvements

- Course Improvement:
  - Course name/title: Small Systems
  - Course Number: ME 495/695: Special Topics in Engineering
  - Offering institution: University of Nevada, Las Vegas
  - Brief course abstract: In the past decade the technological advances of small system engineering, namely microelectromechanical systems and nanoelectromechanical systems, have been truly impressive in both space of development and a number of new applications. The objective of this course is to introduce Mechanical Engineering students (Senior Students and/or Entry Level Graduate Students) to the possibilities of this exciting new engineering field. Also, potential engineering applications, such as sensors, actuators, heat exchangers, and chemical/biological analysis systems, will be discussed.
- New non-EPSCoR research grants with detail, Information to include:
  - Funding Entity: UT-Battelle, LLC
  - Award Name/Title: Technical Support for Corrosion Prevention & Control
  - Value of New Grant: $50,000

List of Products, Publications & Recognitions

  - Internet site(s) that disseminates the results of the research activities
    - https://www.youtube.com/watch?v=sRrcsKkdWUQ;
    - Video showing a surface hydrophobicity, etc.

Student Participation

1. Nishan Pandey, Ph.D. graduate student, Mechanical Engineering, Male, UNR
2. Md Shujan Ali, Ph.D. graduate student, Mechanical Engineering, Male, UNR
3. Blake Naccarato, MS graduate student, Mechanical Engineering, Male, UNLV
4. Kevin Yim, MS graduate student, Mechanical Engineering, Male, UNLV