Status of Development of a Thermal Probe for Icy Planet Exploration - II

Calin Tarau[1], Kuan-Lin Lee[2], Brett Leitherer [3], Krishna Chetty[4], Andy Lutz[5] and Srujan Rokkam[6]
Advanced Cooling Technologies, Inc, 1046 New Holland Ave., Lancaster, PA, 17601

To support NASA's future Ocean Worlds Exploration missions, Advanced Cooling Technologies, Inc. (ACT) is developing a thermal management concept for a radioisotope-powered ice melting probe. The concept consists of a series of integrated thermal features for efficient and reliable ice penetration, designed to deliver maximum power fraction for forward ice melting and to mitigate challenges encountered by a melting probe in icy environments. The main thermal features of the ice melting probe are:

1. **Pumped two-phase (P2P) loop to collect waste heat from the cold end of the thermoelectric convertors and to deliver the waste heat to the front vapor chamber with minimal thermal resistance.**
2. **Front vapor chamber to collect the waste heat from the P2P condenser and distribute the heat uniformly to the inner wall of melting front of the probe. The same vapor chamber will deliver heat to the variable conductance sidewall as needed.**
3. **Liquid displacement system to displace water from the sides of the probe to generate thrust for maneuverability and steering.**

Under NASA SBIR funding, ACT is designing, fabricating and testing a lab-scale ice melting probe prototype consisting of the aforementioned thermal features. This paper presents the development status of the P2P loop that includes bench testing results as well as the lab-scale prototype final design and manufacturing strategy before 3D printing. Since the probe could not be assembled by the time when this paper was written, the only experimental results that were included are for the P2P loop lab testing.

Nomenclature

OD	=	Outside Diameter
P	=	Power
TC	=	Thermocouple
R	=	Thermal resistance
T	=	Temperature

I. Introduction

The extraterrestrial ocean [1] worlds within our solar system are the most promising places to look for life or any signs of life beyond our planet Earth. Therefore, NASA, ESA, and other space agencies around the world have shown considerable interest in studying them. One such object of interest is Jupiter's moon Europa. Magnetometer (MAG) data from NASA Jet Propulsion Laboratory's (JPL) Galileo spacecraft indicated that an ocean of liquid water might exist ~30 km underneath Europa's icy surface. Consequently, ocean access became particularly of interest for Europa and other similar missions. One of the techniques to penetrate an icy crust is to use a thermal probe with a heated front. The heated front is supplied with sufficient heat to first overcome a very large degree of ice subcooling

[1] Principal Engineer, Research and Development, 1046 New Holland Ave Building 2, Lancaster, PA 17601.
[2] Lead Engineer, Research and Development, 1046 New Holland Ave Building 2, Lancaster, PA 17601.
[3] Engineer I, Research and Development, 1046 New Holland Ave Building 2, Lancaster, PA 17601.
[4] Engineer II, Research and Development, 1046 New Holland Ave Building 2, Lancaster, PA 17601.
[5] Engineer III, Research and Development, 1046 New Holland Ave Building 2, Lancaster, PA 17601.
[6] Manager, Research and Development, 1046 New Holland Ave Building 2, Lancaster, PA 17601.

and then to melt/sublimate the ice as the probe itself advances in the crust. Several heated front probes have been tested on Earth [2].

Environmental conditions on Europa present a unique set of challenges for the thermal probe, which can be quite different from the challenges encountered on earth. One of the challenges is the low pressure on its surface, which is expected to significantly affect the melting process. As ice gets heated (by the probe front) below the triple point pressure, during the startup, it immediately sublimes after melting. This can lead to a dramatic drop in the melting efficiency of the probe as heat conduction through vapor is poor compared with a liquid film. As the probe advances within the icy crust, environmental pressure around it increases and the ice ceases to directly sublimate. The probe has a thin film of liquid around it during normal operation.

Thermal conductivity of ice, which is strongly dependent on its temperature, also greatly affects the melting process. Thus, another challenge is the high thermal conductivity of it's low-temperature ice ($6.5\ \mathrm{Wm^{-1}K^{-1}}$ at 100 K), which makes the melting process difficult and energy inefficient [3]. Theoretically, a single General Purpose Heat Source (GPHS) module (that typically releases 250W for many years), isolated from the probe, can penetrate the icy layers on Earth or Mars. But on Europa the module would get stuck in the ice with a surface temperature of less than 200 K, just because of the heat that "runs away" from the source not allowing the surrounding ice to reach the melting point. A feasible melting probe for shallow ice on Europa was initially proposed by a group of German researchers [4]. They conducted an energy analysis for a penetration depth of 10 cm (sample size of 7 $\mathrm{cm^3}$) and the results seemed promising.

In order to reduce penetration time of a radio isotope-powered ice melting probe its vertical footprint needs to be minimized and the power fraction used for forward melting needs to be maximized. Advanced Cooling Technologies, Inc. (ACT) is developing a novel thermal management system that can effectively focus the waste heat to the melting front during normal operation and redistribute the heat passively along the side walls during stalling and/or lateral motion.

To date, two papers were published as a result of the current development carried by ACT. The first paper [5] presented the proof of concept demonstration and the results from the Phase I of this SBIR. Starting with Phase II, the development has been published under the form of updates and status of the progress. The first set of updates and status of the development were presented in [6]. The second set of updates and developmental status are presented in the current paper. It consists of a brief presentation of the lab-scale melting probe prototype final design, manufacturing strategies and related challenges, experimental results from the benchtop testing of the pumped two-phase (P2P) loop, and front vapor chamber wick design.

II. Lab-Scale Prototype Final Design and Manufacturing Strategy

The development of the melting probe prototype by ACT has been an incremental process that resulted in the configuration and design presented in this paper. For a better understanding of the probe's functionality, a schematic of principle that describes how heat flows throughout the probe is presented Figure 1. Heat is generated electrically within the two heater blocks (that normally are GPHSs). Each of these heater blocks form a single body with the evaporators of a pumped two-phase loop (P2P). As seen, the P2P transports the heat from the evaporators all the way down to the front of the probe, into the P2P condenser and further into the front vapor chamber. There are two primary modes which the melting probe operates under. The first mode, Normal Operation, shown in Figure 1(a), assumes that the probe advances through the ice without stalling or refreezing of its tail. In this case most of the heat is transferred from the probe to the ice through the front vapor chamber, for forward metlting. The second mode, the Variable Conductance Wall Operation, shown in Figure 1(b), assumes that the probe has difficulties with forward melting. In this case, the thermal resistance between the nose of the probe and the ice increases and, as a consequence, vapor temperature in the vapor chamber increases as well. Therefore, the Non-Condensable Gas (NCG) – vapor front will move upwards along the side walls to melt laterally and release the probe from refreezing conditions or to allow the probe to melt lateraly for lateral motion.

Figure 2 shows an overview of the design that includes a layout of the lab-scale melting probe prototype both internal view in Figure 2(a) and (b) and external view in Figure 2(c). This prototype is intended to demonstrate the four major thermal features, i.e., P2P loop, front vapor chamber, Variable Conductacne Heat Pipe (VCHP) side walls and the steering system. The overall height of the probe is 69.2 cm, probe diameter is 18.4 cm, wall thickness is 0.31 cm and the material is stainless steel. As part of the additive manufacturing (AM) strategy and to have the thermal features inside the probe accessible, the probe is split into two halves called shells, with each shell having its own independent condenser, vapor chamber, VCHP walls and NCG reservoirs. The leak tight sealing between the two shells is provided by a gasket. The NCG reservoir spaces will be closed/sealed using end caps as shown in Figure 2(a).

Each shell has a set of 8 screw bosses for mechanical fastening as shown in Figure 2(b) and only one instrumentation port is present in one of the two probe shells.

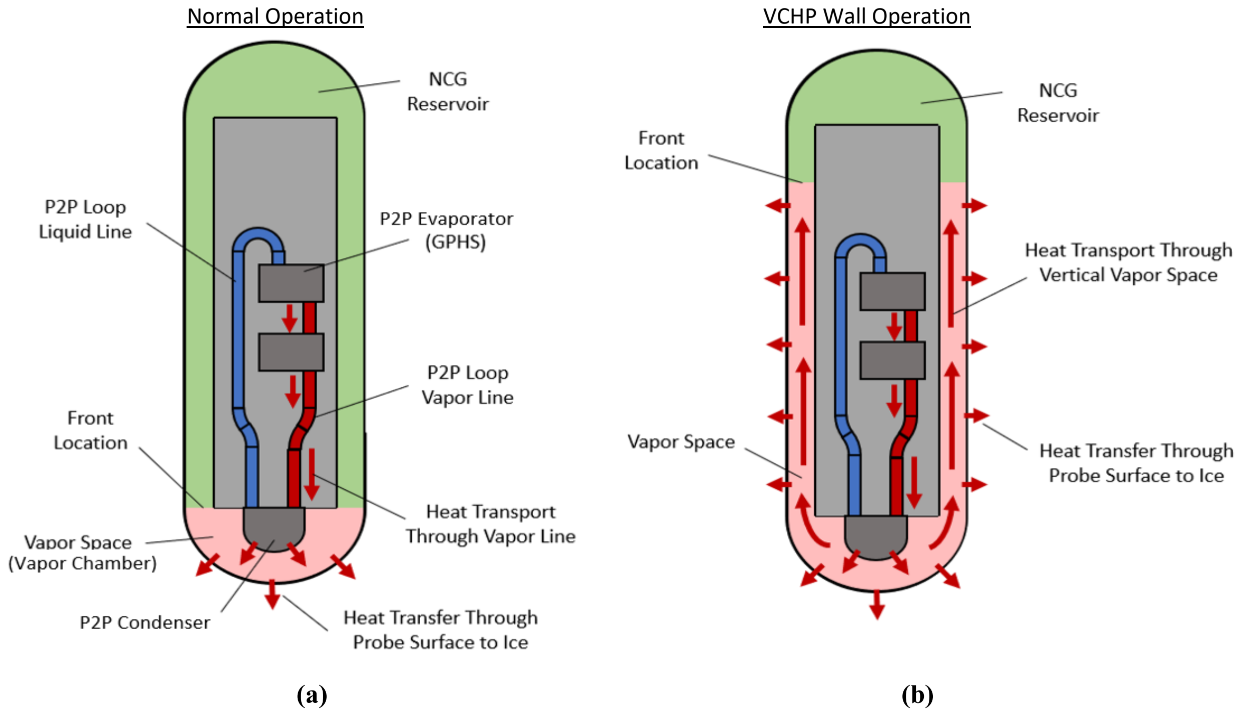


Figure 1: (a) Heat map during normal operating mode with vapor contained in the front vapor chamber and (b) active VCHP wall operating mode with vapor pushing the NCG front up towards the reservoir.

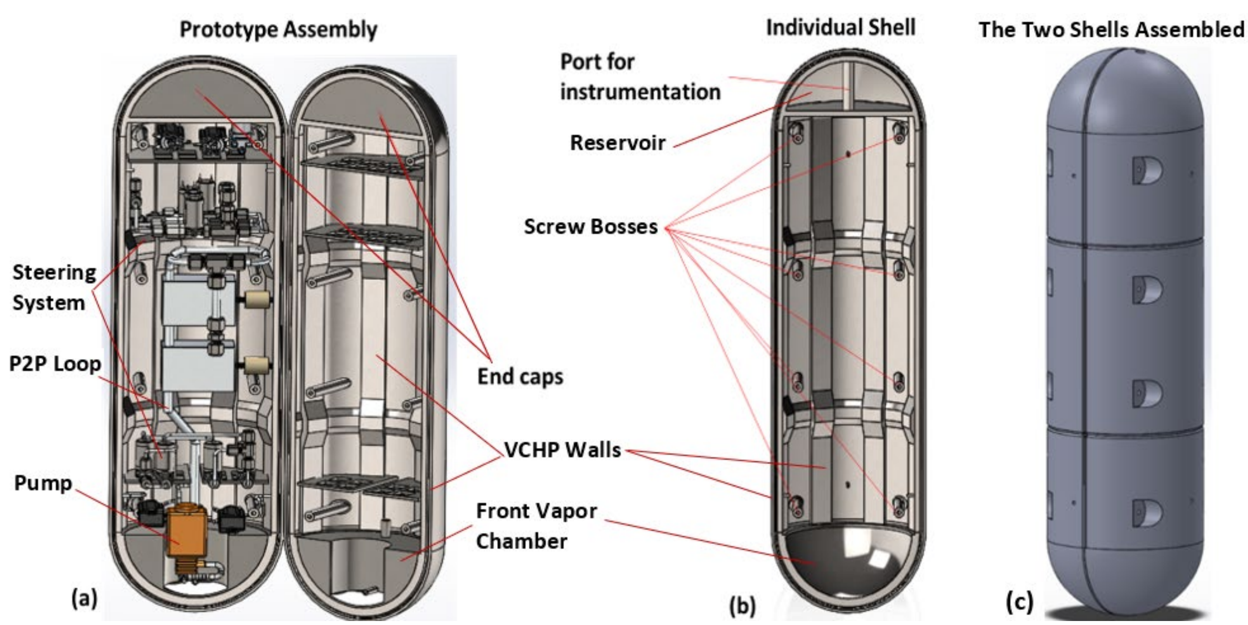
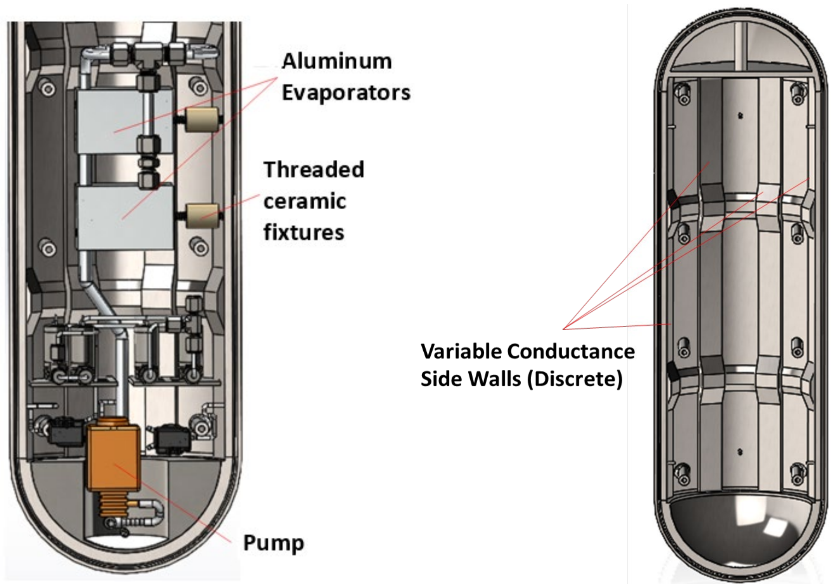


Figure 2: (a) Inside view - CAD model of the full melting probe prototype with P2P loop, front vapor chamber, VCHP walls and liquid displacement (steering) system (b) Inside view of one shell - screw bosses, instrumentation port and VCHP wall are visible (c) Outside view - melting probe prototype with the two shells closed and sealed with a gasket.

As a result of manufacturing strategy of splitting the probe's body in two halves, it was decided that both these halves will share a single P2P loop that will be installed in the center of the probe. However, as seen in Figure 2(a) and Figure 3(a) the single ***P2P loop*** is attached to only one of the halves. As a consequence, the hydraulic connections with the opposite half will be flexible (not shown in figures) and allowing the two halves to open as needed. In this case, the P2P loop has two separate condensers (at the bottom of the two shells) that are embedded within the front vapor chamber.



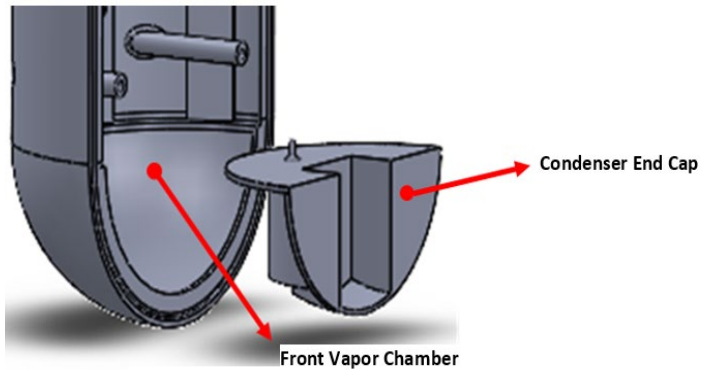
(a) **(b)**

Figure 3: (a) View of the P2P loop inside of one of the two shells of the melting probe prototype (b) Discrete and rectangular VCHP walls embedded within the shell walls of the melting probe prototype

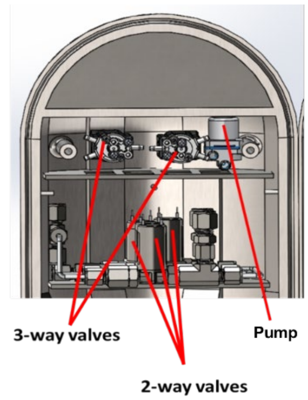
The two P2P loop condensers also play the role of accumulators. The P2P loop will be welded, in house at ACT, to the shell wall where the two P2P evaporators will be supported using threaded ceramic spacers. A liquid metering pump, which is capable of maintaining constant mass flow rate within the P2P loop will be used and is placed at the bottom next to the condenser. The liquid-free surface in the condenser will be determined by the amount of working fluid in the P2P system while the condenser space, surrounding vapor chamber and the pump seat are all located such that the pump inlet is always below the liquid free surface in the condenser.

The ***VCHP walls*** within the melting probe are in the form of discrete tubes and rectangular in cross-section as shown in Figure 3(b). The discrete VCHP tubes connect the vapor chamber at the front to the NCG reservoir at the top of the probe in each of the two probe shells, as opposed to having a continuous annular geometry to reduce lateral heat losses and increase the sensitivity of the NCG front motion/thermal resistance modulation. The thickness of the vapor space for the VCHP rectangular tubes is 0.4 cm and the working fluid for the vapor chamber and VCHP walls is methanol.

Figure 4(a) shows the CAD model of the ***front vapor chamber***. While details in regards to bridges and wick design are presented later in the paper, this figure shows details about the fabrication strategy. As indicated previously, two vapor chambers will be installed in the probe, one in each half/shell. As seen in the figure, the end cap shown in the figure will be 3D printed separately while the vapor chamber cavity will result open after 3D printing for manual wick installation. The initial end cap separation from the vapor chamber cavity is also beneficial for facilitating the connections with the P2P loop. While both the vapor chamber cavity and the end cap are 3D printed, the attachment of the end cap to the chamber will be done by in-house welding.



(a)



(b)

Figure 4: (a) Front vapor chamber space at the bottom of ACT's melting probe prototype (b) Liquid Displacement System (LDS) at the top of the melting probe prototype.

The ***liquid displacement system*** (LDS) feature will enable steering of the probe to enhance the reliability of the mission. There are two LDSs in the current prototype, one at the top and one at the bottom of the probe. Figure 4(b) shows the LDS at the top of the probe and its position right is below the NCG reservoir space. Similarly, the bottom LDS is right above the front vapor chamber of the ice melting probe. The LDS consists of a set of 2-way solenoidal and 3-way valves along with a pump. It is important to note that both LDSs are contained within one of the two probe shells. Both subsystems will be driven by the same pump which is additional to the one for the P2P loop. Also, this pump will be integrated into the system after the first set of testing of the probe in the ice environment at ACT.

ACT plans to use an external vendor to 3D print the melting probe prototype. The total height of the prototype exceeds the 3D printing capabilities, so each half of the probe is divided into three parts or sub-shells as shown in Figure 5. Once the sub-shells are 3D printed, the parts will be winded together in-house at ACT. It can be seen in Figure 5 that there is an additional thickness at the junctions of the sub-shells and its purpose is to enable effective welding of the sub-shells.

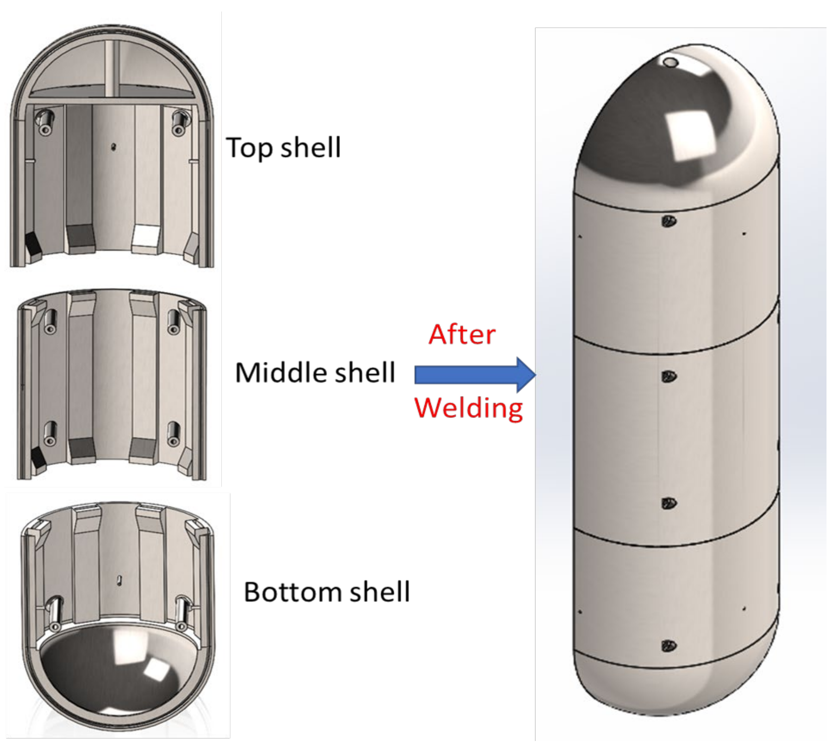


Figure 5: Shell components for fabrication of ice melting probe before and after welding.

III. Pumped 2-Phase Thermal Management System-Benchtop Testing Results

The P2P loop acts as the main thermal bus to transfer waste heat from the thermoelectric cold ends to the melting head of the probe. Previously, two different iterations of the P2P heat delivery system were explored. The first proposed design involved separated two-phase flow evaporators. Previous findings showed this particular configuration produced problematic results. To achieve an improved thermal management system design for the probe, an alternative option was pursued for the second iteration. For this design, the separated two-phase flow evaporators were related with mixed two-phase flow evaporators in series. While this second design improved upon the first, further modifications were necessary to meet the needs of the probe.

This section describes the third iteration developmental activities for the benchtop experimental setup, to demonstrate the design of the P2P loop for the autonomous ice-melting probe. It is important to note that the P2P loop being demonstrated here will be the actual P2P loop that will be integrated into the first porotype of the lab-scale ice-melting probe. The working fluid for this iteration of the P2P loop is acetone as opposed to water and the total power handled by the system will be 800 W compared to 140 W in the second iteration. The new P2P system was fabricated out of aluminum (Al) metal which is compatible with acetone. The P2P was experimentally tested outside first, to characterize its thermal performance, before its integration into the first melting probe prototype. Shown in Figure 6 is the CAD model of the experimental setup for outside testing. The setup consists of two evaporators in series and each evaporator has a set of 4 four serpentine channels in parallel configuration on either side of the Al cold block evaporator. The setup used 0.95 cm outer diameter (O.D.) Al tubes for the main liquid return line from the pump outlet to the first evaporator inlets. For the mixed two-phase flow lines, Al tubes of 0.63 cm O.D. were used. To save space, the condenser also acts as an accumulator. The condenser was placed in a water bath set to 30℃, the temperature of which was regulated using a temperature control unit (TCU). The water inside the condenser bath was recirculated to avoid any temperature gradients. A metering pump was used for the P2P loop to pump the liquid from the condenser outlet all the way to the top manifold from which the liquid acetone is supplied to the first evaporator. Thermocouples (TCs) were attached to the outside surface of the tubes and the evaporator to measure the net ΔT across the loop in a non-intrusive fashion to avoid potential leaks in the P2P system. In addition to the TCs, a pressure transducer was used to measure the pressure in the condenser. The entire P2P operated along the saturation curve and the additional pressure information was directly obtained from the temperature measurements.

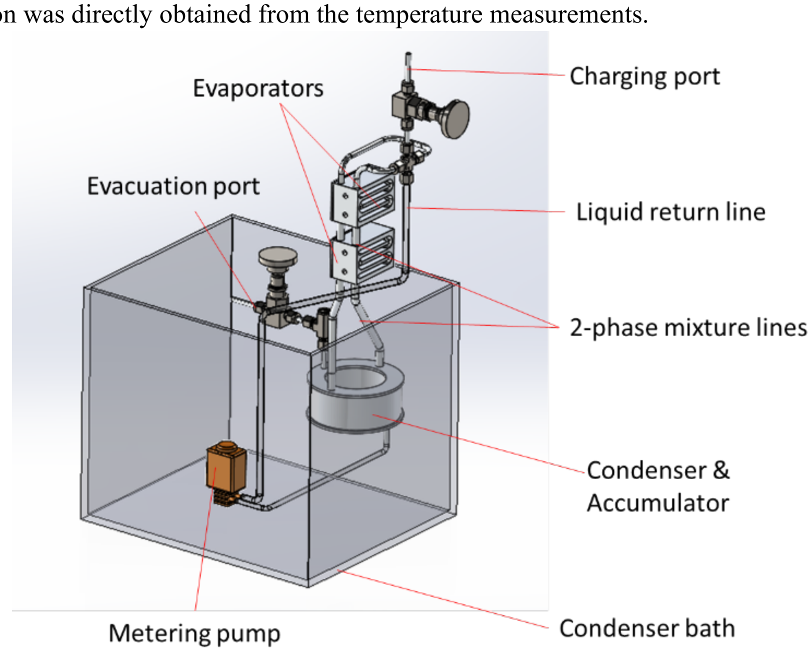


Figure 6: P2P loop with mixed two-phase flow evaporators for 800 W of heat supply.

For designing the P2P loop, pressure drop calculations were performed to determine the net pressure drop, which is dependent on the sizing of the Al tubes, volumetric flow rate of the acetone working fluid, fluid properties, and the total heat supply which is 800 W. Since the P2P loop has mixed two-phase flow, the pressure drop calculations were performed using Homogeneous Equilibrium Model (HEM) [6]. The HEM is based on two major assumptions: (a) both the vapor and the liquid phases are at the saturation temperatures and (b) the vapor and the liquid phases are moving at the same velocity, i.e., no slip between the vapor and the liquid phase. The HEM treats the two-phase flow as a mixture flow and hence offers simplicity. This flow model is derived from the relationship between the mixture mass flux, density, and velocity. Shown below in Figure 7(a) is the pressure distribution in pascals (Pa) within the P2P set up. The total height from the pump outlet to the top liquid manifold is 35.9 cm. As expected, maximum pressure is at the pump outlet and the pressure drop within the P2P loop is dictated by different competing pressure drop mechanisms: frictional, acceleration and hydrostatic pressure drops. Also shown in Figure 7(b) is schematic representation of the pressures at different locations of the proposed P2P system. It is important to note that for the outside testing of this P2P, the Al tubes will be welded to the respective parts. Before inserting this P2P loop into the probe, one of the Al tubes carrying mixed two-phase flow from the second evaporator will be cut and replaced by a flexible of same I.D. to accommodate the shell type architecture of the first melting probe prototype.

P2P Loop - Experimental Testing

The experimental test set up fabricated and used for thermal performance testing of the third iteration of the P2P loop is shown in Figure 8. The entire P2P loop components consisting of two Al evaporators, condenser/accumulator, tubing for the liquid return and vapor flow lines, micro-diaphragm pump, and the cold-water bath were supported using a metal chassis made of Al-6061 rods. Four cartridge heaters were used to provide heat for the evaporator blocks and a variac was used to provide a voltage-adjustable source of alternating current (AC) electricity for the cartridge heaters. Two distinct ports were used along with respective needle valves for the entire P2P loop, one for the evacuation of the P2P loop at the bottom and the other for charging the P2P with the working fluid i.e., acetone, at the top. The P2P condenser was immersed in a water bath contained within a 5-gallon plastic tank for cooling the condenser. A helical copper coil was immersed in the water bath for temperature control of the water by circulating liquid nitrogen (LN) through the coil. To facilitate uniform temperature distribution within the water bath, an immersible circulating pump was used for adequate mixing of the water. The pressure transducer (PT) and the pump were supplied excitation voltage using the same DC supply and an additional voltage supply was used for providing the control signal to the pump to vary the flow rate of the acetone required to carry different power levels efficiently. The entire P2P loop was checked for leaks by first performing a soap-bubble test to resolve any gross leaks and then a helium leak check was performed to arrest any minor leaks present in the P2P loop set up.

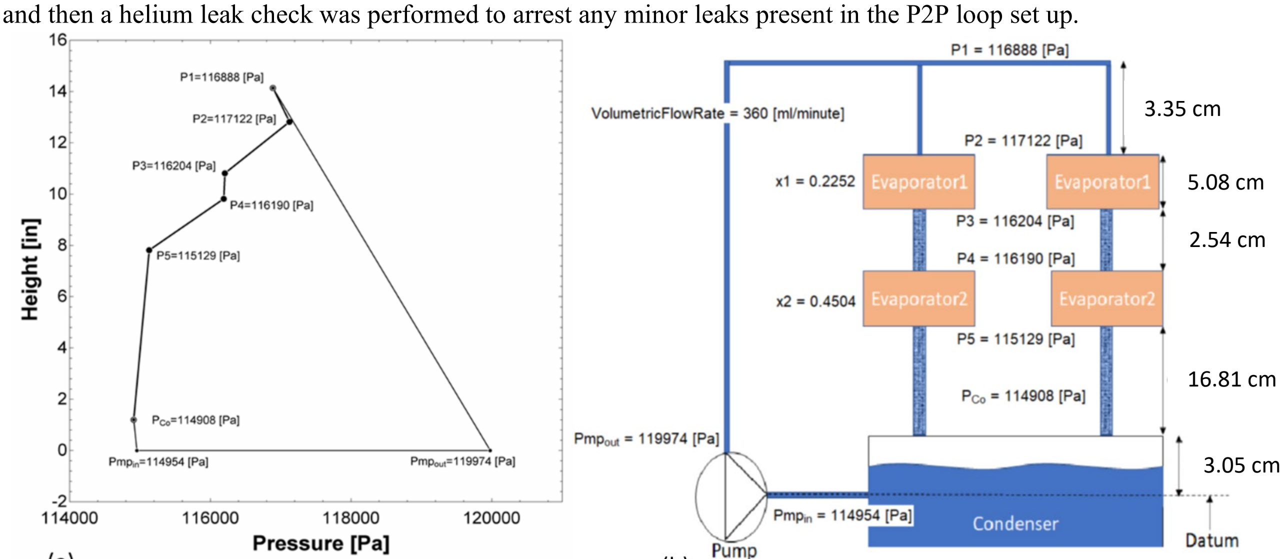


Figure 7: (a) Two-phase pressures drop plot and (b) schematic of the pressure distribution within the 3rd iteration of the P2P loop setup.

The experimental testing was performed to characterize the thermal performance of the P2P loop for different power levels (P) starting from 50 to 800 Watts of waste heat. The initial experimental testing procedure involved increasing the power levels from 50 to 800 Watts while adjusting the volumetric flow rate accordingly to attain 35% average quality within the two evaporators combined. The power levels were increased by 150 Watts once a steady state was reached for each power level. In addition, tests were also performed using the same volumetric flow rate corresponding to 800 Watts for all the power levels starting from 50 Watts. By using T-type thermocouples, the temperatures were recorded for the evaporator surface, across the inlet and outlet of the two evaporators as well as for the condenser surface and the water bath. These temperatures were used to calculate temperature drop $\Delta T(℃) = T_{evaporator\ surface} - T_{condenser}$ to calculate the net effective thermal resistance of the P2P loop as $R_{net}(K/W) = \Delta T/P$.

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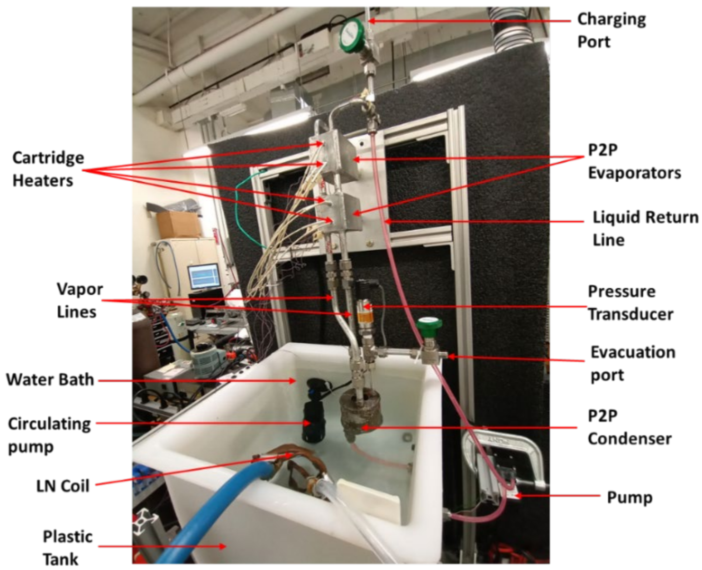


Figure 8: Experimental setup of P2P loop used for thermal performance testing at ACT.

The temperature measurements across the P2P loop for power levels from 50 to 800 Watts using a constant volumetric flow rate corresponding to 800 Watts is shown in Figure 9(a), for power increments of 150 Watts. The water bath was maintained at a constant temperature of 30 ℃ and the P2P system reached a steady state within roughly 20 minutes for each power level. The net temperature drop, $\Delta T(℃)$, across the P2P loop and the thermal resistance R_{net} (K/W) for different power levels are shown in Figure 9(b) and Figure 9(c) respectively. As expected, for increase in the power, the net temperature drop across the P2P loop increases but the thermal resistance decreases. It can be inferred that the average thermal resistance offered by the third iteration of the mixed two-phase flow P2P loop is approximately $R_{net}^{avg} = 0.09\ (K/W)$

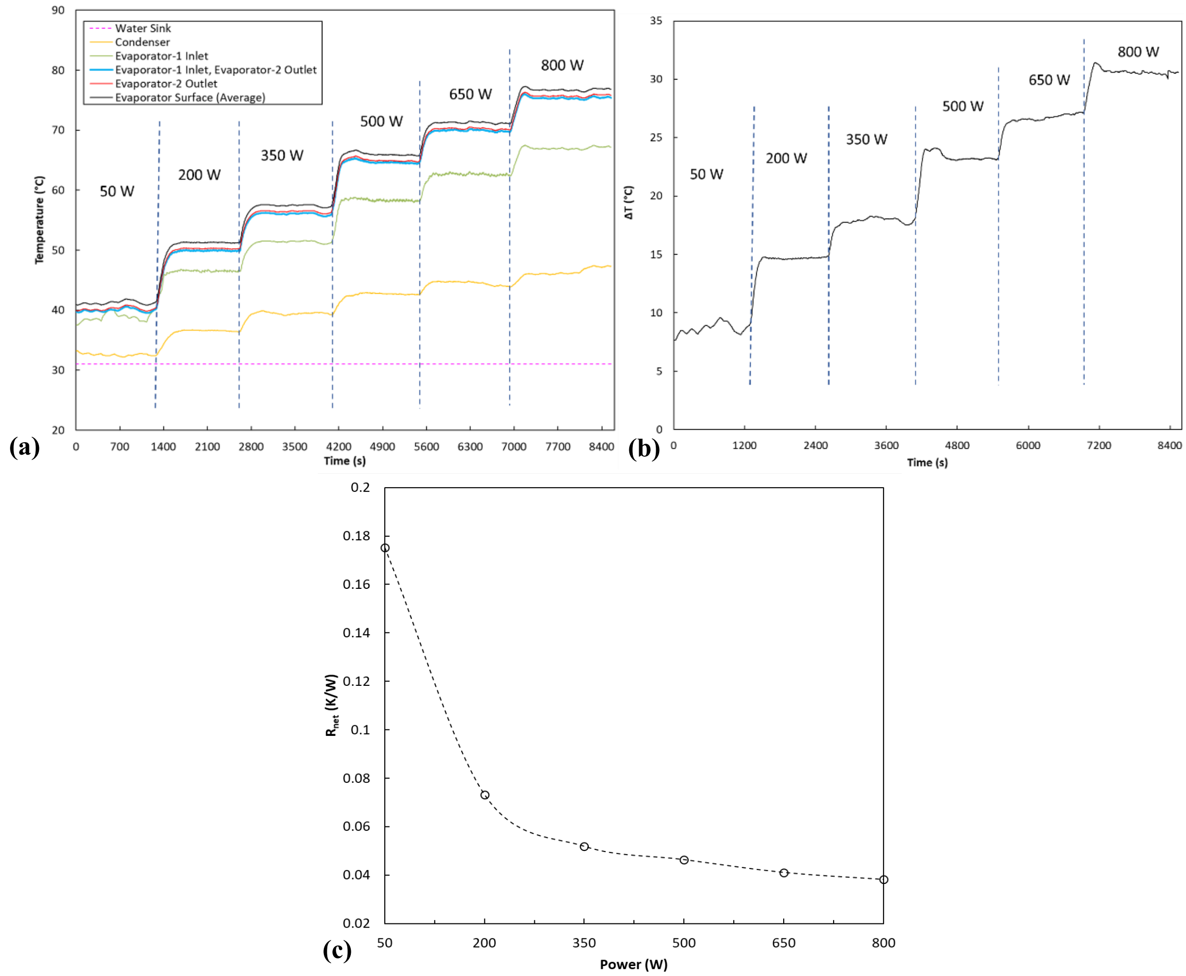


Figure 9: (a) Temperature measurements for P2P loop for power levels from 50 to 800 Watts with constant volumetric flow rate of 0.6 liters/minute corresponding to 800 Watts power, (b) P2P loop temperature drop ΔT (°C) for power levels from 50 to 800 Watts, (c) Thermal resistance $R_{net}(K/W)$ of P2P loop for power levels from 50 to 800 Watts.

With the P2P loop thermal performance validated through experimental testing, it is now ready to be implemented into the melting probe prototype. Figure 10(a) depicts a CAD model of how the P2P loop will be attached to the condenser piece prior to completing probe assembly. Additionally, Figure 10(b) demonstrates the P2P loop after fitment into the melting probe prototype shell.

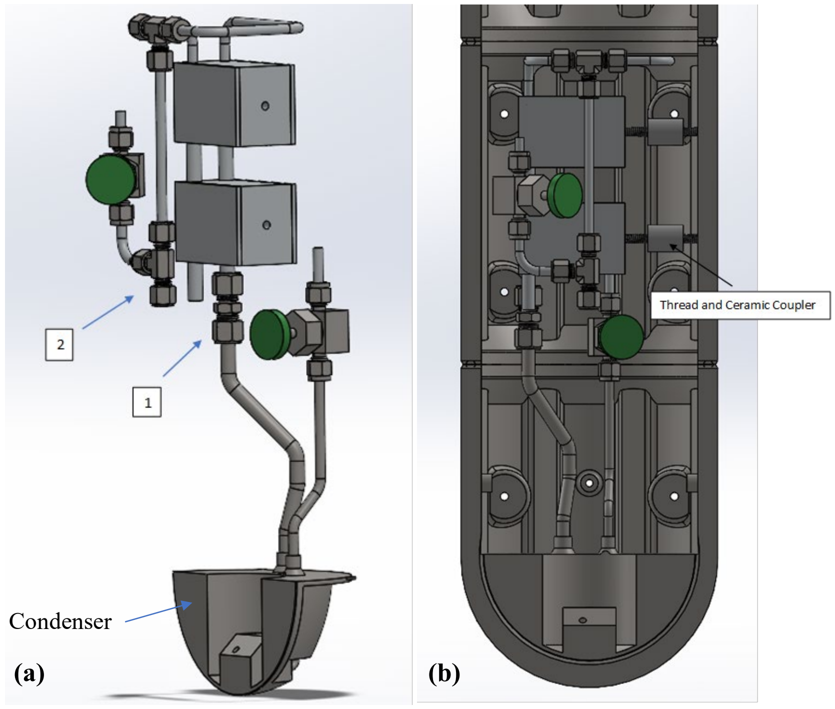


Figure 10: (a) Condenser and evaporator assembly, (b) Condenser and evaporator assembly fit into probe shell

The tubing geometry and components of the P2P loop have been designed in such a way that once assembled, they do not impact any other features present in the probe. Minimizing the geometric footprint of the P2P loop within the probe was critical for the overall design.

IV. Front Vapor Chamber – Wick Design Strategy

The front vapor chamber is a crucial component of the melting probe's thermal management system since it is the main "melting" component and the only heat sink of the P2P loop. The heat is received from the P2P loop through a low thermal resistance heat exchanger that has wick at the interface which is always saturated with liquid. The heat evaporates the liquid from the heat exchanger wicked surface. The vapor will travel a short distance and condense in the wick of the inside of the front wall giving up the latent heat. This heat will conduct through the wall into the outside ice/water/environment. An optimized vapor chamber design would provide the following advantages: (1) low thermal resistance interface between P2P loop condenser and the vapor chamber environment, (2) uniform temperature distribution at melting interface and (3) provide vapor to the side walls/variable conductance walls as needed. Heat transfer from the inner surface of the vapor chamber to the probe wall outer surface consists of two components: (1) vapor condensation at the inner surface of the probe head (2) conduction through the SS-316 probe wall.

The front vapor chamber wick design is challenging because of two reasons: the complexity of its internal architecture and the fact that the vapor chamber works "against gravity" meaning that the evaporation sites are elevated compared to the condensation sites and the liquid return needs to be pumped against gravity forces. Shown in Figure 11(a) is the CAD model of the front vapor chamber space inside the proposed ice melting probe prototype. The vapor chamber design will consist of bridges made of stainless-steel 316 screen wick. The bridges will be supported using bridge support structures as shown in Figure 11(a). There are three levels of support structures which have a staggered arrangement (for vapor flow), and they are inclined at an angle of 12 degrees with respect to the horizontal orientation. The purpose of the support structures is to divide the vapor chamber volume evenly with respect to the power distribution and to avoid the liquid flowing/pumped through the porous wick from falling to the bottom of the vapor chamber volume due to gravity. In other words, the presence of the bridges allows part of the liquid return to be guided direct to the evaporation surface (the external surface of the P2P condenser) decreasing this way potentially overwhelming liquid mass flow rates need to return from the bottom up to the evaporator. It is important to note that the entire internal surface of the vapor chamber is wicked and this wick layers are placed and sized strategically to uniformize the liquid return to the evaporator and avoid dry out spots because of excessive liquid flow local pressure drops. The vapor chamber is intended to transfer 800 W of power at desired working temperature of 300 K with sufficiently large margin.

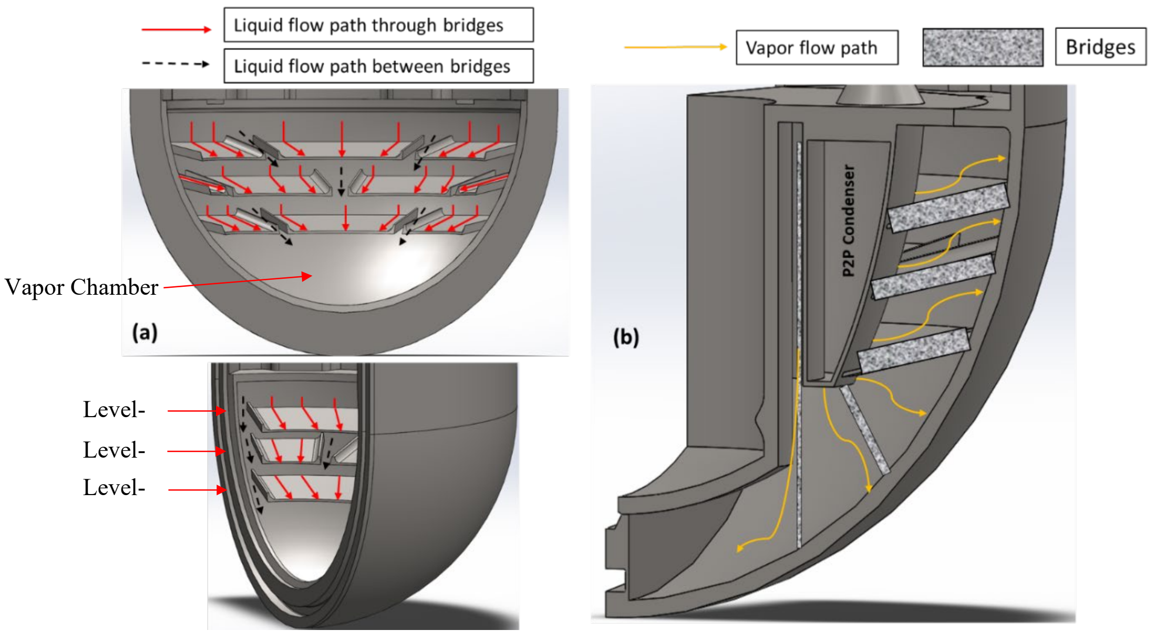
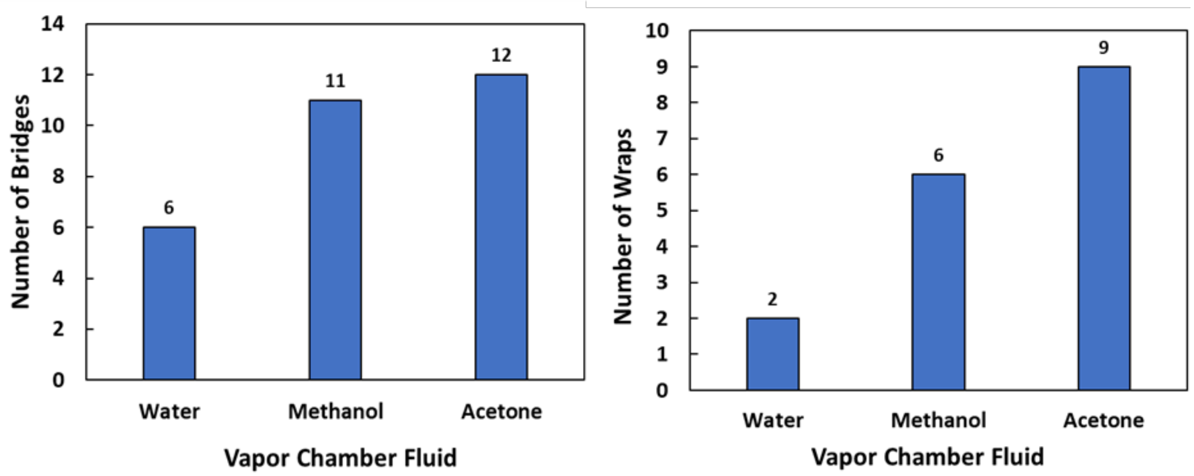


Figure 11: (a) Liquid flow path through and between the bridges within one of the two vapor chamber volumes, (b) Vapor flow path inside one of the two vapor chamber volumes.

Shown in Figure 11(a) and (b) are the flow paths for the two phases of the working fluid, liquid, and vapor inside one of the two vapor chambers. According to Figure 11, the entire volume of a single vapor chamber can be divided into five sub-volumes and each sub-volume is designed to be able to manage 80 W of power (vapor flow) so that each of the two vapor chambers will deliver 400 W of power. Based on this strategy, intensive heat pipe calculations, modeling and trade studies were performed for the vapor chamber heat transfer capability based on capillary and entrainment limits. As a result, titanium screen mesh will be used with 0.066 mm wire diameter and 60/cm (150/in) mesh size. Three potential working fluids were initially considered: water, acetone and methanol. In Figure 12, it can be seen that water performs best in terms of requiring the least number of wraps and bridges, followed by methanol and acetone. But a possible issue with water will be freezing during experimental testing at ACT, when the melting probe prototype will be idling. Hence, the next best option of methanol is chosen as the working fluid. To corroborate the selection of methanol as the working fluid for VCHP side walls, the sensitivity of the vapor-NCG front location with respect to a decrease in the front liquid film heat transfer coefficient is shown in Figure 13. It can be seen that even for the variable conductance wall performance, water performs the best with methanol as the second-best.



(a) **(b)**

Figure 12: Parametric study of number of bridges (a) and wraps (b) required to transfer 1kW of heat for ACT' ice melting probe prototype.

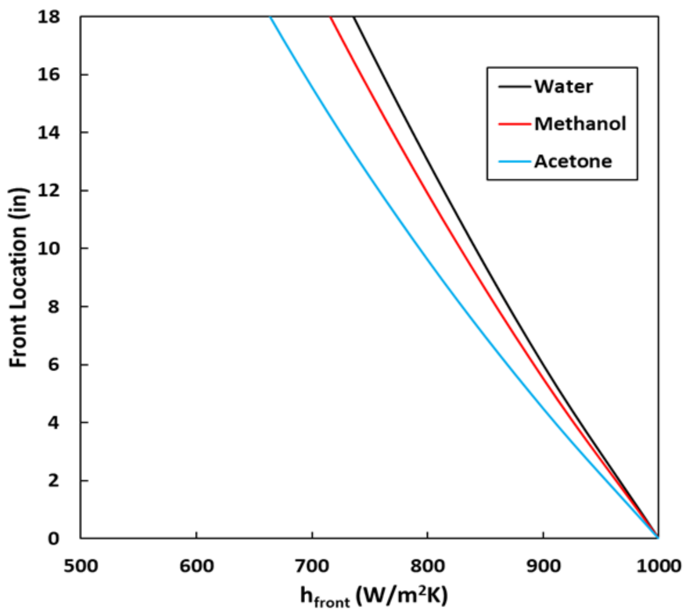


Figure 13: Sensitivity of the vapor-NCG front location for different working fluids for decrease in the front liquid film heat transfer coefficient.

V. Conclusions

Under an SBIR Phase II program, Advanced Cooling Technologies, Inc (ACT) is developing a thermal concept for Europa ice melting probe. This paper presents updates and the developmental status and is the second update of the development of the post proof-of-concept performance. The lab-scale prototype is the main focus of the presented work. The thermal management architecture of the developed system consists of following novel features:

a) A P2P heat transport and delivery system that can uniformly acquire the waste heat from the cold ends of the thermoelectric convertors and focus it into the vapor chamber with minimal temperature drop and using minimal pumping power. A third system that uses minchannel evaporators was modeled, fabricated and tested. This system will be installed in the actual lab-scale prototype.
b) A front vapor chamber that effectively transfers the heat from P2P condenser to the melting head. The analysis shows reasonable margin and based on this, the wick configuration was designed.

c) Variable Conductance walls that passively move heat from the front vapor chamber along the side walls for lateral melting, as needed. A discretized design based on rectangular tubes resulted.
d) A steering system based on liquid displacement that allows the probe to tilt or even move laterally as needed. This featured was also design based on a multidirectional valving system.

The probe design is complete and an additive manufacturing strategy is in place. The resulted design was impacted by this strategy and the resulted components were presented in this paper. Currently, the probe is under fabrication in an additive manufacturing facility.

Acknowledgments

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