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Advanced hybrid cooling loop technology for high performance thermal management

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Advanced hybrid cooling loop technology has been developed for the high performance cooling systems for such as U.S. Army next generation vehicles, "Future Combat System (FCS)" and Directed Energy Weapons (DEW), high power Solid State Laser Systems. The hybrid cooling loop combines the active liquid pumping with the passive capillary liquid management in the sintered wick structure of the evaporator and its liquid/vapor separation. The prototype hybrid cooling loop using planar evaporator design was tested to be capable of managing up to 4kW cooling load which is equivalent to the heat flux up to 30W/cm² over the cooling surface area of 135cm² (=7.6cm×17.8cm). From the temperature results, however, much higher heat flux conditions are very likely to be achieved. The measured boiling thermal resistance was as low as 0.16°C-cm²/W and remained relatively constant during heat load variations except cold start conditions. This paper discusses the operating principle of the hybrid cooling loop with single evaporator and presents the test results under various power cycles. The results represent major improvements over the state-of-art heat pipes, loop heat pipes and two-phase spray and jet impingement cooling devices in terms of heat flux, cooling surface area and design simplicity.

I. INTRODUCTION

The ever-increasing waste heat dissipated from electrical/electronic devices such as power electronics and electrical actuators presents great challenges to the capabilities of conventional air or liquid cooling systems in terms of the amount of heat dissipation and heat flux. The "drive-by-wire" trend replacing conventional mechanical powertrain and actuators with the electrical counterparts will become more common in many military applications.

As an example, U.S. Army's next generation vehicle, Future Combat System (FCS) utilizes electric-driven powertrain and electronic components to attain multi-functionality and multi-mission capability because of the flexible reconfiguration using electrified components. Typical power electronic will require cooling systems managing multiple kilowatt waste heat. The increased cooling requirements for the electrical components will likely result in prohibitively bulky and energy-guzzling systems for the future military applications. Another emerging cooling challenge is due to the high heat flux cooling requirement found in Directed Energy Weapon (DEW) systems such as high-power solid-state laser systems. The solid-state laser generates the high heat flux waste heat from various laser components ranging 100W/cm² to 500W/cm² over the large surface areas on the order of 100cm². The already severe burden is increased by very tight temperature control requirements for its efficiency and lifetime requirement [Huddle et. al., 2000; Ramalingam, et. al, 2003; Hale et. al., 2004].

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Two-phase cooling systems using evaporation and condensation are known to be the best way to meet demanding cooling requirements in terms of compactness, weight and energy-consumption. As one of the fundamental advantages of the two-phase systems, the large heat transfer coefficient of film boiling in the cold plate ranges from 10,000~100,000W/m²-°C which is one order of magnitude larger than that of the conventional liquid-cooling cold plates. The larger heat transfer coefficient is translated into a smaller thermal resistance and consequently high heat flux capability [Park et. al., 2005c].

Another advantage is due to the large latent heat capability of a two-phase cooling system which could be typically two orders of magnitude larger than the sensible heat of a liquid-phase cooling system. Therefore, the two-phase system requires much less coolant flow resulting in a very compact pumping system. Furthermore, isothermal evaporation is another important feature of the two-phase cooling systems because excessive temperature non-uniformity in silicon chips will reduce their reliability due to thermal stresses causing functional failures. The synergic effect by the high heat flux capability with good isothermality, small liquid flow requirement of the two-phase cooling systems will effectively address the challenging cooling demands we are facing.

DOD and NASA have already identified two-phase flow technologies as the promising solution to meeting the challenging requirements for emerging cooling needs based on performance, mass, reliability and cost considerations [Kuszewski and Zerby, 2002; Ponnappan, et. al., 2002]. The widely-used passive two-phase cooling technologies includes heat pipe, loop heat pipes (LHP) and capillary pumped loops (CPL). They are very reliable and highly thermal conductive devices. However, the passive operation relying on the capillarity will ultimately limit the advance in heat flux, transport distance and dimension capabilities [North et al., 1997]. Pumped two-phase cooling technologies using micro channel and spray and jet impingement have been developed to overcome the aforementioned problem of the passive devices [Kawaji and Chung, 2003; Estes and Mudawar, 1995]. Because of the pumping pressure and flow rate requirements, such pumped systems require large pumping and complex fluid nozzle/reconditioning systems which impair reliability needed for many commercial applications.

II. Hybrid Cooling Loop Technology

The pumped and capillary-driven (or hybrid) two-phase cooling technologies have been developed for past years to overcome the previously discussed shortcomings of the two-phase systems [Ambrose et. al., 1992; U.S. NRL 2005; Park et. al., 2005a, 2005b, 2005c, 2004]. In this paper, we will present an advanced hybrid loop technology with an innovative evaporator design which is applicable to high performance cooling systems for such as power electronics and solid state laser cooling.

The hybrid cooling loop as illustrated in Figure 1 consists of an evaporator, a condenser, a liquid reservoir and a pump as the simplest design. Because of the active pumping system, the hybrid loop system could manage multiple evaporators in various configurations. The developed evaporator uses a planar design which is the most desirable form factor for the planar heat source devices. The proprietary evaporator design combines the passive capillary pumping with the active liquid pumping while separating liquid and vapor phases for best boiling condition.

The typical pressure profile of the hybrid cooling loop is shown in Figure 2. The node notation used for discussion is also shown in Figures 1 and 2. The active pumping feeds the liquid to evaporator, while the passive capillarity draws the liquid to the vapor volume of the evaporator. The evaporator wick design adopts the "inverted meniscus scheme" for better control of liquid and vapor flow in the wick . That is, the liquid pressure (node 6) in the liquid volume which isolates the vapor from the liquid is lower than the vapor pressure (node 2) in the vapor volume where the boiling (or heat acquisition) occurs. The passive capillary assures the film evaporation in the wick of the evaporator and the pressure balance between the vapor and liquid zones. As the heat input increases, the system temperature and pressure increase. In addition, the subcooled liquid temperature of the reservoir which is determined by the heat loss by the excess liquid return and the condenser cooling, governs the system temperature resulting in lower boiling thermal resistances. The vapor generated from the evaporator is forced by the vapor pressure to the condenser and then to the reservoir. The excess liquid returns to the liquid reservoir through a separated liquid loop. Even though the overall system pressure drop is extended by the active pumping beyond the capillary pumping limit, the maximum heat flux will still be limited by the capillary capability of the wick structure of the evaporator.

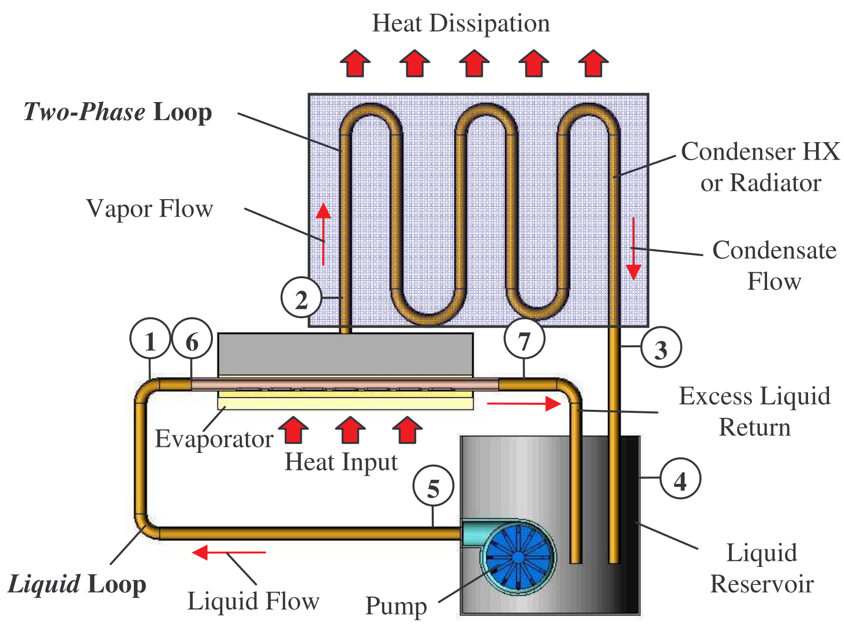

Figure 1 Schematic diagram of hybrid cooling loop.

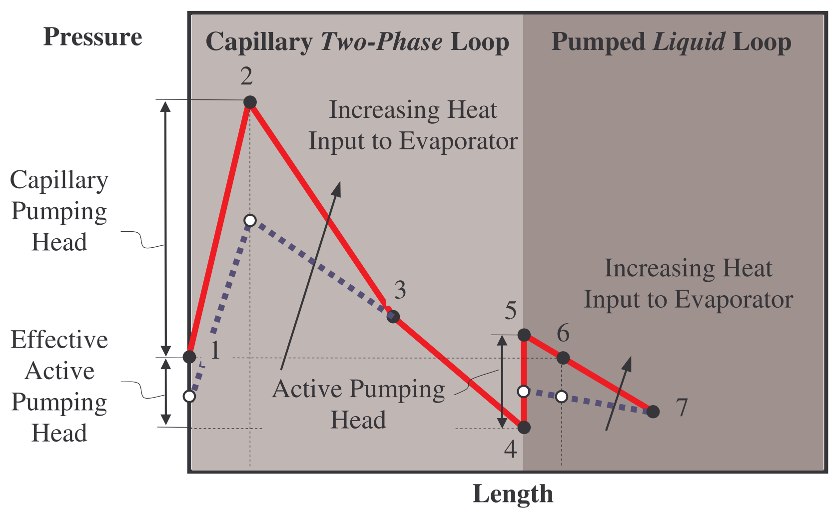

Figure 2 Pressure profile of hybrid cooling loop as the heat input to evaporator increases at constant pump speed.

Major advantages of the hybrid cooling loop are summarized as below:

- Advanced Hybrid Cooling Loop Design: The capillary-driven two-phase flow loop can acquire and transport large heat loads at high heat fluxes while the pump-driven liquid loop provides subcooled liquid and removes excess liquid.
- High Heat Flux Capability: The sintered wick design can handle over 100W/cm² heat fluxes.
- Large Cooling Surface Capability: The innovative evaporator design is easily scalable for large planar surface areas over 100cm². The evaporator wick design provides excellent passive liquid management and phase separation for the best boiling condition.
- Compact and Reliable Design: The superior two-phase cooling performance and advanced hybrid loop design can achieve miniaturized designs providing great flexibility and reliability.

III. Test Results

The schematic of the hybrid cooling loop used for testing is shown in Figure 3. Main components for the hybrid loop include an evaporator (or cold plate), a reservoir, a pump and a condenser. For a clear understanding on the hybrid loop operation, a single evaporator system was built and tested. The evaporator has a rectangular cooling surface area of 135cm² (=7.6cm×17.8cm). Three fluid lines of the liquid supply, excess liquid return and vapor exit as shown in Figures 1 and 3, are connected to the evaporator in the system. De-ionized water was used as a working fluid for the system. The instrumentation used to monitor the hybrid loop operation includes pressure, flow rate and temperature sensors. The heat input into the evaporator was measured by a wattmeter. As further verification, the calorimetery was performed for both the condenser and the reservoir. Prior to charging fluid, the entire system was checked for any leaks using a helium mass-spectrometer leak checker.

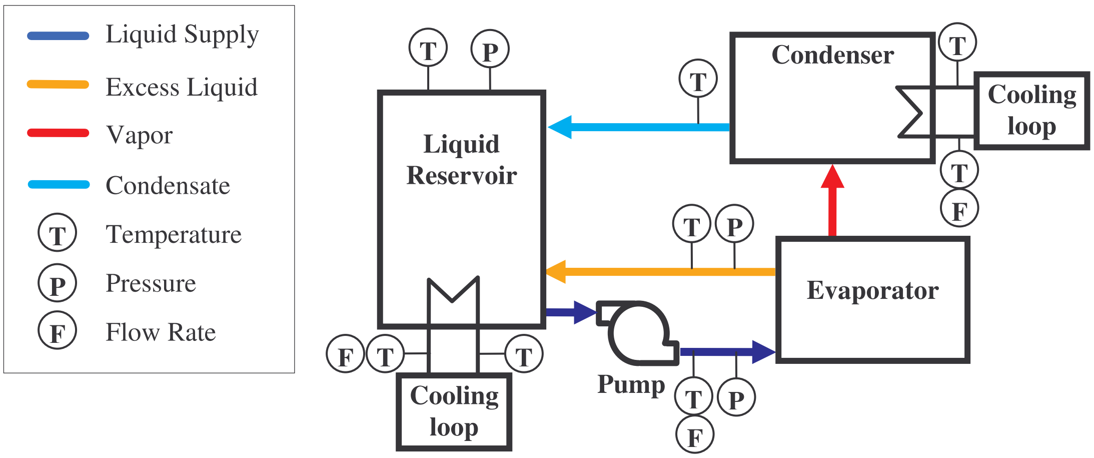

Figure 3 Schematic of hybrid cooling loop with single evaporator.

Typical test starts first by turning on the liquid pump to circulate the liquid along the loop. Once the pump speed is adjusted to have a certain liquid flow, the pump condition was kept the same during the testing. Three joule-heating cartridge heaters were used to provide the heat input to the evaporator, according to pre-set power cycles in which the heat input is incrementally increased from zero to a maximum and then decreased to the initial. The peak heat load ranges from 2.5 up to 4kW or the heat fluxes of 18.5 up to 30W/cm². At each power step, the system was allowed to reach steady-state conditions.

Figure 4 shows the temperature profiles under a power cycle. At the maximum heat load of 2.5 kW, the evaporator body temperature reached to approximately 55°C and the vapor temperature was approximately 52°C which are higher than the subcooled liquid temperatures entering into the evaporator and leaving the evaporator at approximately 20°C and 46°C respectively. The liquid supplied to the evaporator was also at the same temperature as the condensate. The condensate temperature was at 26°C at the maximum heat load and approximately 21°C at the lowest heat input. The subcooling at the condenser and supplemental cooling at the reservoir was to compensate the parasitic heat leak through the excess liquid return.

The pressure and liquid flow measurement results are shown in Figure 5. The liquid pressure was averaged between the inlet (at liquid supply) and outlet (at excess liquid) of the liquid line for the evaporator. The vapor pressure was always higher than the liquid pressure in the evaporator by about 1”Hg, which is a desirable condition for the system to operate in capillary pumping mode. The liquid flow was not affected by the variation in the heat load. For the current test, the liquid flow from the pump was set to be around 0.3LPM. The excess liquid flow rate at a peak heat input condition is about 60.7% of the liquid supply.

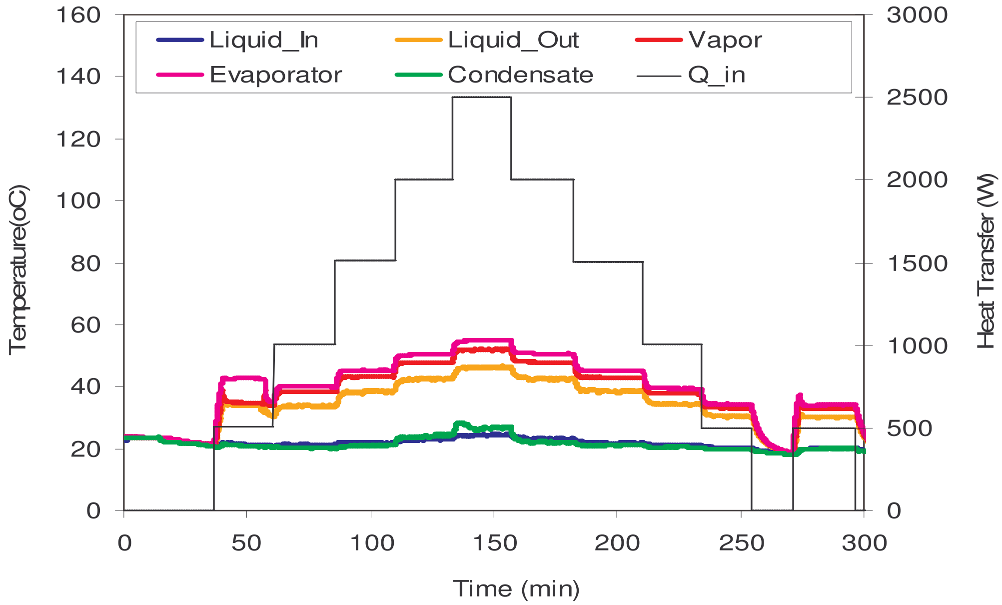

Figure 4 Temperature variations of hybrid cooling loop vs. heat input.

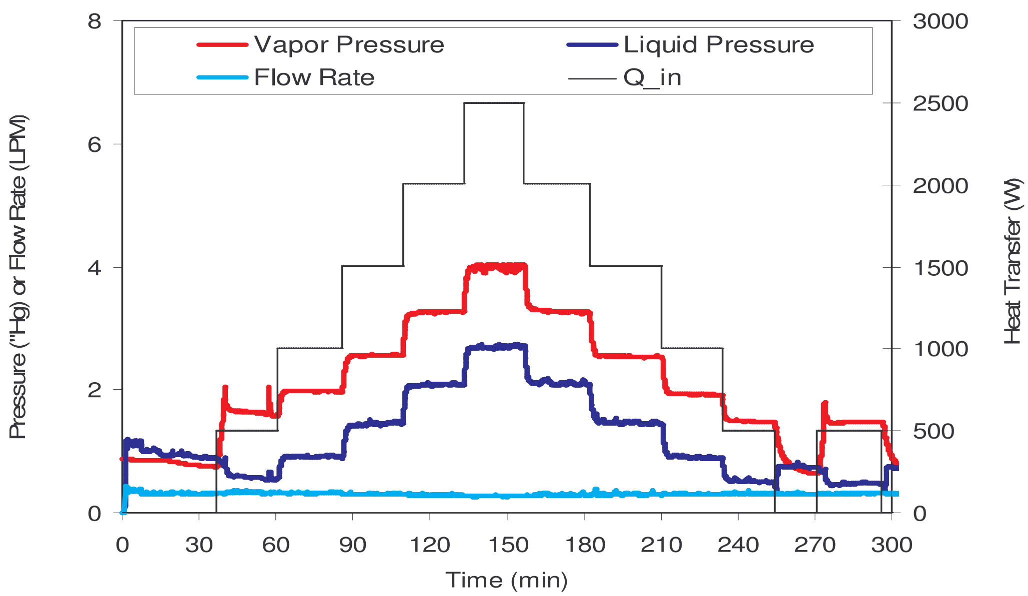

Figure 5 Pressure and liquid flow rate variation of hybrid cooling loop vs. heat input.

The calorimetery measurement as shown in Figure 6 indicates that 10 ~ 20% of the total heat input removed from the reservoir, is the heat leak through the excess liquid return. The heat leak remained relatively steady over various heat input conditions. But the calorimetery measurement shows some discrepancy in system energy balance. Figure 7 shows the boiling thermal resistance of the evaporator. The thermal resistance was defined as the ratio between the vapor and heater surface temperatures. The boiling thermal resistance of the evaporator varied between 0.23 and 0.17°C-cm²/W at the lowest and the highest heat input respectively. The low thermal resistance was achieved as a result of the subcooled liquid and thin film boiling. Note that at the cold start at the heat input of 500W, the thermal resistance is highly fluctuating. This fluctuation is attributed to the pre-existing liquid in the vapor volume. The fact can be confirmed by the lack of such fluctuation during the power ramp-down.

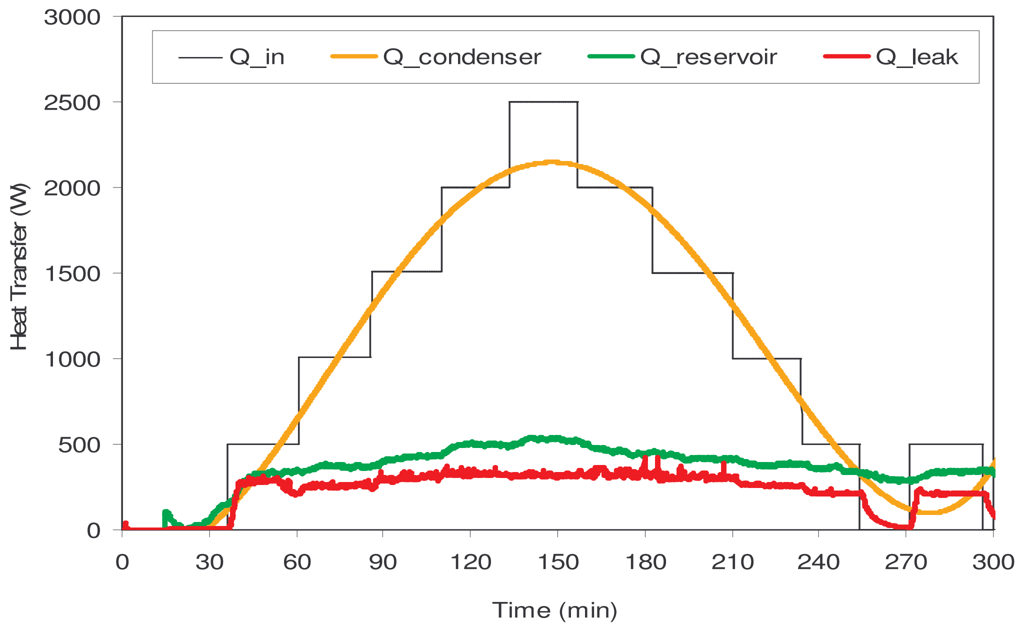

Figure 6 Calorimetery of hybrid cooling loop.

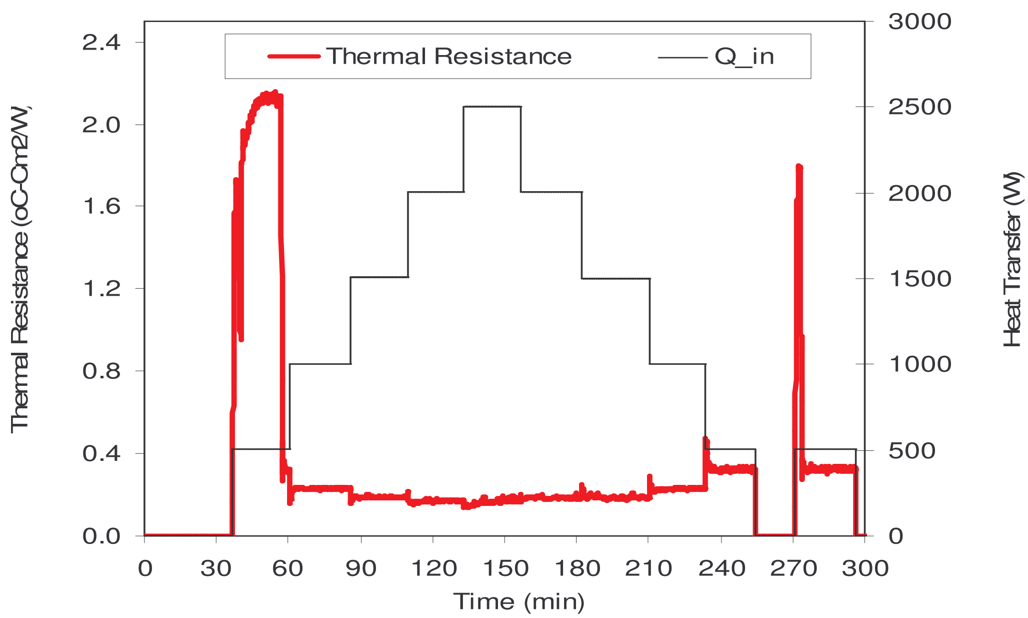

Figure 7 Thermal resistance variation of hybrid cooling loop vs. Heat input.

In order to characterize the cold start and high heat flux capability of the hybrid cooling loop, another testing using a new power cycle ranging from 100W to 4kW as shown in Figure 8 was performed. The minimum heat input for the two-phase cooling onset was measured to be above 500W (or 3.7W/cm²) from the measured boiling thermal resistance. The fluctuation in temperatures at the cold start conditions seen in the Figure 8 is attributed to the pool boiling in the evaporator wick which was initially flooded. Keeping the pumping condition the same, only the heat input was gradually increased up to 4kW (or 30W/cm²) which was limited by the heater capacity. Considering the evaporator temperature around 63.7°C at the maximum heat condition, much higher heat loads could be managed without experiencing dry-out. At the maximum heat load condition, the heat loss through the excess liquid return was measured to be 11% of the heat input of 4kW. At the end of the power ramp down when the heat load was increased from 400W to 600W, the unstable fluctuating temperature was observed again because of the cold start operation.

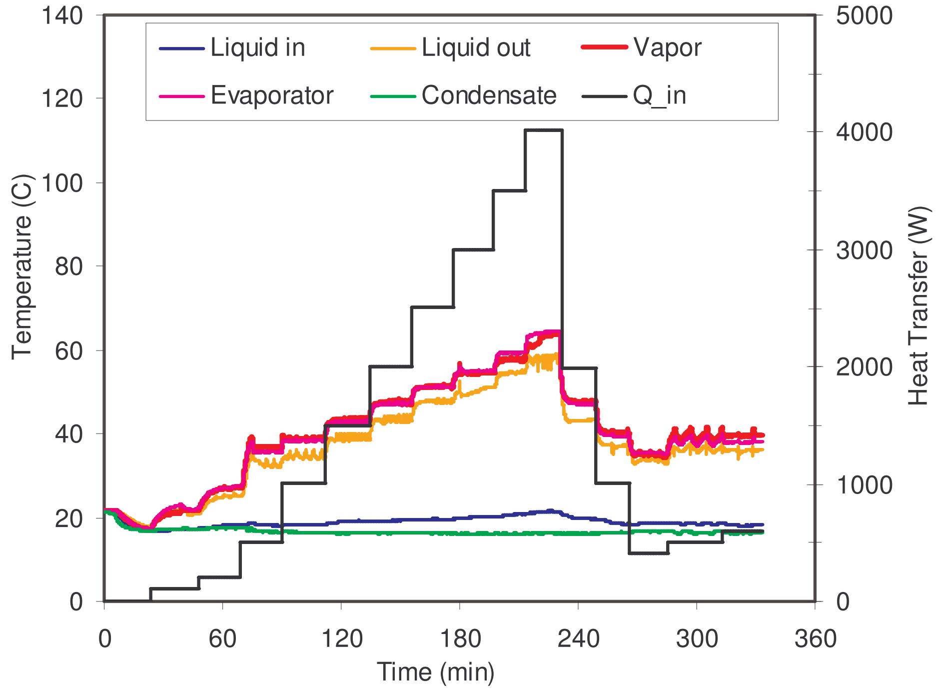

Figure 8 Temperature variations of hybrid cooling loop vs. heat input.

As future work, the hybrid cooling loop with multiple evaporators which is a more applicable design for multiple heat source systems will be tested. The testing will examine the interaction between evaporators under asymmetrical heat loading and various gravitational orientation and acceleration conditions.

IV. Conclusion

Advanced hybrid cooling loop technology was developed through the prototype testing using a hybrid cooling loop with a planar evaporator. The hybrid cooling loop was capable of managing up to 4kW cooling load which is equivalent to the heat flux up to 30W/cm² over the rectangular cooling surface area of 135cm² (=7.6cm×17.8cm). The measured boiling thermal resistance was as low as 0.16°C-cm²/W and remained relatively constant during heat load variations except cold start conditions. The much higher flux cooling capability is expected considering the evaporator temperature. More complete understanding on the hybrid cooling loop is required through rigorous experimental testing and numerical analysis with simpler systems with single or two evaporators.

The major achievements from this work are summarized as follows.

- Advanced Hybrid Cooling Loop Design: The advanced hybrid cooling loop technology was demonstrated through the prototype testing.
- High Heat Flux Capability. The hybrid cooling loop using single planar evaporator with sintered wick design managed high heat flux over 30W/cm². The much higher heat flux could be very likely achieved considering the system temperature results.
- Large Cooling Surface Capability: The innovative evaporator with a large planar surface area of 135cm² provided the excellent passive liquid management and phase separation for the best boiling condition. The evaporator design is easily transferable to high performance cooling applications requiring much larger area and various form factors.
- Compact and Reliable Design: The hybrid cooling loop demonstrated the superior two-phase cooling performance and the flow requirement and high performance and yet simple hybrid cooling loop design will allow miniaturized designs providing great flexibility and reliability.

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