# Vapor Compression Hybrid Two-Phase Loop Technology for Lunar Surface Applications

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**Abstract.** NASA's vision for Space Exploration that would return humans to the Moon by 2020 in preparation for human explorations of Mars. This requires innovative technical advances. The lunar mission requires a temperature-lift (heat pump) technology to reject waste heat to hot lunar surface (heat sink) environments during lunar daytime. The lunar outpost and Lunar Surface Access Module (LSAM) to operate *anywhere* during the *hot lunar daytime* require a high performance and energy-efficient, yet reliable refrigeration technology. A vapor compressor-driven hybrid two-phase loop was developed for such high temperature-lift applications. The vapor compression loop used an advanced porous wick evaporator capable of gravity-insensitive capillary phase separation and excess liquid management to achieve high temperature-lift, large-area, isothermal and high heat flux cooling capability and efficient compression. The high temperature lift will allow the lunar surface systems use compact radiators by increased heat rejection temperature.

**Keywords:** Vapor Compression, Evaporation, Two-phase, Thermal, Electronics, Cooling, Hybrid, Compressor, Pump, Capillary, Heat Pump, Temperature Lift, Lunar.
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## INTRODUCTION

Lunar surface systems are subject to a big variation of the lunar surface temperature, for example, at the lunar equator ranging from -173 °C to 121 °C (Swanson et al., 1990; Ewert, 1993; Nikanpour and De-Parolis, 1996; Aidoun, Nikanpour and De-Parolis, 1996; Morton et al., 1998). Figure 1 shows the lunar surface temperature variation over an earth month at different latitudes (Nikanpour and De-Parolis, 1996).

The lunar surface is the main heat sink in the lunar surface environment besides the deep space. Figure 2 shows the effective heat sink temperature available for the horizontal and vertical radiators located at the lunar equator (Ewert, 1993). The maximum radiator heat sink temperature is about 320K at the lunar equator during lunar noon. Because the heat source temperature of the lunar surface systems is expected to be about 273K, the temperature lift of about 50°C is required to reject the waste heat.

The temperature-lift (or heat pump) technologies for the lunar surface systems also has to offer energy-efficient, lightweight, but robust, reliable and gravity-insensitive designs which can collect, upgrade, transport and reject heat with low thermal resistances using reduced complexities requiring minimal active control under the lunar reduced gravity environment.

Based on performance, mass, reliability and cost considerations, NASA and DOD have identified two-phase flow technologies as the potential solution to meeting future challenging thermal requirements. The two-phase flow technologies are critically required for power, propulsion, life support, and environmental control systems in numerous NASA's human and robotic exploration missions (Swanson and Butler, 2006; Birur, 2006; Kuszewski and Zerby, 2002; Ponnappan, Donovan and Chow, 2002).

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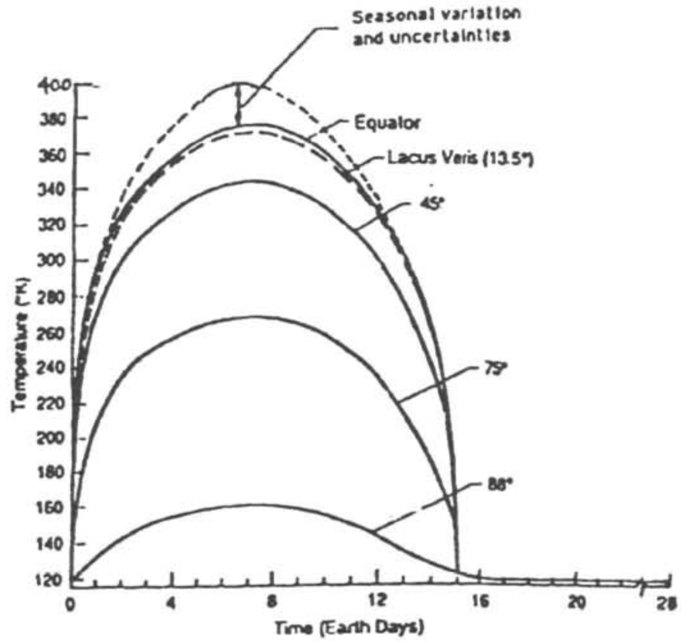


**FIGURE 1.** Lunar Surface Temperature Variation Over an Earth Month at Different Latitudes (Nikanpour and De-Parolis, 1996).

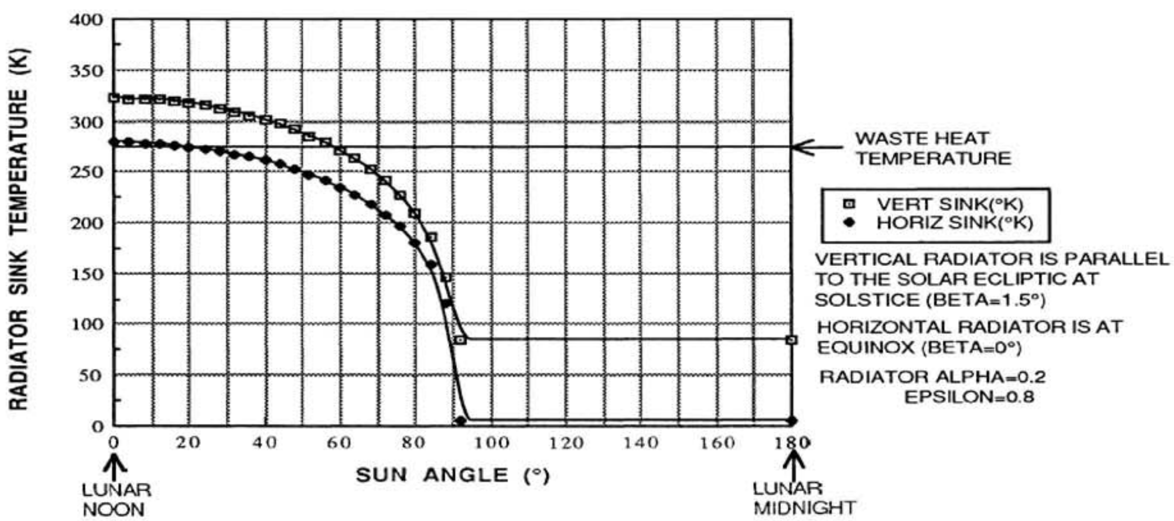


**FIGURE 2.** Effective Heat Sink Temperature of the Horizontal and Vertical Radiators Located at the Lunar Equator (Ewert, 1993).

Past years, there were great advances in the two-phase thermal management technologies using active and/or passive heat transfer devices such as pumped two-phase cooling loops, loop heat pipes (LHP), capillary pumped loops (CPL) and heat pipes. The successful implementation of a mechanical pump into the liquid cooling loops of Mars Exploration Rovers established the active cooling systems as a viable cooling solution for future NASA applications facing challenging cooling requirements (Birur, 2006). Recently, the pumped two-phase loop, called Hybrid Two-Phase Loop (HTPL) has been developed to offer an advanced high performance two-phase cooling technology for high power electronics (IGBT inverter) cooling which provides a robust, reliable, compact, large-area, high heat flux, gravity-insensitive cooling solution (Park et al., 2007a, 2007b, 2006, 2005a, 2005b; Zuo, Park and Sarraf. 2004). For the high temperature-lift refrigeration (or heat pump) for the lunar missions operating under hot heat sink environments, the Vapor Compression Hybrid Two-Phase Loop (VCHTPL) was developed based on the advanced HTPL design. The detailed description of the proposed VCHTPL is discussed in the following sections.

## VAPOR COMPRESSION HYBRID TWO-PHASE LOOP TECHNOLOGY

The Vapor Compression Hybrid Two-Phase Loop (VCHTPL) technology was developed based on the conventional vapor compression refrigeration system. The VCHTPL used an advanced evaporator capable of passive capillary phase separation for excess liquid management. The evaporator using a porous structure will improve high flux performance and vapor compression especially, during transient heat input conditions.

Figure 3 illustrates the VCHTPL design with an evaporator as the simplest configuration. The vapor compression system consists of two fluid loops: a two-phase loop (thin line) and a liquid loop (thick line). The two-phase loop includes an evaporator, a compressor, a condenser, a vapor transport line and a condensed liquid return line; the liquid loop consists of a pump and a liquid reservoir and an excess liquid return line. The compressor and pump are the active components which consume electrical power.

The excess liquid return design of the evaporator allows passively separate vapor from liquid using capillary action in the evaporator porous wick. Because of the thin film boiling heat transfer due to capillary phase separation, the evaporator is capable of managing high heat flux heat with low thermal resistance and feeding only high-quality and saturated vapor into the compressor of the VCHTPL. The high quality compression improves compressor efficiency and protects the compressor from possible damage due to liquid slugging. The passive capillary phase separation of the evaporator is not affected by gravitational force and requires neither any active flow control nor fluid reconditioning.

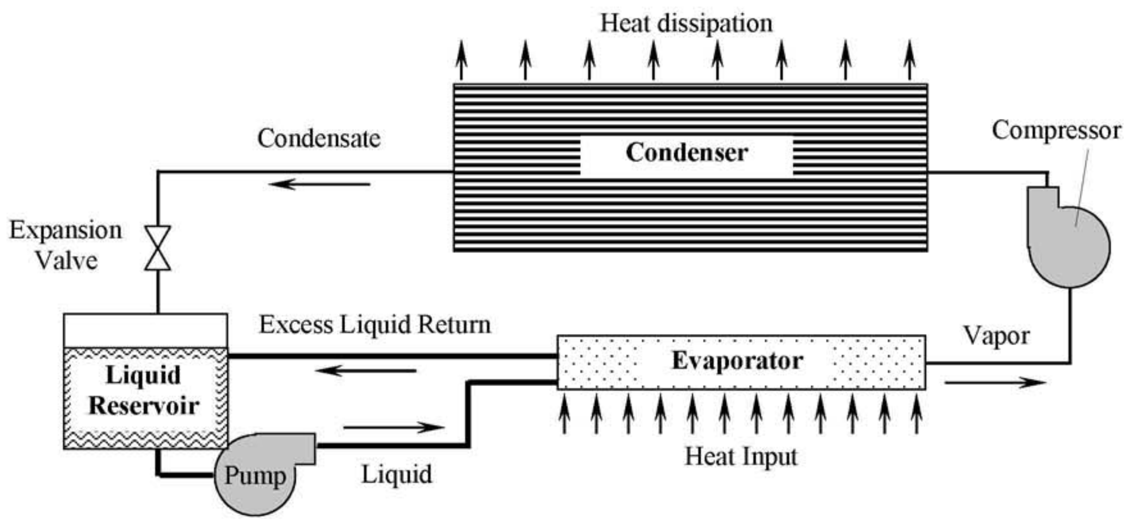


**FIGURE 3.** Vapor Compression Hybrid Two-Phase Loop (VCHTPL) Concept Using Phase Separation Evaporator.

Briefly speaking of the operation of the VCHTPL, the pump circulates liquid to the evaporator and the liquid reservoir in the liquid loop. The liquid in the evaporator is drawn into the evaporator wick by the capillary force and then fully vaporized absorbing the heat input to the evaporator. The excess liquid from the evaporator is returned to the reservoir through the excess liquid return line. The excess liquid is heated and carries some of the heat input (called as "heat leakage") while flowing through the evaporator. The vapor from the evaporator is compressed by the compressor into the condenser. Then, the condensate from the condenser is pushed through the expansion valve (or pressure reducing device) and stored into the liquid reservoir. The "heat leakage" into the reservoir by the excess liquid return must be canceled by expansion cooling in the expansion valve and sub-cooling of the condensate in the condenser. The heat leak is the common issue found in the LHP and CPL operations.

Also similar to the LHP, the design of the liquid reservoir in the VCHTPL must satisfy three constraints: (1) the reservoir must be sufficiently large to contain the liquid that is displaced from the transport and condenser lines upon startup, ensuring the lines will be clear during operation; (2) the aspect ratio or geometry of the reservoir must be chosen such that the pump will always be primed, ensuring the loop will operate in any gravity orientation and micro gravity environment; and (3) the reservoir size should be minimized to avoid pickup of undesired heat from environment, minimizing the amount of sub-cooling required in the condenser.

It should be noted that there are no valves or other control mechanisms required to operate the VCHTPL. The passive capillary separation of the liquid and vapor phases in the evaporator removes the need for active control during varying heat input conditions (within the designed heat flux limit) while guaranteeing high quality and saturated vapor out of the evaporator.

## TEST RESULTS OF VAPOR COMPRESSION HYBRID TWO-PHASE LOOP

A small-scale prototype was fabricated to demonstrate the feasibility of the VCHTPL concept. Figure 4 shows the schematic of the prototype VCHTPL consisting of an evaporator, a compressor, a pump, a condenser, a liquid reservoir and a fixed pressure expansion valve. The evaporator body was constructed of copper material. The evaporator wick was fabricated with copper powder and screen which were bonded using multiple sintering processes to create 3-dimensional porous structures. The prototype VCHTPL used various Commercial Off-The-Shelf (COTS) parts for conventional refrigeration systems. The VCHTPL system used R-134a as the working fluid. For the test, the heat input of the evaporator and the liquid temperature downstream of the expansion valve were used as the test variables while the compressor and pump speeds were kept the same.

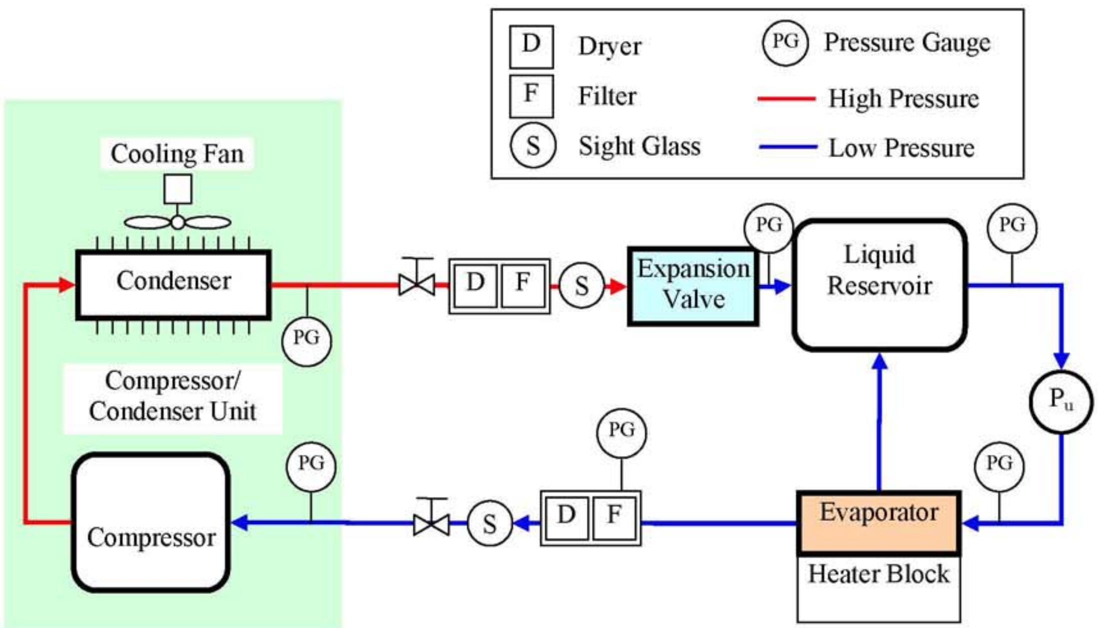


**FIGURE 4.** Schematic of the Vapor Compressor-Driven Hybrid Two-Phase Loop.

Figure 5 shows the temperature results of the VCHTPL using a power cycle. The test started first by turning on the compressor, pump and heater at the same time. The maximum heat input of the power cycle was 308.8W (or heat flux of 5.3 W/cm²). After the temperatures reached the steady state condition, the heat input was adjusted following a pre-determined power schedule. During the power cycle test, the expansion valve setting, compressor and pump speeds were kept constant. As shown in Figure 5, the condenser temperature measured at the condenser inlet was 83°C at the maximum heat input. The temperature lift ($\Delta T_{lift} = T_{condenser} - T_{evaporator}$) was ranged from 45.9°C to 63.1°C during the power cycle test. The power consumptions of the pump and compressor were measured to be 1.3W and 450W respectively. Therefore, the maximum COP for cooling was calculated to be 0.68 (COP_cooling = 308.8W/(1.3W + 450W)). The maximum Carnot COP for cooling [$\mathrm{COP}_{Carnot} = T_{evaporator} / (T_{condenser} - T_{evaporator})$] was 7.11 at the maximum heat input condition. Therefore, the refrigeration efficiency [$\eta_R = \mathrm{COP}_{\mathrm{cooling}} / \mathrm{COP}_{Carnot}$] was 0.96.

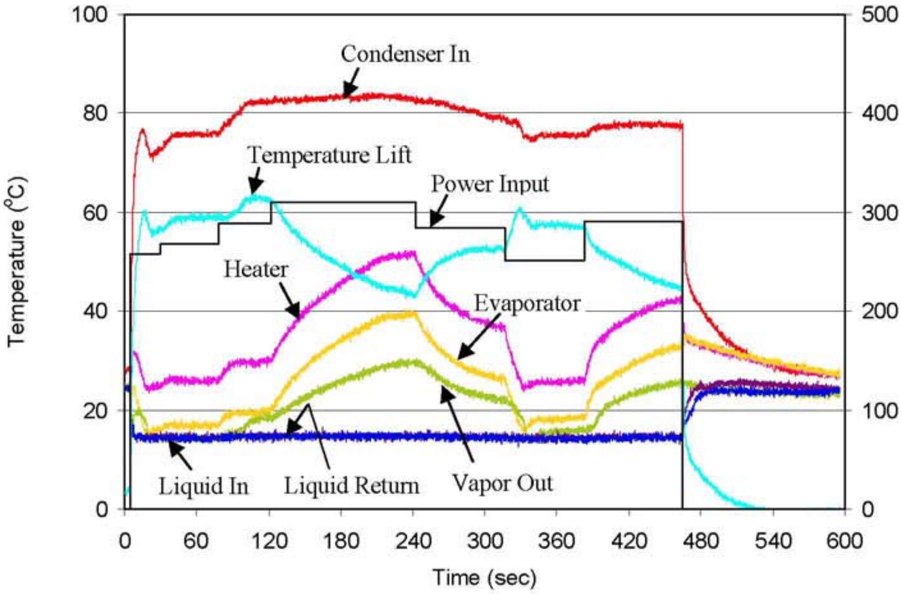


**FIGURE 5.** Temperature and Power Input Profiles of the Vapor Compressor-Driven Hybrid Two-Phase Loop.

Figures 6 and 7 show the test results of the VCHTPL at a constant heat load of 254W while the liquid temperature was varied by adjusting the expansion valve setting. Figure 6 shows the temperature results of the VCHTPL. As the liquid temperature decreased, the temperature lift decreased due to the increased evaporator temperature. It is attributed to the fact that as the liquid temperature gets colder, more heat leak from the ambient deteriorates the pump priming due to cavitation and evaporator performance. Figure 7 shows the COP of cooling, refrigeration efficiency and evaporator thermal resistance. The thermal resistance [K/W] of the evaporator was defined as $R = (T_{evaporator} - T_{vapor})/Q$. The figure shows that when the liquid temperature decreased, the thermal resistance and refrigeration efficiency decreased.

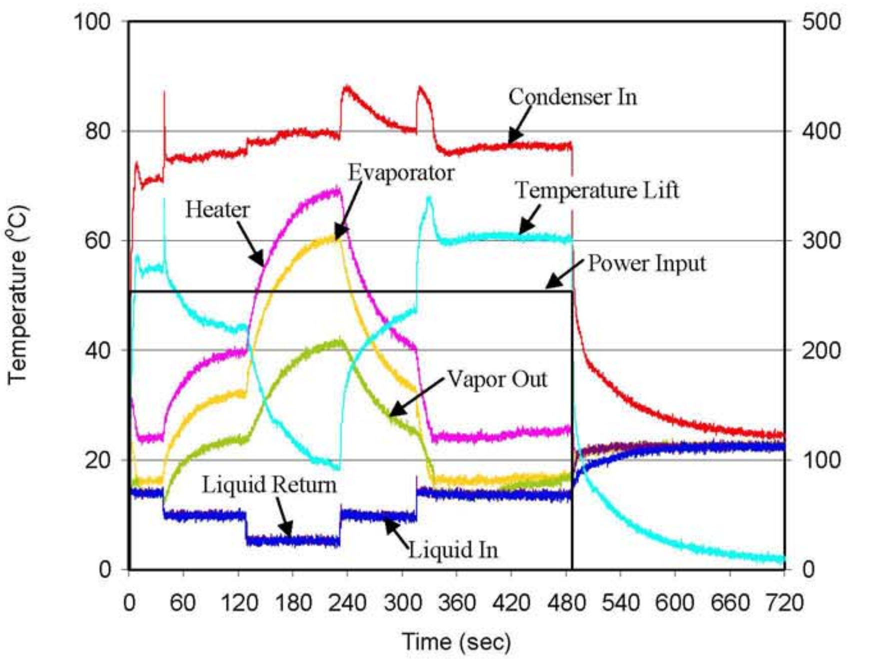


**FIGURE 6.** Temperature and Power Input Profiles of the Vapor Compressor-Driven Hybrid Two-Phase Loop as the Liquid Temperature After the Expansion Valve was Varied.

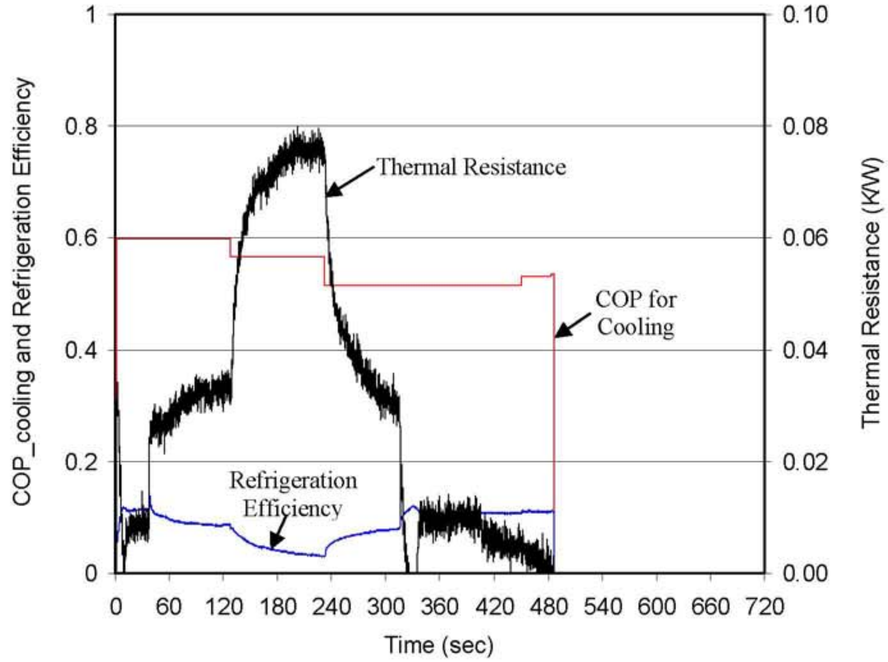


**FIGURE 7.** Coefficients of Performance for Cooling, Refrigeration Efficiency, and Thermal Resistance of Vapor Compressor-Driven Hybrid Two-Phase Loop as the Liquid Temperature After the Expansion Valve was Varied.

## CONCLUSION

The vapor compressor-driven hybrid two-phase loop (VCHTPL) technology was demonstrated through a series of testing using a small-scale prototype. The vapor compression system used an advanced evaporator design for passive liquid/vapor separation and high heat flux heat transfer capability. The evaporator used passive capillary pumping to feed a well-balanced liquid for thin film boiling heat transfer which enhances high heat flux capability. Because of the passive capillary flow control of the evaporator, the vapor compression system did not require the active flow control device such as thermal expansion valve for varying heat input conditions. The high temperature-lift performance and gravity-insensitive capillary phase separation makes the VCHTPL very suitable for lunar missions operating under hot lunar and reduced gravity environment. Some highlights of the technical results and achievements are summarized below.

- High Temperature Lift: The maximum condenser temperature was measured to be 83°C at the heat input of 309W. The maximum temperature lift was 62.7°C at the heat input of 288W. Note that because the maximum radiator heat sink temperature is about 320K at the lunar equator during lunar noon and the heat source temperature of the lunar surface systems is expected to be about 273K, the temperature lift of about 50°C is required to reject the waste heat.
- Gravity-Insensitive Design using Capillary Phase Separation and Oil-less Compression: The capillary phase separation in the evaporator of the VCHTPL removed the gravity-sensitive excess liquid management issue commonly found in other two-phase cooling systems such as evaporative spray cooling. The use of oil-less compressor eliminated the need of the oil separation for compressor lubricant recovery, which relies on gravity force.
- High Heat Input Capability: The evaporator of the VCHTPL was capable of handling high heat flux heat inputs. The evaporator was tested up to 309W (or heat flux of 5.3W/cm$^2$). The evaporator's heat transfer area was 58.1cm$^2$ (= 3 inch × 3 inch).
- No Active Flow Control: The passive liquid/vapor separation using capillary action in the evaporator wick did not require the active flow control which is an indispensable design for the conventional refrigeration systems. The VCHTPL using the capillary phase separation showed a robust operation under variable heat loads.

- Robust Hybrid Two-Phase Loop Design: The VCHTPL combining active mechanical compression and pumping with passive capillary pumping demonstrated its robust hybrid two-phase loop operation.

## NOMENCALTURE

COP = Coefficient of Performance, $T_{evaporator}/(T_{condenser}-T_{evaporator})$
Q = Heat Flux (W/m²)
R = Thermal Resistance (K-m²/W)
T = Temperature (°C, or K]
$\eta_R$ = Refrigerating efficiency, $COP_{cooling}/COP_{Carnot}$

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## REFERENCES

Aidoun, Z., Nikanpour, D. and De-Parolis, L., "Vapor compression heat pump for a lunar lander/rover thermal control," *26th International Conference on Environmental Systems*, Monterey, California, 1996, SAE paper no. 961537.

Birur, G., "JPL Advanced Thermal Control Technology Roadmap-2006," *17th Aerospace Spacecraft Thermal Control Workshop*, El Segundo, California, 2006.

Ewert, M., "Investigation of lunar base thermal control system options," *23th International Conference on Environmental Systems*, Colorado Springs, Colorado, 1993, SAE paper no. 932112.

Kuszewski, M. and Zerby, M., 2002, "Next generation Navy thermal management program," Carderock Division Naval Surface Warfare Center Report CARDIVNSWC-TR-82-2002/12.

Morton, D.R., Bergeron, D., Hurlbert, K.M., Ewert, M. and Cornwell, J., "Proof of Concept high lift heat pump for a lunar base," *28th International Conference on Environmental Systems*, Danvers, Massachusetts, 1998, SAE paper no. 981683.

Nikanpour, D. and De-Parolis, L., "Space-based heat pumps for a lunar lander/rover thermal control," *26th International Conference on Environmental Systems*, Montery, California, 1996, SAE paper no. 961536.

Ponnappan, R., Donovan, B. and Chow, L., "High Power Thermal Management Issues in Space-Based Systems," in the proceedings of *Space Technology and Applications International Forum* (STAIF 2002), edited by M.S. El-Genk, AIP Conf. proceedings 608, Melville, NY, 2002, pp.65-72.

Park, C., Vallury, A., Zuo, J., Perez, J. and Rogers, P., "Electronics Thermal Management using Advanced Hybrid Two-Phase Loop Technology," in the proceedings of *2007 ASME-JSME Thermal Engineering Summer Heat Transfer Conference*, Vancouver, British Columbia, CANADA, 2007a, paper no. HT2007-321962.

Park, C., Vallury, A., Zuo, J., Perez, J. and Rogers, P., "Spacecraft Thermal Management using Advanced Hybrid Two-Phase Loop Technology," in the proceedings of *2007 Space Technology and Applications International Forum (STAIF 2007)*, edited by M.S. El-Genk, AIP Conf. proceedings 608, Melville, NY, 2007b, pp. 65-72.

Park, C., Vallury, A. and Perez, J., "Advanced hybrid cooling loop technology for high performance thermal management," in the proceedings of *4th International Energy Conversion Engineering Conference*, San Diego, California, 2006, paper no. AIAA 2006-4059.

Park, C., Zuo, J. and Perez, J., "Advanced Hybrid Loop Technology for High Heat Flux Laser Cooling," *3rd International Energy Conversion Engineering Conference*, San Francisco, California, 2005a, paper no. AIAA 2005(a)-5696.

Park, C., Zuo, J., Rogers, P. and Perez, J., "Two-Phase Flow Cooling for Vehicle Thermal Management," 2005 *SAE World Congress*, Detroit, Michigan, 2005b, SAE paper no. 2005-01-1769.

Swanson, T., Radermacher, R., Costello, F., Moore, J., and Mengers, D., "Low-temperature thermal control for a lunar base," *20th Intersociety Conference Environmental Systems*, Williamburg, Virginia, 1990, SAE paper No. 901242.

Swanson, T. and Butler, D., "NASA/Goddard Thermal Control Technology Roadmap-2006," *17th Aerospace Spacecraft Thermal Control Workshop*, El Segundo, California, 2006.

Zuo, J., Park, C. and Sarraf, D., "Hybrid Loop Cooling of High Heat Flux Components," *2nd International Energy Conversion Engineering Conference*, Providence, Rhode Island, 2004, paper no. AIAA 2004-5612.