Development and Application of a Passive Variable Conductance Loop Thermosyphon

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Moon exploration and using it as a platform for further exploration missions in the solar system brings unique electrical, electronic, and thermal challenges. Large quantities of electronic devices and power generation systems will be deployed to the Moon. Rejecting the large amounts of waste heat from such devices (e.g., ~kWs from Polymer Electrolyte Membrane Fuel Cells "PEMFC") in an environment with significant temperature swings while keeping the devices' temperature within an optimal range requires novel concepts. In order to address this unique challenge, Advanced Cooling Technologies Inc. (ACT) developed a novel passive Variable Conductance Loop Thermosyphon (VCLTS) that can passively remove large amounts of heat and maintain the evaporator (heat source) temperature within a required range regardless of the significant swings in the sink temperature. Key thermal performance results as well as different configurations of the VCLTS are presented.

I. Nomenclature

ACT = Advanced Cooling Technologies
LTS = Loop Thermosyphon
MW = Megawatt
NCG = Non-Condensable Gas
PEMFC = Polymer Electrolyte Membrane Fuel Cells
VCHP = Variable Conductance Heat Pipe
VCLTS = Variable Conductance Loop Thermosyphon

II. Introduction

In conventional thermal management systems, the temperature is controlled by active means (e.g., mechanical or electrical). For example, in regular cars, a thermostat is used to control single-phase coolant flow to control the temperature. Active thermal control results in significant weight penalty (e.g., pump, actuators, etc.), reduction of the overall efficiency of the system (e.g., pumping power), and less reliability and durability due to the fact of having moving parts. On the other hand, passive thermal control devices overcome those disadvantages. This makes them ideal for applications such as planetary landers and surface systems where a thermal management system failure may result in the whole mission failure. The development of advanced lunar landers and surface systems is challenging since there is a need to extend the duration of the missions in both cold and hot environments, including lunar and planetary surface systems. The heat rejection turn–down ratio of the increased thermal loads in the above-mentioned conditions is crucial for minimizing vehicle resource needs (e.g. power). For example, lunar or planetary surface systems will include high-power generation systems ($\geq$ 10 kW) such as Polymer Electrolyte Membrane Fuel Cells (PEMFC) which also need to operate within an optimal temperature range. Therefore, future exploration activities will need advanced thermal management systems that can passively remove large amounts of heat and control the device temperature in extreme environments. In addition to the lunar and planetary applications, multiple terrestrial applications would benefit from passive thermal control devices such as PEMFEC for power generation systems, trucks, and electric aircraft.

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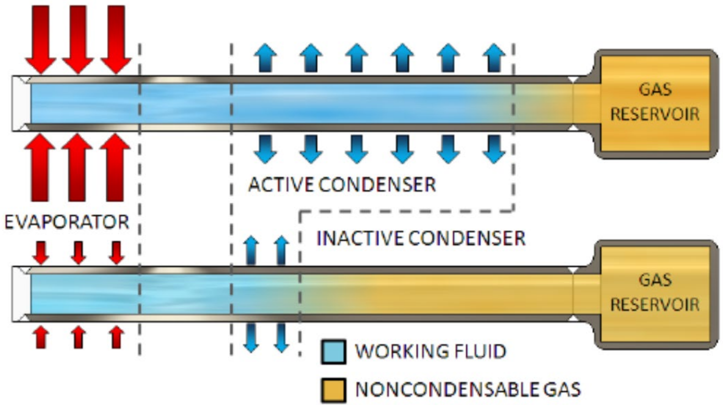


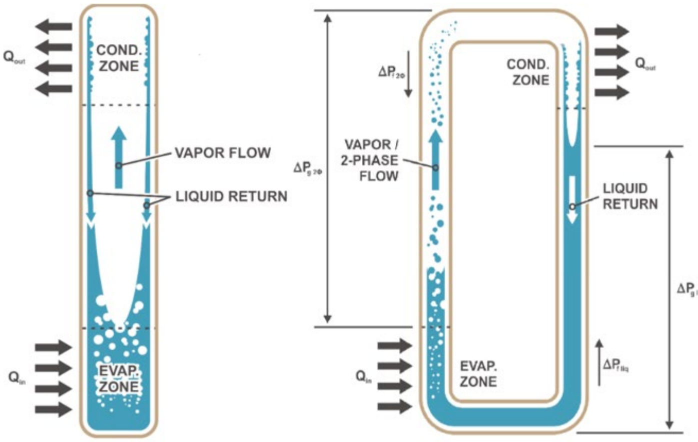
Fig. 1 Illustration of the working principle of VCHP. At high heat load, the saturation pressure of the working fluid is high and compresses the non-condensable gas (NCG) into the reservoir (fully open condenser). At lower heat input the saturation pressure is lower and NCG expands into the condenser (partially open condenser) [4].

Variable Conductance Heat Pipes (VCHPs) can be used in aircraft and spacecraft thermal control when the evaporator (electronics) temperature must be maintained as the power and heat sink conditions vary. It is similar to a conventional heat pipe but has a reservoir and controlled amount of non-condensable gas (NCG) inside the reservoir. Figure 1 shows a schematic of how a VCHP works. The VCHP works by varying the amount of heat rejection area in the condenser to the working fluid. As the evaporator temperature increases, the vapor temperature (and pressure) rises, the NCG compresses (Fig. 1 top) and more condenser area is exposed to the working fluid. This increases the conductivity of the heat pipe and drives the temperature of the evaporator down. Conversely, if the evaporator cools, the vapor pressure drops and the NCG expands (Fig. 1 bottom). This reduces the heat rejection area in the condenser, decreases the heat pipe conductivity, and maintains the evaporator temperature within a small range. ACT has a long history of developing VCHPs for different applications [1].

Although VCHPs (e.g., cold and hot reservoirs configurations) offer good passive thermal control, they can only transfer limited power (e.g., ~100s W per pipe) over short distances (e.g., < 1 m) due to the limited wick pumping capability. These limitations show the need for a passive thermal control device that can transfer large amounts of heat (e.g., ~kWs) over long distances (e.g., >1 m) while maintaining the evaporator temperature within the required range under different heat sink conditions. Such a device can satisfactorily address the thermal management needs of sophisticated applications such as MW-class commercial electric aircrafts, heavy-duty hydrogen fuel cells, lunar and planetary surface systems, etc. Therefore, ACT developed a novel variable conductance loop thermosyphon that can meet all the requirements and satisfy those sophisticated applications.

III. Loop Thermosyphon (LTS) vs. Variable Conductance Loop Thermosyphon (VCLTS)

A loop thermosyphon (LTS) is a specialized configuration of thermosyphons that uses two-phase heat transfer (evaporation/condensation) to deliver heat effectively and passively. In a regular single-tube thermosyphon (as shown in Fig. 2 (a)), a working fluid absorbs heat and boils in an evaporative region. Vapor rises along the tube to the condenser, where it condenses, releasing thermal energy. The condensed liquid returns to the evaporator via gravity, falling along the walls of the thermosyphon, counter-current to the vapor flow. The flooding limit constrains the maximum power of a thermosyphon and is imposed by shear forces between a high-velocity, upward vapor flow, and downward liquid return flow. The flooding limit can be bypassed by using a loop thermosyphon. LTS operation is illustrated in Fig. 2 (b). In an LTS, the condensate returns to the evaporator in a line separate from the rising vapor phase. With separate vapor and liquid lines, shear between the phases is eliminated, removing the flooding limit constraint. In other words, for the same pipe diameter LTS can transport higher power than a single-tube



(a) (b)

Fig. 2 Operation schematics of (a) Traditional single-tube thermosyphon and (b) Loop thermosyphon [2].

thermosyphon. The gravitational head of the liquid condensate beneath the condenser ($\Delta P_{g,liq}$) is the passive pumping force in the loop thermosyphon and should overcome all the pressure losses in the loop. Resisting this positive head is the gravitational head of the two-phase flow ($\Delta P_{g,2\Phi}$) and frictional pressure drops in the liquid ($\Delta P_{f,liq}$) and two-phase lines ($\Delta P_{f,2\Phi}$). The sum of acceleration ($\Sigma\ \Delta P_a$) and minor pressure losses ($\Sigma\ \Delta P_m$) also resist the fluid flow and must be accounted for. During steady-state loop thermosyphon operation, these six pressure components must be in equilibrium. ACT developed a model to predict the total pressure losses and the thermal performance of a loop thermosyphon. To estimate thermal losses from the loop thermosyphon and better predict heat transfer within the evaporator and condenser, heat transfer coefficients were calculated throughout the single and two-phase sections of the loop. ACT developed loop thermosyphons for different applications [2].

Leveraging ACT's expertise in passive thermal control technologies [1], ACT developed a **novel passive variable conductance loop thermosyphon** (VCLTS) concept, which allows the system to maintain operating temperature within a narrow band regardless of heat load/sink changes. This can be achieved by integrating an NCG reservoir into the adiabatic section of the loop thermosyphon. The modes of operation of VCLTS are described in Fig. 3.

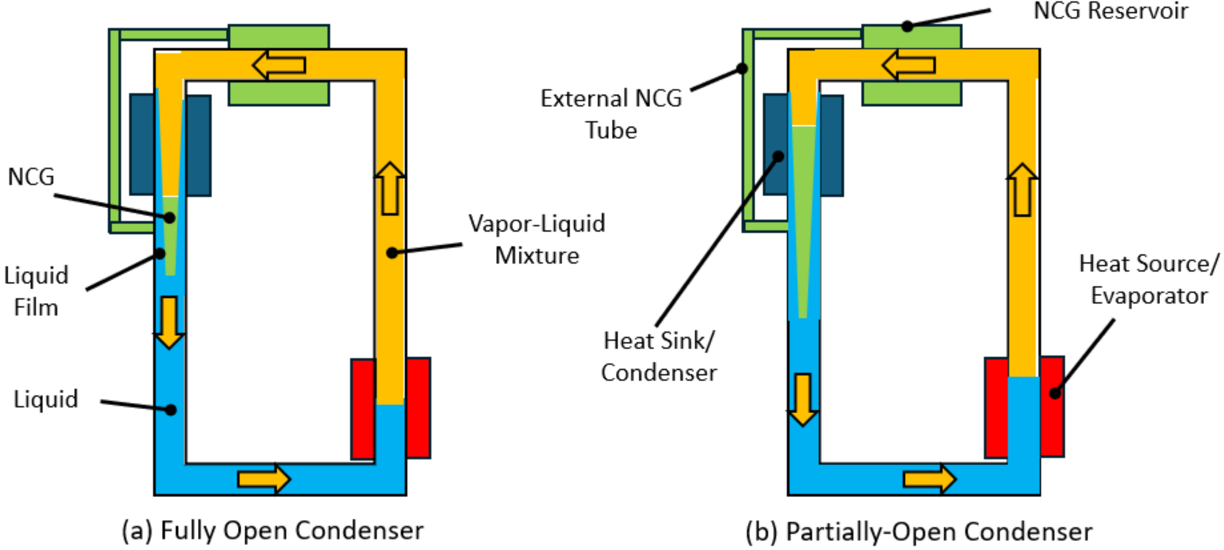
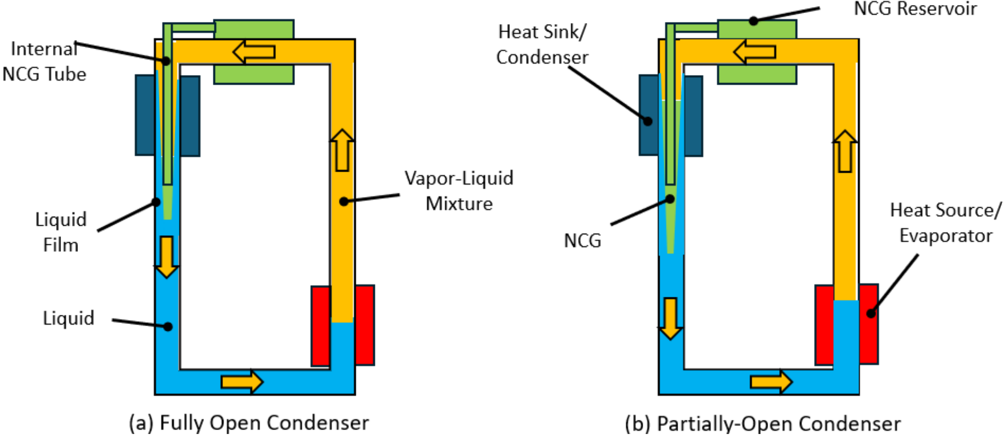


Fig. 3 A schematic of two operation modes of a VCLTS. (a) VCLTS with a fully open condenser and (b) VCLTS with a partially open condenser. Arrows indicate the two-phase flow direction.

- In Fig. 3 (a), the system is in the nominal operating mode where it is designed to reject all the heat added by the heat source/evaporator through a fully open heat sink/condenser (i.e., all the condenser surface area is used for heat rejection) at a maximum sink temperature. In this case, most of NCG is in the reservoir while a certain amount of NCG is compressed below the condenser between the working fluid vapor and liquid. At the nominal operating mode, the vapor pressure and temperature are at their maximum operating values (both values are coupled since the system is under saturation conditions). The front/interface between the NCG and vapor is under equilibrium (i.e., the pressure forces on both sides are balanced).
- Another operation mode is when the heat load decreases and/or the heat sink temperature decreases. If there is no variable conductance feature, the whole system temperature will decrease. However, with the variable conductance feature, as illustrated in Fig. 3 (b) when the vapor saturation pressure tends to decrease (due to reduction of vapor temperature), the interface between the vapor and NCG will move up to reach a new pressure equilibrium state. NCG expansion will partially blanket the condenser and lead to a reduction of heat rejection rate. The heat source temperature can be controlled within the specified range. It is important to note this this temperature adjustment mechanism is fully passive, meaning that no moving parts, no power and no feedback control algorithm are needed.

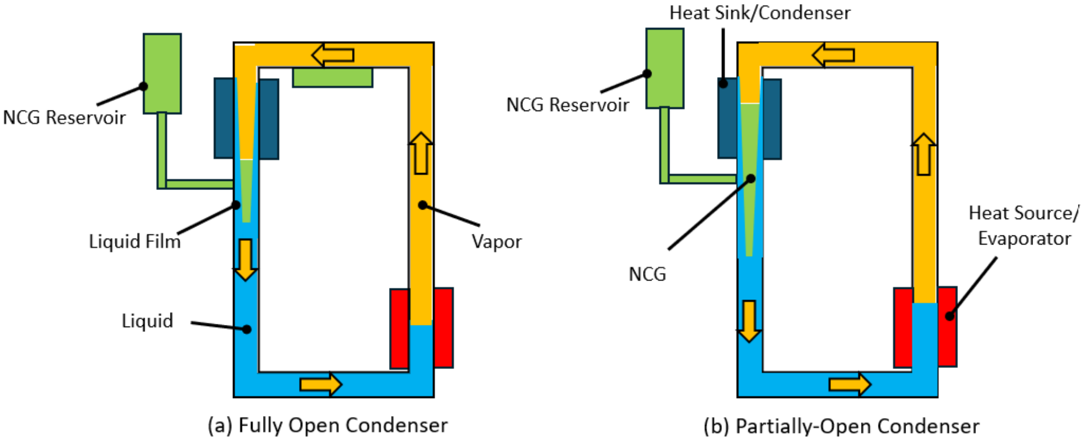
The system illustrated in Fig. 3 is only one specific realization of the VCLTS concept. The system can have an arbitrary number of configurations. Figure 4 shows a different configuration of the VCLTS where the NCG tube is inserted into the downcomer of the LTS. Note that the operation theory is the same as the original VCLTS configuration in Fig. 3. Other versions of the VCLTS are presented in Fig. 5-7. In Fig. 5, the NCG reservoir is cold-biased and is affected by the sink temperature. The thermal control of the cold-biased reservoir is not as tight as that of the hot reservoir version. To further improve thermal control of the VCLTS simple active features can be utilized. To improve the thermal control capability of the cold-reservoir version, the reservoir conditions can be controlled by a heater (see Fig. 6). Tighter thermal control can be achieved by using a pressure-controlled reservoir where the reservoir body is flexible (e.g., bellow) and its volume is controlled by a step motor or actuator (see Fig. 7).The VCLTS can be easily integrated with a multitube condenser (e.g., two-phase radiator) as shown in Fig. 8. The vapor line is connected to the upper condenser manifold while the external NCG tube is connected to the lower condenser manifold bypassing all the condenser body. The vapor condenses in multiple vertical tubes. NCG can partially block those multiple vertical tubes based on the thermal control design parameters. ACT has filed a non-provisional patent (18/956,984, 2024-06) of this work.



(a) Fully Open Condenser

(b) Partially-Open Condenser

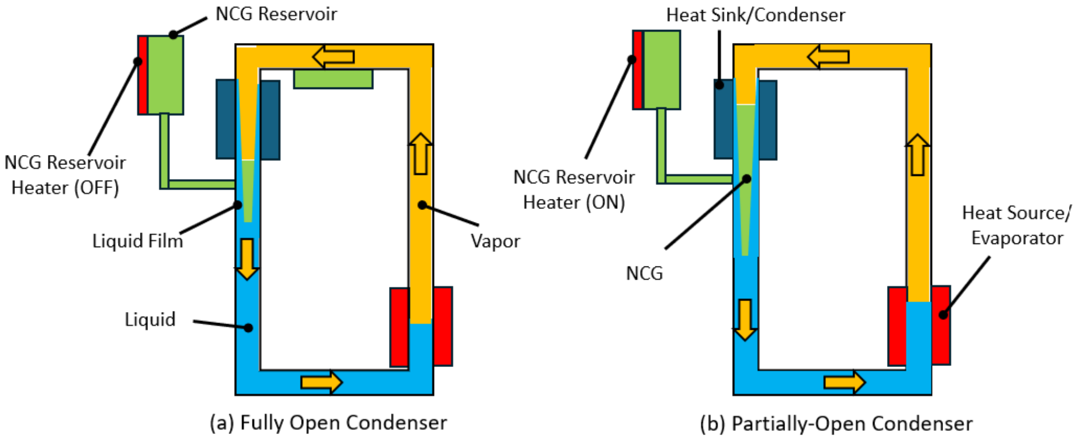
Fig. 4 A schematic of another configuration of the VCLTS where the NCG tube is inserted into the downcomer of the LTS. (a) VCLTS with a fully open condenser and (b) VCLTS with a partially open condenser. Note that the operation theory is the same as the original VCLTS configuration in Fig. 3.



(a) Fully Open Condenser

(b) Partially-Open Condenser

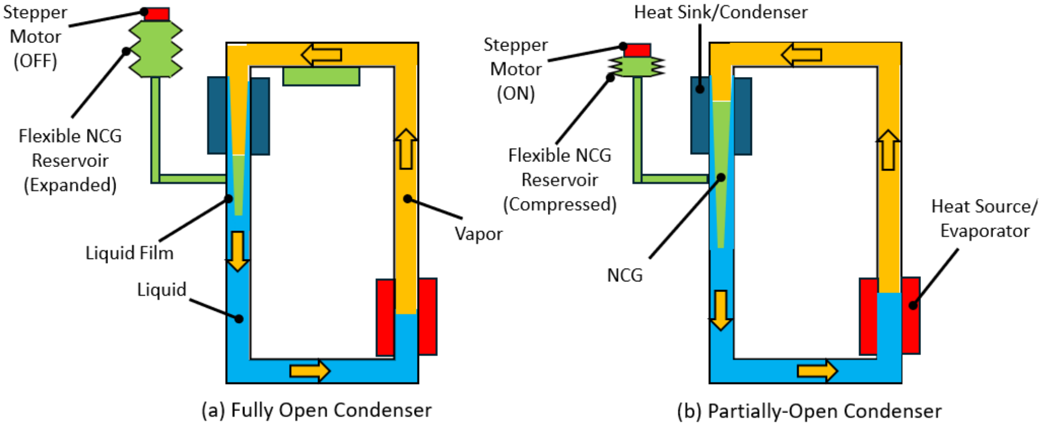
Fig. 5 A schematic of another configuration of the VCLTS where the NCG reservoir is cold-biased (the reservoir temperature is affected by the sink temperature). (a) VCLTS with a fully open condenser and (b) VCLTS with a partially open condenser.



(a) Fully Open Condenser

(b) Partially-Open Condenser

Fig. 6 A schematic of another configuration of the VCLTS where the NCG reservoir conditions are controlled by a heater. (a) VCLTS with a fully open condenser and (b) VCLTS with a partially open condenser.



(a) Fully Open Condenser

(b) Partially-Open Condenser

Fig. 7 A schematic of another configuration of the VCLTS where the NCG reservoir is flexible and controlled by a step motor or actuator. (a) VCLTS with a fully open condenser and (b) VCLTS with a partially open condenser.

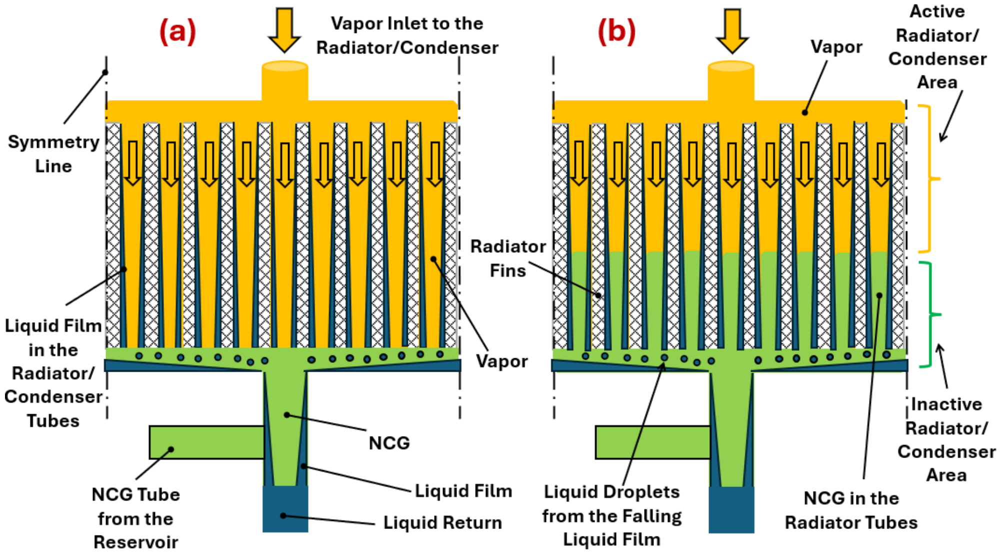


Fig. 8 Multitube condenser (e.g., air-cooled radiator) version of the VCLTS. (a) Fully open condenser and (b) Partially open condenser.

IV. VCLTS Prototype Development and Testing

To demonstrate the proposed passive thermal control feature, a VCLTS prototype was built and tested (see Fig. 9). The prototype was made of stainless steel. Heater blocks were used as a heat source. The reservoir is integrated to the vapor line. Note that the reservoir is welded on the external wall of vapor line (i.e., the vapor tube is concentric inside the reservoir pipe which means the vapor and NCG do not communicate in the reservoir). Multiple experiments were conducted to demonstrate the passive thermal control feature by observing evaporator temperature changes while significantly varying heat load and/or sink temperatures. Two working fluids (de-ionized water and methanol) were tested while in both tests, argon was used as the NCG.

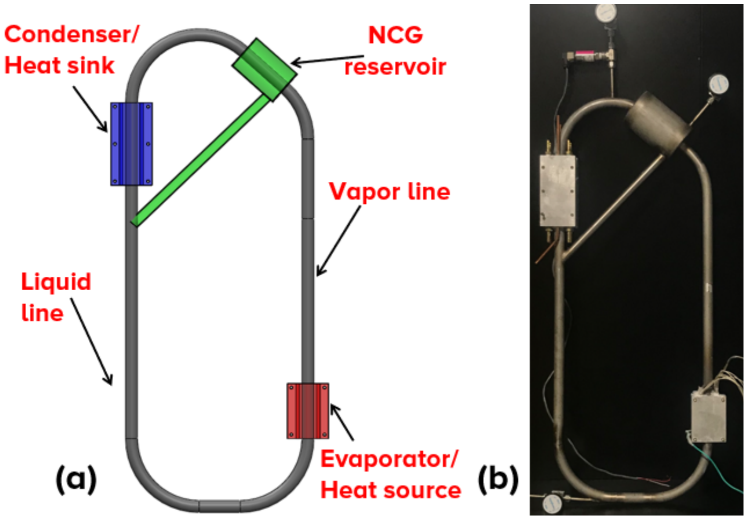


Fig. 9 ACT’s VCLTS: (a) CAD model and (b) actual prototype.

Figure 10 shows temperature measurements along the VCLTS components while maintaining the heat input at 900 W during the whole test and significantly varying the sink temperature from 45˚C to -32˚C and back to 45˚C. De-ionized water is used as the working fluid. Note that the sink temperature is the temperature of the chiller block not the working fluid inside the VCLTS. The lowest sink temperature was selected to make sure the water does not reach freezing temperatures. The sink temperature dropped by 77˚C while the evaporator dropped by only 18˚C. In other words, the thermal conductance of the device passively changed from 18 W/°C (at the maximum sink temperature) to 8.8 W/°C (at the minimum sink temperature) to keep the evaporator temperature from dropping significantly.

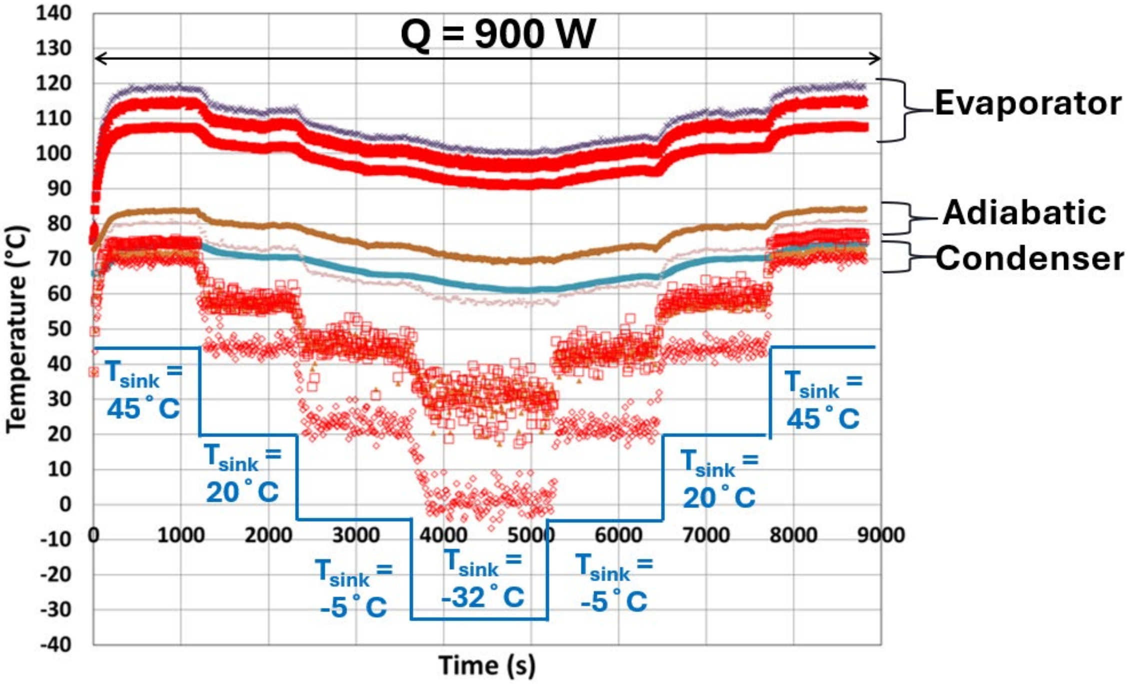


Fig. 10 Temperature measurements along the VCLTS components while maintaining the heat input at 900 W and significantly varying the sink temperature from 45˚C to -32˚C and back to 45˚C. De-ionized water is used as the working fluid. Note that the sink temperature is the temperature of the chiller block not the working fluid inside the VCLTS. The lowest sink temperature was selected to make sure the water does not reach freezing temperatures.

In order to test the thermal performance of the VCLTS under extremely low sink temperatures, the VCLTS was charged with methanol as the working fluid. Figure 11 shows the temperature measurements along the VCLTS components under two different testing scenarios: first, maintaining the power constant at 300 W while significantly varying the sink temperature from 40˚C to -80˚C and then maintaining the sink temperature constant at -80˚C and significantly varying the power from 300 W to 100 W. In this test, methanol was used as the working fluid. The very low sink temperature (-80˚C) used in this test shows that this concept can handle extreme temperatures. It can be observed that the evaporator temperature dropped by 32˚C when the sink temperature significantly dropped by 120˚C (from 40˚C to -80˚C) while the power was maintained at 300 W. In addition, the evaporator temperature dropped by around 11˚C while the power was significantly reduced by 67% (from 300 W to 100 W) and the sink temperature was kept constant at -80˚C. A turndown ratio of 12 was achieved in these testing conditions (i.e., the thermal conductance passively decreased from 10 W/°C at maximum power and sink temperature to 0.83 W/°C at minimum power and sink temperature).

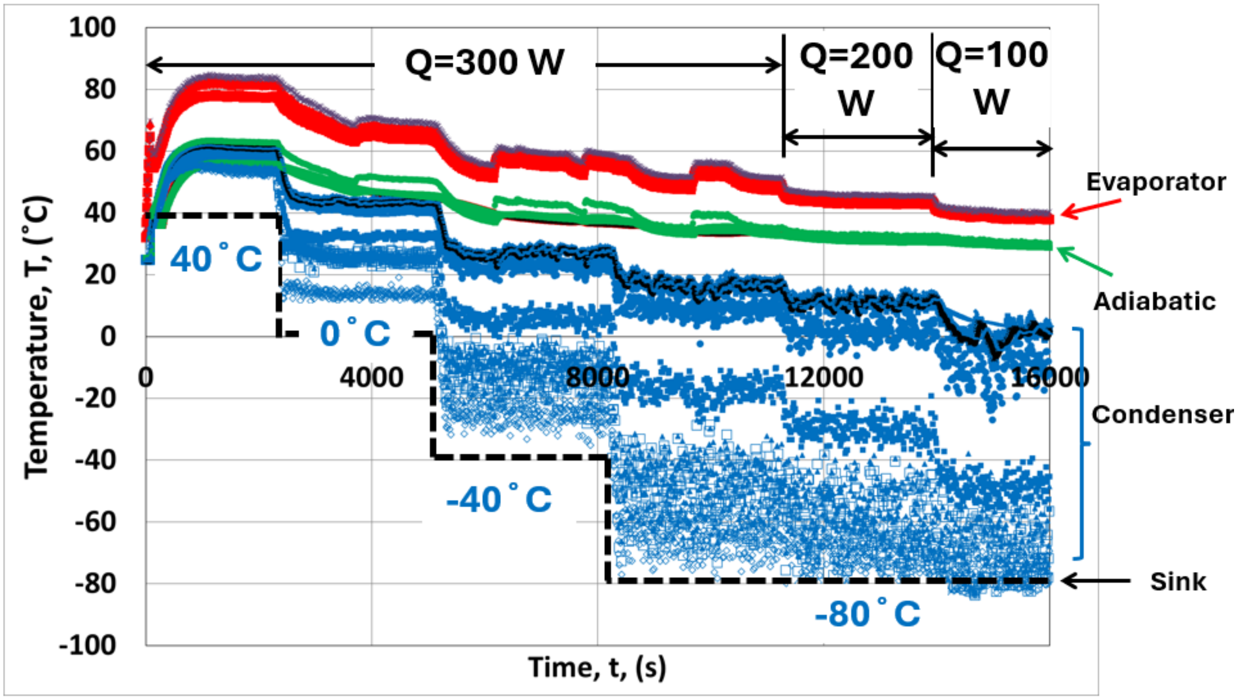


Fig. 11 Temperature measurements along the VCLTS components under two different testing scenarios: maintain the power constant at 300 W while significantly varying the sink temperature from 40˚C to -80˚C and then maintaining the sink temperature constant at -80°C and then maintaining the sink temperature constant at -80˚C and significantly varying the power from 300 W to 100 W.

The variable conductance feature effectiveness is shown in Fig. 12 through a comparison between the maximum evaporator temperature of LTS (without NCG reservoir) and VCLTS at various heat loads. Without a variable conductance feature, the evaporator temperature dropped by 29˚C (32%) when the power was turned down by 67% while in the case of the VCLTS, the evaporator temperature dropped only by 16˚C (17.7%). Figure 13 shows the conductance (W/˚C) values of both LTS and VCLTS at different sink temperatures (-32˚C to 45˚C) and a constant power (900 W). In this test, water was the working fluid. It can be observed that the VCLTS passively changed its conductance from maximum value at the maximum sink temperature (45˚C) to minimum value at the lowest sink temperature (-32˚C).

The dynamic response of the thermal management system is important since it will indicate how long the system will experience certain thermal conditions when a parameter is varying. In terms of a thermal system, the thermal mass of each component is considered, which depends on the mass and specific heat capacity. Higher thermal inertia leads to longer heat-up times of coolant and components. Further, during harsh ambient conditions, components can be operated longer at maximum power. As shown in Fig. 14, the VCLTS took around 6.6 minutes to reach steady state conditions when the power was reduced by 33% (around 60% faster than the LTS). Compared to a pumped single-phase loop, it is expected that VCLTS can have faster thermal response because (1) less fluid amount (this system has a fill ratio of only 30-35%), (2) vapor is at saturation state, (3) less thermal mass (e.g., no pump exists. In addition, this concept allows for a radiator size reduction which will lower the system's thermal mass).

This novel device can provide superior advantages when compared to actively controlled single-phase liquid cooling systems such as:

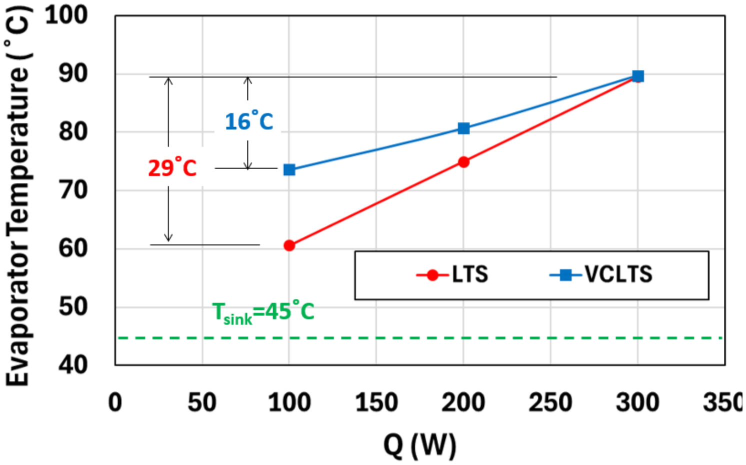


Fig. 12 Comparison between the maximum evaporator temperature of both LTS and VCLTS at different power values. Methanol is the working fluid.

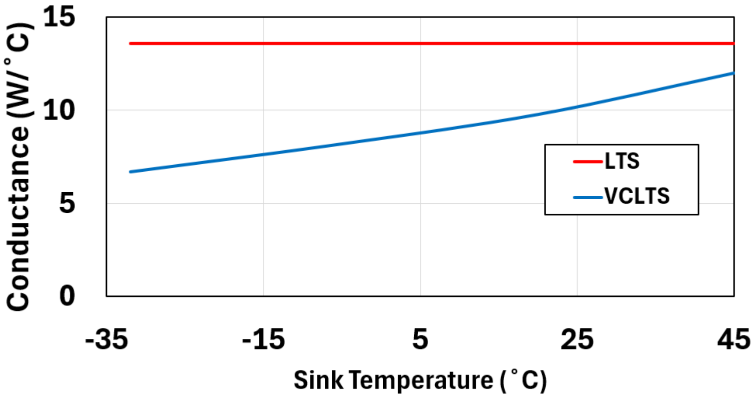


Fig. 13 Conductance (W/˚C) values of both LTS and VCLTS at different sink temperatures (-32˚C to 45˚C) and a constant power (900 W).

- Increased efficiency: There are two main factors that allow efficiency increase: (1) maintaining the heat source (e.g., electronics, fuel cells, etc.) temperature passively in the optimum range to ensure it can operate at high efficiency all the time and (2) the elimination of the pumping power
- More compact radiator: There are two main factors that reduce the radiator size when compared to the common pumped single-phase system: (1) higher heat transfer coefficients at both evaporator and condenser that allows the radiator to work at higher temperature for the same evaporator temperature and (2) isothermal tubing in the radiator (as opposed to the temperature gradient that single-phase causes).
- Simplicity: The variable conductance feature allows passive temperature control and eliminates complex valves, pump, and feedback control system.

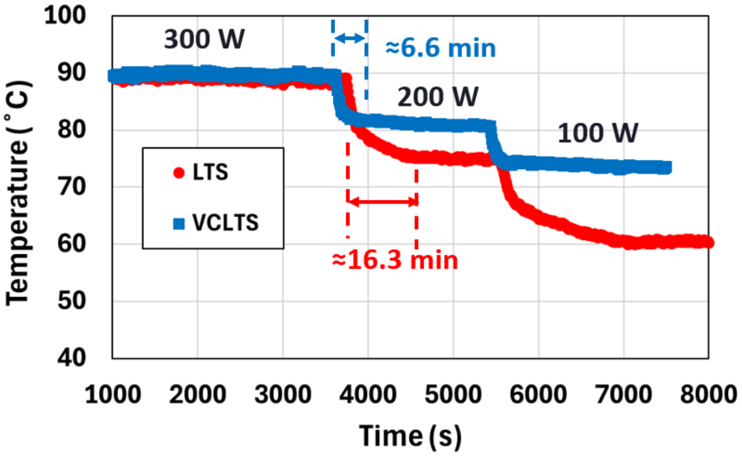


Fig. 14 Dynamic response of the LTS and VCLTS when the power is reduced.

- High reliability and improved durability due to the elimination of moving parts (e.g., pumps) and the stabilization of heat source temperature (electronics, fuel cell, etc.).
- Cost-effective: Shrinkage of radiator, elimination of moving parts and coolant control system reduces capital and operational costs.
- Reduced noise levels: Due to the pump elimination, the proposed system does not generate noise.
- Fast dynamic response: Because of both the reduced thermal mass (significantly less working fluid and more compact radiator) and the variable conductance feature, the proposed thermal management system is expected to respond faster to dynamic situations. In addition, the system will enable faster startup from cold conditions and, consequently, less energy consumption.

V. Conclusions and Future Work

ACT successfully developed a novel passive variable conductance loop thermosyphon (VCLTS). Two working fluids (methanol and water) were tested. Argon was used as an NCG. A non-provisional patent (18/956,984, 2024-06) of this work has been filed. The conclusions are listed below.

- Different design configurations of the VCLTS are presented.
- A prototype VCLTS was fabricated and demonstrated that the evaporator temperature can be passively maintained within ±9˚ while the sink temperature significantly varied by ±39˚C.
- Without a variable conductance feature, the evaporator temperature of this prototype dropped by 29˚C (32%) when the power was turned down by 67% while in the case of the VCLTS, the evaporator temperature dropped only by 16˚C (17.7%).
- The VCLTS provides a faster dynamic response to significant changes in the sink temperature or the power when compared to the LTS. The VCLTS took around 6.6 minutes to reach steady state conditions when the power was reduced by 33% (around 60% faster than the LTS).
- The VCLTS can provide higher efficiency and reliability, lower cost, smaller radiators, and no noise when compared to an equivalent pumped single-phase liquid cooling system.

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