Two-Phase Thermal Switch for Spacecraft Passive Thermal Management

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Future manned and unmanned spacecraft will venture far beyond the relatively benign environment of low Earth orbit. The combination of extreme environments and high turndown requirements present a significant challenge for spacecraft thermal control systems. Thermal switches are among the thermal control devices that will be required to dissipate a wide range of heat loads in widely varying environments. A novel two-phase passive thermal switch technology has been developed and demonstrated. This technology uses the condensing vapor of a saturated two-phase working fluid to both transfer the heat and provide the contact pressure for the heat transfer surfaces of the switch. The switching mechanism is passively triggered by the temperature of the heat source. In addition to the On/Off capability of a thermal switch, the technology serves as a variable thermal link while in the On condition to maintain a heat source set point temperature. This set point temperature is determined by the design of the switch. In this paper, the principles of operation of the two-phase thermal switch are presented. A prototype switch was built and tested over a range of conditions. The set point temperature was determined for a range of enclosure gas counter pressures, and the maintenance of a heat source set point temperature is demonstrated. The performance of the unoptimized prototype switch is characterized and shown to have a nominal On thermal conductance of 0.7 W/K and an On/Off conductance ratio of 20.

Nomenclature

A_c	=	heat transfer surface cross-sectional area
k	=	bellows spring constant
P_g	=	enclosure gas counter pressure
P_v	=	saturated vapor pressure
T	=	temperature
T_0	=	initial temperature
Δy_{ext}	=	bellows extension from initial compressed length
Δy_T	=	bellows compression at increased vapor temperature
Δy_0	=	initial bellows compression

I. Introduction

Future human spacecraft will venture far beyond the relatively benign environment of low Earth orbit. Astronauts will transit through deeps space, but may also encounter warm transient environments. Additionally, unmanned spacecraft such as satellites, and science missions such as the Mars rover, experience large swings in environment temperature. Some spacecraft elements may be launched untended and would operate at comparatively low power levels as they transmit to their final destination. The combination of extreme environments and high turndown capability requirements will be a significant challenge for future spacecraft thermal control systems. In these conditions, thermal switches, also called heat switches, are among the thermal control devices used to dissipate a wide range of heat loads in widely varying environments, while minimizing use of the limited spacecraft mass, volume, and power resources. In the NASA Office of Chief Technologist roadmap, it is clearly stated that "improvements in

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thermal switch technology are possible". The primary goals for improvement are higher On thermal conductance with lower device mass, and higher ratios of conductance between the On and Off conditions.

In this paper, a novel two-phase passive thermal switch technology is presented. This technology uses a saturated working fluid to both transfer heat and provide pressure for the contacting heat transfer surfaces. In addition to operating as a traditional thermal switch with On/Off capabilities, the technology serves as a variable thermal link while in the On condition to maintain a fixed heat source set point temperature, which is determined by the design of the switch. The theory and design of the two-phase thermal switch and experimental results are presented here.

II. Current Thermal Switch Technologies

There are many thermal switch configurations that have been developed in the past for spacecraft thermal control, in particular for cryogenic systems. Each configuration is based on a different working principle, but the purpose of all of them is to modulate a break in thermal contact in order to reduce the parasitic heat load from a redundant refrigeration system, or to break the thermal contact between a heat source and heat sink. Two primary generic types of thermal switches have received particular attention: mechanical thermal switches, and gas-gap thermal switches.

Mechanical thermal switches control heat flow through the contact of two surfaces with passive control of the mechanical contact. Examples of mechanical thermal switches include the paraffin actuated thermal switch used on the Mars Exploration Rover (Sunada et al., 2002), a cryogenic thermal switch based on two materials with differences in coefficients of thermal expansion (Marlan et al., 2002), and a cryogenic thermal switch based on a shape memory alloy (You et al., 2004). The primary disadvantages of thermal switches of this nature are their relatively complex configurations and precision manufacturing and assembly requirements.

The gas-gap thermal switch typically consists of two cylindrical pieces separated by a small gap, which is filled with a conductive gas (Bugby et al., 1999). Gas-gap thermal switches are actively controlled, and require a complex system to introduce and extract the gas. This is usually accomplished by a sorption pump and an imbedded heater, or by a pressurized gas reservoir. A major disadvantage of gas-gap thermal switches is the extremely narrow and highly precise flat gap, hermetic seals, and the sorption pump for active control. Additionally, gas-gap thermal switches often require a long and thin gas transportation line between the sorption pump and the gas gap in order to reduce the heat leak. This makes the gas in the gap difficult to be evacuated, leading to long response times to turn the switch Off.

III. Two-phase Thermal Switch Design and Operation

A. Thermal Switch Operation

The two-phase thermal switch, shown schematically in Figure 1, consists of a metallic bellows encapsulated in an enclosure. The bellows is hermetically sealed and contains a small amount of a saturated working fluid. One end of the bellows is attached to the inner surface of the enclosure, which in turn is attached to the heat source. The opposite end of the enclosure is attached to the heat sink. The space surrounding the bellows inside the enclosure can either be vacuum or filled with a non-condensable gas (NCG).

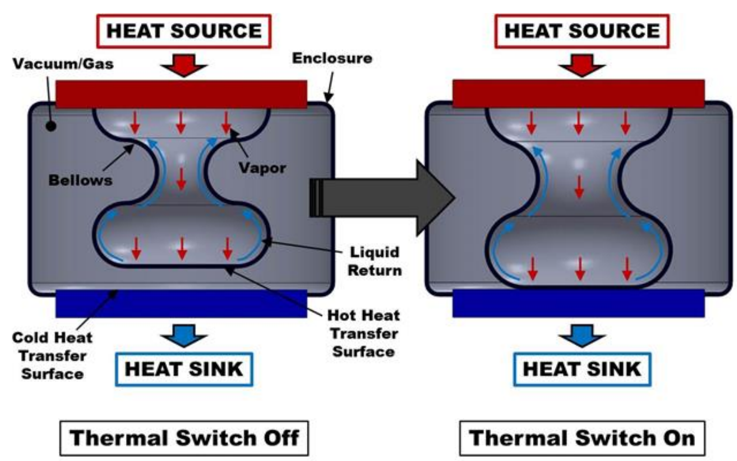

Figure 1. Conceptual schematic of the two-phase thermal switch.

The two-phase thermal switch works in a similar manner to two-phase heat transfer devices such as heat pipes. A screen wick structure is present inside the bellows to allow liquid working fluid to be transported by capillary action from one end of the bellows to the other. Heat from the heat source vaporizes the liquid from the wick and the vapor flows to the heat transfer surface located at the opposite end of the bellows. Here the vapor condenses and releases its latent heat, while the condensate is pumped back to the hot end through the wick structure.

The vapor pressure inside the bellows is the driving force that causes the displacement that allows the end of the bellows to come in contact with the enclosure surface. As heat is transferred into the bellows, the temperature of the saturated working fluid increases, and thus the vapor pressure increases accordingly. At a certain temperature, the bellows will have expanded to the point where it is in contact with the heat transfer surface of the enclosure. The vapor temperature at which the bellows makes contact can be determined from the design of the thermal switch. As a first order model, the bellows extension as a function of vapor temperature can be predicted by performing a force balance on the bellows. In this model, the counter pressure of the NCG in the surrounding enclosure (P_g) is balanced by the vapor pressure inside the bellows, $P_v(T)$, and the force resulting from Hooke's Law (compression and extension of the bellows). For a constant bellows spring rate k and contact surface area A_c, the initial compression of the bellows, Δy_0, when the temperature is at ambient temperature T_0, can be found from Eq. (1).

$$\Delta y_0 = \frac{A_c}{k}\left(P_g - P_v(T_0)\right) \tag{1}$$

From this initial compression, the extension of the bellows, Δy_{ext}, for increased vapor temperature T, can be found from Eq. 2. Also refer to Figure 2.

$$\Delta y_{ext} = \Delta y_0 - \Delta y_T = \Delta y_0 - \frac{A_c}{k}\left(P_g - P_v(T)\right) \tag{2}$$

A set point temperature can be defined for the two-phase thermal switch as the vapor temperature at which the bellows comes into contact with the heat transfer surface on the inside of the enclosure. This temperature can be determined from the above equations. If the distance to contact is set to be equal to the initial compression of the bellows, then the set point temperature is the working fluid saturation temperature when the vapor temperature is equal to the NCG counter pressure. The set point temperature can also be determined for other initial distances to contact from the above force balance.

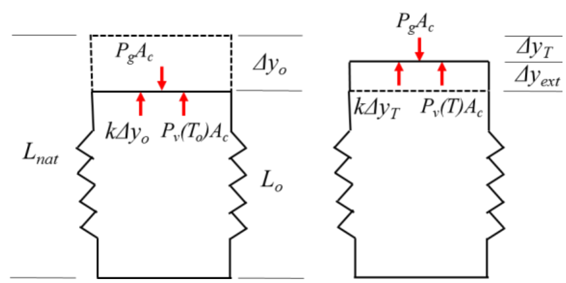

Figure 2. Force balance for determining bellows extension and thermal switch set point temperature.

In reality, the operation of the two-phase thermal switch is more complicated than the static model above. The two-phase thermal switch operates in two modes. The first is similar to a conventional thermal switch; when no heat source is applied, the bellows is compressed and no contact is made, and therefore the switch is Off. When heat is applied, the vapor temperature increases and the bellows expands until the set point temperature is reached and contact between the heat transfer surfaces is made. The switch is therefore On. However, while the switch is On, the contact between the heat transfer surfaces is not continual. When the bellows makes contact with the heat sink, some heat is transferred from the bellows, slightly lowering the vapor temperature, causing the bellows to contract slightly and disconnect from the heat sink surface. As heat continues to be applied, the vapor temperature rises again until the bellows comes back in contact with the sink, where heat is transferred, lowering the vapor temperature, and so forth. This dynamic mode of operation causes the bellows to oscillate and be in periodic contact with the heat sink, with the frequency of oscillation dependent on the temperature of the sink and the applied power. As the sink temperature is reduced, the vapor temperature, and corresponding heat source temperature, will not drop below the set point. In this way, the two-phase thermal switch also acts as a variable thermal conductance device in addition to an On/Off switch.

B. Thermal Switch Prototype Design

A prototype two-phase thermal switch was designed and built to demonstrate the principles of operation. This prototype is shown in Figure 3. An off-the-shelf beryllium copper bellows with a spring rate of 19 lbf/in (3328 N/m) was used so that water could be used as the working fluid. A copper mesh screen wick structure covered the inside surface of the copper end caps, and provided a liquid return such that the thermal switch could operate in any orientation. The wall of the thermal switch enclosure was fabricated from a low thermal conductivity polymer to reduce heat leaks, while the end caps of the enclosure were fabricated from copper. The end caps of the enclosure also serve as the heat source and heat sink, with an embedded cartridge heater and embedded liquid nitrogen cooling, respectively. The prototype two-phase thermal switch was instrumented to measure the vapor temperature inside the bellows, the counter pressure of the enclosure NCG, and the temperatures of the heat source and heat sink.

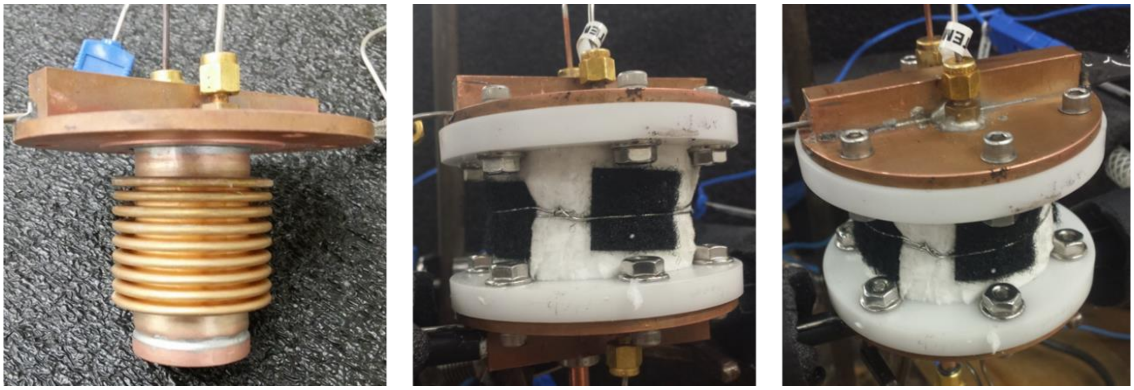

Figure 3. Two-phase thermal switch prototype. Finished assembly of bellows heat pipe (left), and fully assembled and partially insulated prototype (middle and right).

IV. Two-Phase Thermal Switch Testing

Testing of the prototype two-phase thermal switch was performed in two phases. The first set of tests were to determine the set point temperature for the switch as a function of enclosure NCG counterpressure and demonstrate set point maintenance as the sink temperature varies. The second set of tests was to characterize the performance of the two-phase thermal switch and determine relevant parameters such as thermal conductance and On/Off conductance ratios.

A. Set Point Determination

The first tests of the two-phase thermal switch were performed in gravity-aided orientation, i.e., the heat sink is located above the heat source, and the condensed liquid is returned by gravity. The counter pressure of the gas inside the enclosure was set, and a constant power of 30 W was applied by the heat source. The temperature of the heat sink was reduced from 0°C to less than -70°C, and the heat source temperature and vapor temperature were recorded. This test was performed at enclosure gas counter pressures of 7, 12, and 15 psia (48.3, 82.7, and 103.4 kPa). The results of the measurement at 12 psia are shown in Figure 4 as an example.

The next tests were performed in an against-gravity orientation, requiring the condensed liquid to be returned by capillary action in the wick structure. Again, in each test a constant power of 30 W is applied by the heat source, and the heat source and vapor temperatures are recorded as the sink temperature is reduced. Four tests were performed at enclosure gas counter pressures of 5, 7, 10 and 14.7 psia (34.5, 48.3, 68.9, and 101.4 kPa). The results of the measurement at 14.7 psia are shown in Figure 5 as an example.

Note in both orientations that as the sink temperature is reduced, the vapor temperature, i.e., the set-point temperature, decreases as well, but to a much smaller extent. There is an approximately 3°-5°C drop in the vapor temperature as the sink temperature drops from 0°C to -70°C. This may be partially due to increased heat losses back through the enclosure at lower sink temperatures. This is also likely due to the change in the frequency of oscillation for the bellows; as the sink temperature is lowered, heat is transferred more quickly from the bellows, and thus the contact time is shorter, which would affect the overall average conductance and lead to a lower vapor and source temperature. The measured set point temperature at each enclosure gas counter pressure is given in Figure 6 for both orientations. The testing of the two-phase thermal switch has shown that its performance is gravity and orientation independent due to the wick structure internal to the bellows. The testing has also demonstrated the variable thermal conductance aspect of the device, to maintain the heat source at a set point temperature within a small window.

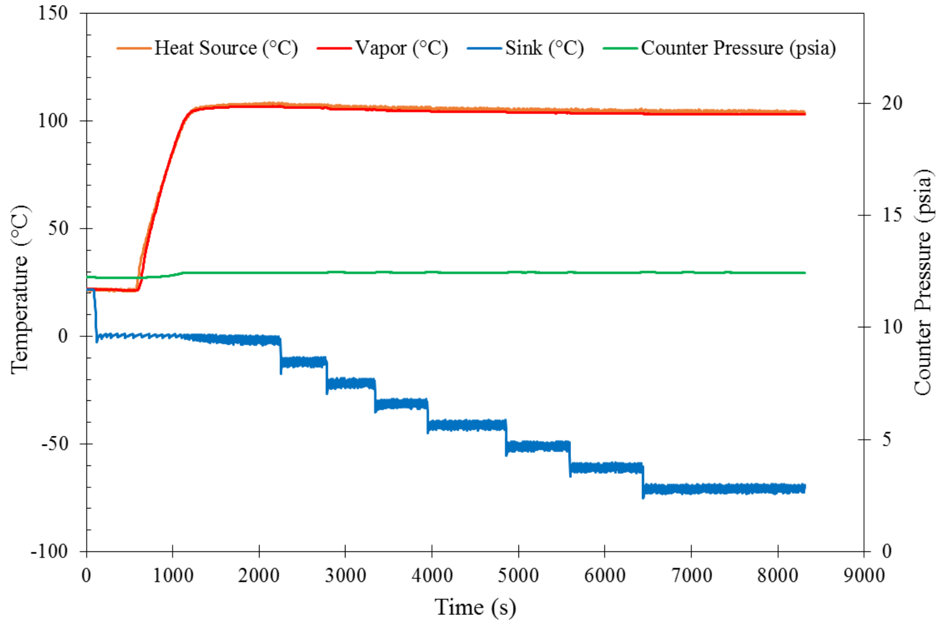

Figure 4. Two-phase thermal switch set-point determination at 12 psia NCG counter pressure in gravity aided orientation.

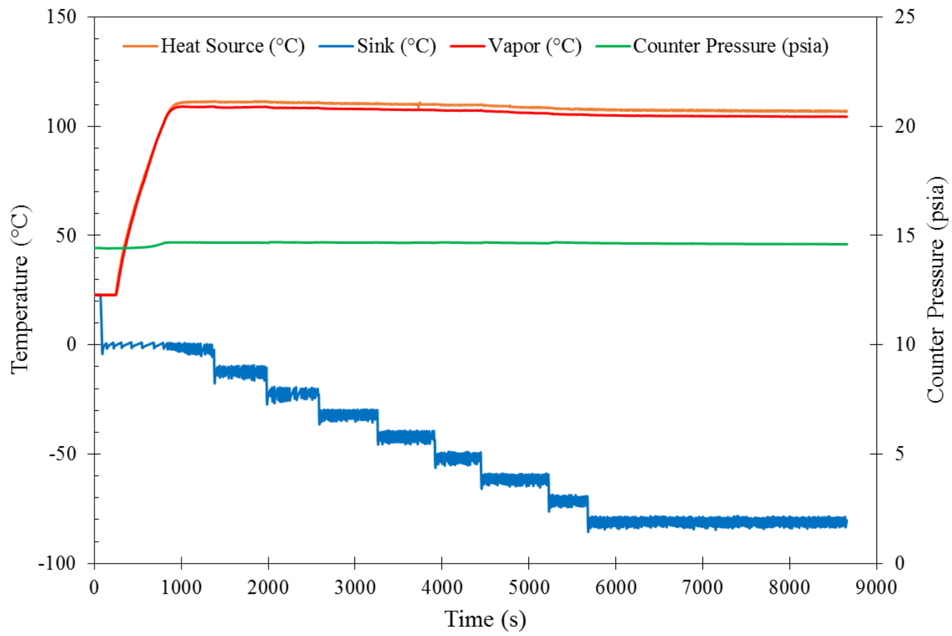

Figure 5. Two-phase thermal switch set-point determination at 14.7 psia NCG counter pressure in against gravity orientation.

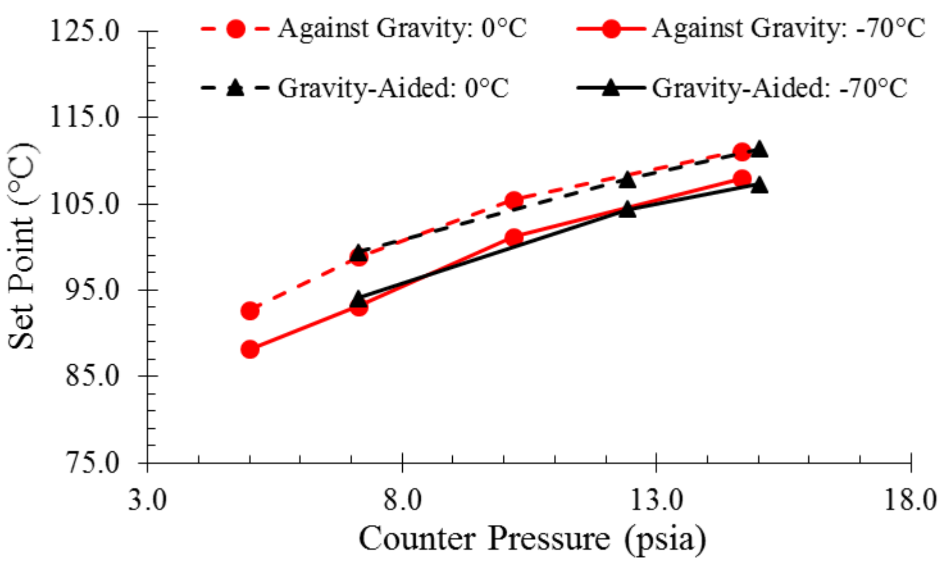

Figure 6. Measured two-phase thermal switch set point temperature at sink temperatures of 0°C and -70°C as a function of enclosure gas counter pressure.

B. Performance Characterization

Testing was also performed to characterize the thermal conductance and On/Off conductance ratio of the prototype two-phase thermal switch. Five measurements were performed in which the sink temperature was held constant, while the power applied was varied. The applied power was initially increased to its maximum, and then decreased in small increments to determine the point at which the bellows breaks contact with the condenser permanently. This power is determined to be the heat leaks from the thermal switch, both through the enclosure and to the ambient. The heat leaks to the ambient are characterized by allowing the sink to come to ambient temperature, and further reducing power until no cooling is required to maintain the sink at ambient temperature. These heat leaks were determined to be approximately 3.5W, or about 30-50% of the total measured heat leaks. The thermal conductance was then calculated by subtracting the heat leaks from the minimum supplied power and dividing by the temperature difference between the sink and the heat source. A sample of the experimental data for the 5 psia enclosure gas counter pressure and 15°C sink is given in Figure 7 and the five measurements are summarized in Table 1.

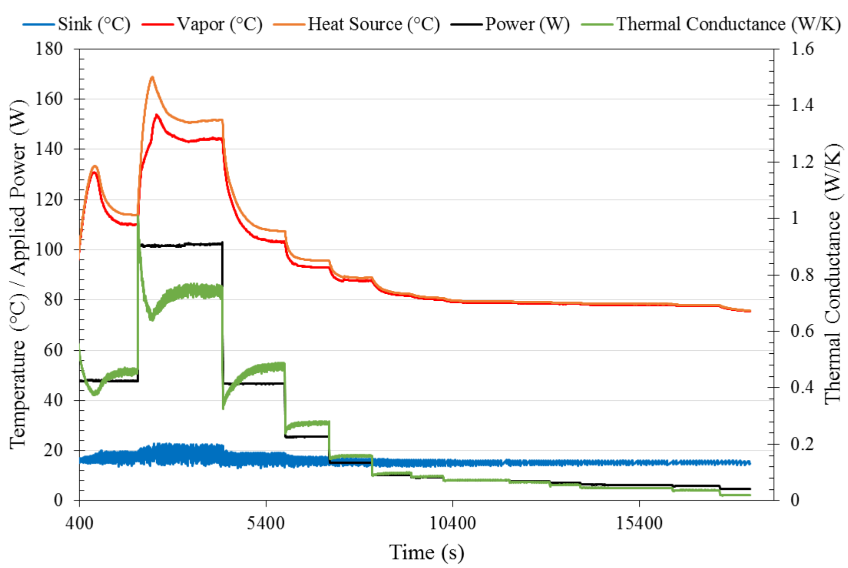

Figure 7. Two-phase thermal switch characterization at 5 psia enclosure gas counter pressure and 15°C sink temperature.

Table 1. Thermal conductance characterization of the two-phase thermal switch.

Case	Maximum Conductance (W/K)	Minimum Conductance (W/K)	Conductance Ratio
14.7 psia, 0° Sink	0.70	0.04	16.1
14.7 psia, -40° Sink	0.56	0.04	14.8
5 psia, 0° Sink	0.69	0.04	17.2
5 psia, -40° Sink	0.64	0.03	20.1
5 psia, 15°C sink	0.74	0.04	19.9

When observing the data, it becomes apparent that the conductance of the thermal switch is not a fixed value, but is dependent on the power applied and the temperature of the sink. Furthermore, it is shown that the set-point temperature is actually a minimum temperature that the thermal switch may operate at. The thermal switch may operate higher than the minimum set point temperature, again depending on the combination of sink temperature and applied power. It is not fully understood why, but it may be that at these conditions, the heat transfer rate between the contacting surfaces is such that the contact is continual rather than periodic, and as the applied power increases, so does the vapor temperature.

The thermal conductance as measured here may not be the most appropriate characterization of the two-phase thermal switch. Though the thermal conductance as measured is only slightly lower than conventional thermal switch technologies, the low value is surprising considering that conventional heat pipes can have thermal conductances on the order of 10,000-100,000 W/K. The reason for the lower measured value is that the measured "thermal conductance" is actually an average value that depends on the frequency and duration of the periodic contact. The actual thermal conductance varies from very high when the heat transfer surfaces are in contact, to very low when they are not. The thermal conductance integrated over time yields the experimentally determined thermal conductance and On/Off conductance ratio.

Even though this lower thermal conductance value is inherently due to the nature of the operation, there is much room for improvement. The prototype built here for the demonstration of the concept was not optimized. For instance, the heat transfer contact surfaces were simply bare, unpolished copper. The use of thermal interface materials, and interlocking surfaces to increase heat transfer surface area, could be used to improve the contact conductance of the heat transfer contact surfaces and increase the effective On conductance. Similarly, methods of reducing the heat leaks and losses through the enclosure and to ambient can be used to reduce the Off conductance and improve the On/Off conductance ratio.

V. Conclusion

A two-phase thermal switch technology has been developed as a thermal management component for spacecraft thermal control. The technology utilizes a hermetically sealed flexible metal bellows containing a small amount of a working fluid to essentially operate as an expandable heat pipe. The bellows expands and contracts based on the vapor temperature, and associated vapor pressure of the working fluid. As heat is applied to the switch, the bellows expands to come in contact with the heat sink. While in this On condition, the switch undergoes periodic contact with the sink and oscillates at a frequency dependent on the temperature of the sink and the power applied. This allows the two-phase thermal switch to operate as a variable thermal conductance device to maintain a fixed heat source set point temperature.

A prototype two-phase thermal switch based on a copper-water bellows heat pipe was built and tested. The set point temperature at a range of enclosure gas counter pressures was determined, and the variable conductance aspect was demonstrated. The gravity and orientation independence of the device due to the internal wick structure was also demonstrated. The performance of the switch was further characterized. A measured On thermal conductance of 0.7 W/K and an On/Off conductance ratio of 20 was demonstrated. Though these values can be measured, they do not tell the whole story as they are a consequence of the thermal switch set point which is determined by design, the power applied to the heat source, and the heat sink temperature, again demonstrating the variable thermal conductance aspect of the device.

Further improvements to the technology can be made. For instance, heat leaks through the enclosure can be further minimized, and the contact thermal resistance between the contacting heat transfer surfaces can be improved. Initial results from an unoptimized prototype show the potential for a promising and useful thermal management device, but further research is required to fully understand the dynamic operation of the two-phase thermal switch.

Acknowledgments

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