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Status of the Development of a Vapor Chamber with Phase Change Material-Based Wick Structure

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A traditional vapor chamber operates very similar to a heat pipe, and usually consists of a sintered wick structure, a working fluid in saturation state, and an envelope that serves as mechanical structure. These devices are typically used in high heat flux applications, where effective heat spreading is crucial. The Phase Change Material (PCM) vapor chamber is based on similar principles, except that the design has been altered with innovative features to support thermal storage requirements. The PCM vapor chamber consists of a packed bed of microencapsulated PCM particles surrounded by a two-phase working fluid. The microencapsulated PCM particles serve two functions. First, they act as a highly effective thermal storage medium. Second, the packed microencapsulated PCM particles serve as a wick structure for capillary pumping of the two-phase working fluid for effective liquid return. In comparison to the traditional approach of designing PCM heat sinks, the PCM vapor chamber eliminates the need for embedding high thermal conductivity metal fins or carbon foams to transfer heat into bulk PCM, which typically consumes at least 50% of the system mass. In addition, the PCM vapor chamber can serve as either a stand-alone thermal capacitor or a dual thermal capacitor/heat exchanger capable of heat transfer from surface to surface. This paper describes the novelty of the concept and the status of the development of the vapor chamber with PCM based wick structure.

I. Introduction

Under NASA Small Business Innovation Research (SBIR) program, the objective of the project was to develop a high performance, light-weight thermal storage PCM heat exchanger that was capable of minimizing temperature fluctuation during high heat load or changing sink temperature conditions. The primary design goal of the system was to have a high ratio of PCM mass to total heat exchanger mass, while maintaining a reasonably high effective thermal conductance. The PCM vapor chamber concept was developed using microencapsulated PCMs as the capillary wick structure for thermal management systems. By incorporating the microencapsulated PCMs into a vapor chamber design, the two-phase working fluid of the vapor chamber eliminates the need for the solid conduction enhancement materials, since the heat of vaporization/condensation is more efficient for melting and freezing the PCM. The PCM vapor chamber can operate as both thermal capacitor and two-phase heat exchanger, eliminating the need for two separate devices.

II. Background

Phase change material (PCM) is a substance with a high heat of fusion which is capable of storing and releasing large amounts of energy during a phase transition. PCM can absorb thermal energy (heat) at near constant temperature during the phase transition. During this transition, the latent heat is at least one or two orders of magnitude higher than the sensible energy that can be stored by the specific heat of material in its solid or liquid phase. The first consideration when designing a PCM heat sink should be the PCM's melting temperature. Typically, the PCM is selected to provide a melting temperature that is several degrees lower than the maximum component temperature throughout the mission. The second consideration is the energy that must be stored and the duration. The combination of these two factors, along with the thermal properties of the PCM, will ultimately determine the amount of PCM required for the heat sink. Paraffins, a family of saturated hydrocarbons with the

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chemical formula C_nH_{2n+2}, are the most common PCMs used for latent thermal energy storage (LTES) applications due to chemical compatibility with metals, large latent heat, and wide temperature range[1]. Several investigations of thermal characteristics of paraffins during solidification and melting processes have been performed, showing no thermal properties degradation occurred after numerous melting/freezing cycles[2]. The major drawback is the low thermal conductivity of most paraffin wax PCMs (0.2 W/m-K). As a solution, heat transfer enhancement structures, such as metal fins and metal foams, are often embedded into the PCM to increase the effective thermal conductivity of the PCM heat exchanger and provide more uniform melting of the PCM[3]. Unfortunately, the addition of these solid conduction materials tends to consume at least 50% of the system mass. Figure 1 shows an example of a PCM heat sink that utilizes an aluminum folded fin stack to enhance the thermal conductivity through the PCM. The mass of these embedded materials quickly dominates the total mass of the heat exchanger, making it very difficult to achieve a high ratio of PCM mass to total system mass..

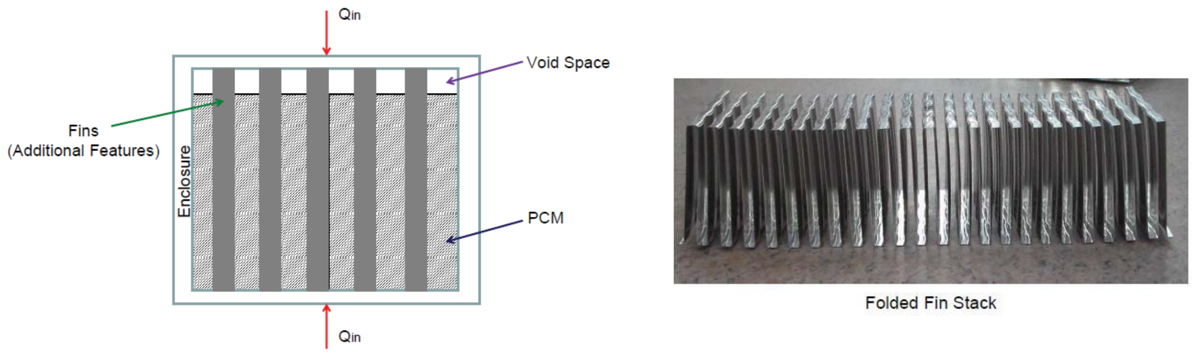

Figure 1. Folded Fin Stack PCM Heat Sink

A traditional vapor chamber operates very similar to a heat pipe, and usually consists of a sintered wick structure, a working fluid in saturation state, and surrounding structure as shown in Figure 2. A high heat flux source is applied to one surface of the vapor chamber and vaporizes the working fluid. The vapor spreads throughout the entire internal volume and condenses over a much larger surface. A wick structure lines the inner wall of the chamber and is used to pump the liquid back to the heat source via capillary action. The vapor chamber is essentially a rectangular, highly effective two-dimensional heat spreader, with effective thermal conductivities orders of magnitude higher than pure copper. These devices are typically used in high heat flux applications (> 25 W/cm^2), where effective heat spreading is crucial.

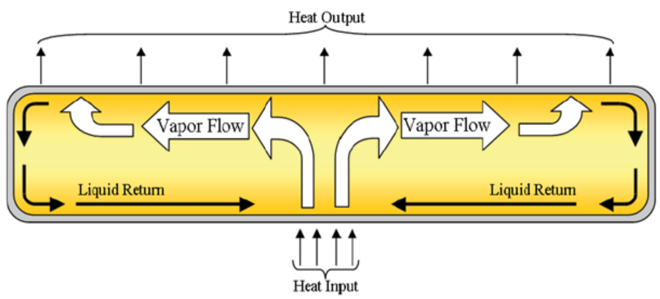

Figure 2. Standard Vapor Chamber.

The PCM vapor chamber is based on similar principles as the standard vapor chamber, except the design has been altered with innovative features to support thermal storage requirements for terrestrial and spacecraft applications.

III. PCM Vapor Chamber

As in the heat pipe and traditional vapor chamber, the PCM vapor chamber is designed to transport heat with very small temperature difference between the heat source and heat sink. The basic concepts of the PCM vapor chamber are shown in Figure 3. The PCM vapor chamber consists of a packed bed of microencapsulated PCM beads surrounded by a working fluid in saturation state, wire mesh screens, and an external structure. This innovative approach is benefited by utilizing a two-phase working fluid to provide uniform heat to microencapsulated PCM beads. By utilizing microencapsulated PCM beads as both thermal storage medium and as a capillary wick structure for two-phase working fluid, the PCM vapor chamber eliminates the need for solid conduction enhancement materials as in the traditional PCM heat sink.

The PCM vapor chamber will operate in the following order. When heat is applied to the surface, liquid evaporates from the saturated microencapsulated PCM wick structure and flows through the vapor space into the opposite side of the surface where heat is removed. The liquid subsequently returns to the heated surface through the microencapsulated PCM wick structure. When the operating temperature is below the PCM melting temperature, the PCM will remain in the solid state. During this nominal operation, the two-phase working fluid can provide efficient heat transfer between hot and cold surfaces. The PCM vapor chamber is operating as a highly efficient, two-phase heat exchanger. When the condenser side surface cannot reject the heat load, the PCM vapor chamber temperature will increase. As the operating temperature rises above the PCM melting temperature, the latent heat of the working fluid will be transferred to the PCM by condensing on the outer surface of the PCM particles. During the change of phase from solid to liquid, the generated heat is absorbed via latent heat of fusion by the PCM at a near constant temperature as shown in Figure 4. The reverse cycle occurs as the operating temperature drops below the melting temperature, where the PCM changes from liquid to solid by releasing latent heat of fusion at a constant temperature during the phase change.

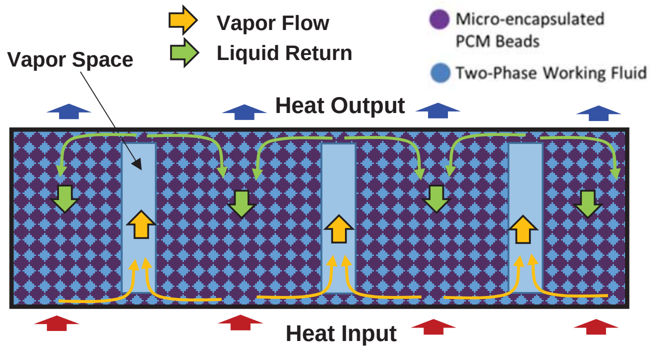

Figure 3. ACT's PCM Vapor Chamber.

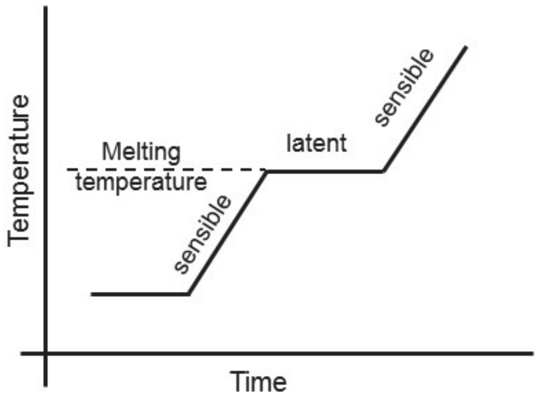

Figure 4. PCM Vapor Chamber Temperature Profile

Table 1 shows the mass-break-down of an aluminum finned PCM heat sink and a nominal PCM vapor chamber design. Both devices were constrained to have equal amount paraffin PCM mass of 2.0kg. To simplify the analysis, both devices were assumed to have the same height (5.1 cm). For the finned PCM heat sink, aluminum was used for both fins and envelope structure. The PCM vapor chamber utilized stainless steel, microencapsulated PCMs and methanol as the two-phase working fluid. From Table 1, it is apparent that by replacing the traditional finned PCM heat exchanger with the PCM vapor chamber the overall mass reduced by slightly more than half. The PCM vapor chamber not only has the potential to exceed a high PCM mass ratio using paraffin wax, but also provides several advantages over the state-of-the-art. By replacing the metal fins or foams with a two-phase working fluid, it is possible to increase the thermal conductance of the PCM vapor chamber, due to the high latent heat of vaporization/condensation of the working fluid. In addition, the PCM vapor chamber can serve as either a stand-alone thermal capacitor or a dual thermal capacitor/heat exchanger capable of transferring heat from surface to surface. A summary of the advantages of the PCM vapor chamber is provided below:

Table 1. Mass Comparison between a Finned PCM Heat Sink and the PCM Vapor Chamber

	Traditional PCM Heat Sink (Al Fins)	PCM Vapor Chamber (SS/methanol)
PCM Mass (kg)	2.0	2.0
PCM Shell (kg)	N/A	0.3
Al Fins (kg)	7.0	N/A
Working Fluid (kg)	N/A	0.3
Envelope (kg)	3.1	3.0
Screen (kg)	N/A	0.1
Total Mass (kg)	12.1	5.7

- Significantly reduces mass of system by replacing heavy conduction enhancement materials (metal fins and foam) with two-phase heat transfer provided by the working fluid.

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- Able to achieve high ratio of PCM mass to total heat exchanger mass.
- Microencapsulated PCM spheres enable relatively large heat transfer surfaces due to the high surface area to volume ratio.
- Can operate as a dual thermal capacitor/two-phase heat exchanger, eliminating the need for two separate devices.
- Packed bed PCM wick structure allows device to operate in the against gravity orientation.
- Completely passive.
- Low cost and relatively easy fabrication.

In addition to operating as a thermal capacitor, the PCM vapor chamber can also operate as a highly efficient, two-phase heat exchanger. For instance, during nominal TCS operation or when thermal storage is not required, the two-phase working fluid can provide efficient heat transfer between hot and cold surfaces of the device via latent heat. Traditional PCM heat exchangers, on the other hand, can only operate as thermal storage devices, due to the poor through-plane conduction associated with metal fins and carbon foam. This dual feature of the PCM vapor chamber provides an opportunity to save additional mass at the system level by replacing the stand-alone thermal capacitor and liquid/liquid heat exchanger with one PCM vapor chamber.

IV. Copper/Water Proof-of-concept Prototype

In order to demonstrate proof-of-concept of the PCM vapor chamber, a copper/water PCM vapor chamber prototype was fabricated as shown in Figure 5. The prototype PCM vapor chamber consisted of a bottom lid (evaporator), a vapor chamber, a removable top lid with an integral heat sink (condenser), fine mesh screens, and a vapor space. Vapor channels were incorporated to the bottom lid to increase the evaporation heat transfer coefficient, hence reducing the overall system temperature drop. Fine mesh screen was used to prevent the encapsulated PCM particles from migrating into the evaporator channels. The evaporator bottom lid was brazed to the vapor chamber. A Kapton heater was attached to the bottom lid. The cylinder body was made of copper with 12.7cm OD x 0.102cm wall x 7.62cm long. The removable top lid has an integral heat sink to eliminate the thermal contact resistance associated with the chiller block. One thermocouple probe was inserted through the top lid to measure the vapor temperature in the middle of the vapor chamber. A pressure transducer was used to measure the internal pressure of the system.

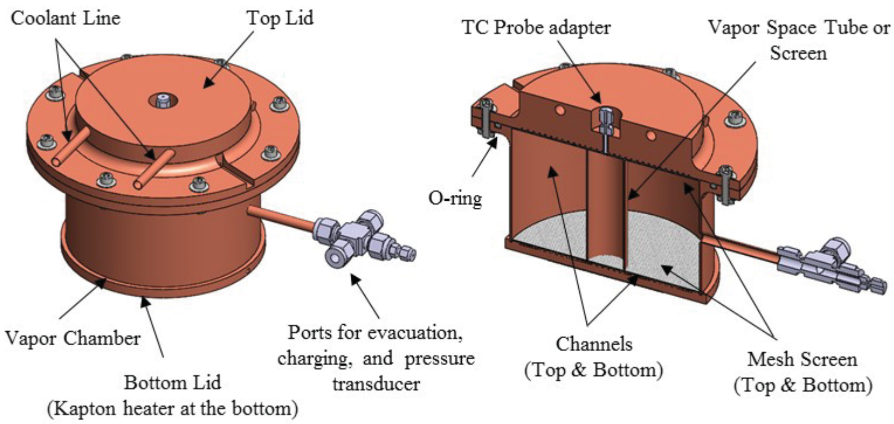

Figure 5. Copper/Water PCM Vapor Chamber Prototype

ACT is collaborating with Southwest Research Institute (SwRI) to develop microencapsulated PCMs for use as wick structures in vapor chambers. Two PCM melting points are going to be considered in the development of the microencapsulated PCM particles. Encapsulated PCM particles with a melting point around 50°C will be used with water as working fluid for initial development. The reason is the fact that working with water during the investigation and proving the concept is easier. Microencapsulated PCM particles with a melting point around 25°C will be developed for the final applications using methanol or ammonia as the working fluid. SwRI is developing

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processes for making both categories of PCM particles. This development effort is ongoing in parallel with the present development.

V. Thermal Model

As shown in Figure 6, a prototype copper/water PCM vapor chamber model was developed using C&R Thermal Desktop software (graphical user interface for SINDA/FLUINT). SINDA/FLUINT is a comprehensive package which is a NASA-standard analyzer for thermal control systems. The PCM vapor chamber was modeled similar as in heat pipe modeling that has been used for years in aerospace industry. The key to this approach is a massless node representing the vapor saturation temperature (T_{vap}). All evaporator and condenser wall nodes are attached to this vapor node with a conductive connection where the conductance is based on the evaporation or condensation heat transfer coefficient and internal surface area. FUSION subroutine which is a phase change material (PCM) simulation routine was used for modeling latent energy within diffusion nodes.

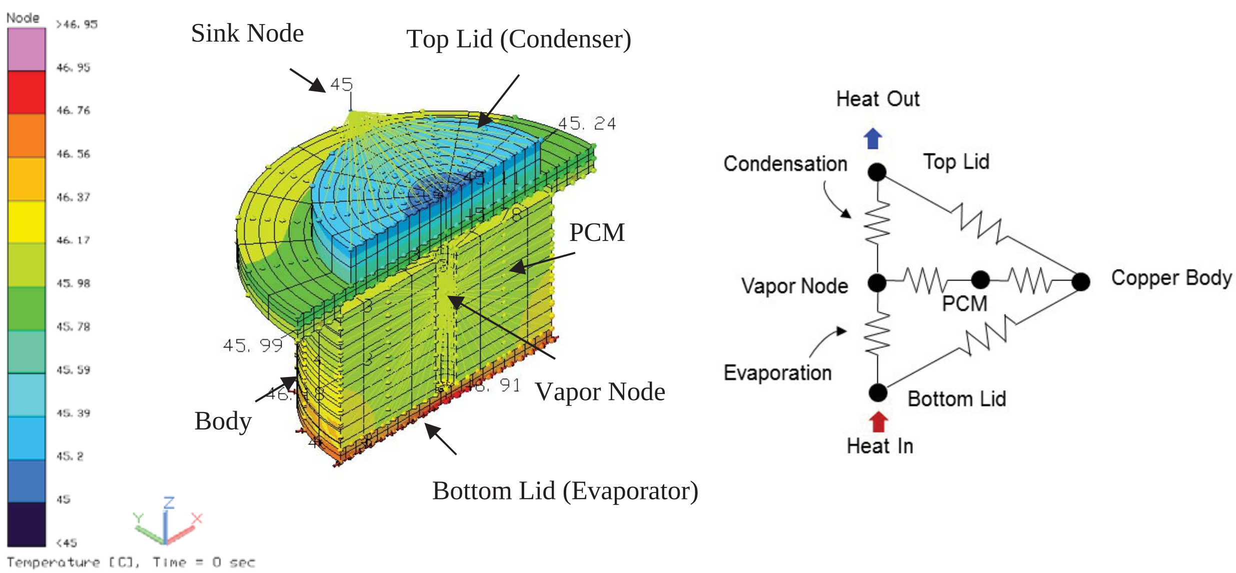

Figure 6. Detailed PCM Vapor Chamber Thermal Model.

Table 2 lists the key input parameters for the thermal model. Figure 7 shows the predicted transient temperature profile for a heat load of 100W applied to the bottom lid. The initial chiller set-point was 45°C. After 10 minutes, the chiller was turned off to allow the vapor temperature to heat up above the PCM melting temperature of 55°C. When the vapor temperature reached slightly above the PCM melting temperature, the vapor chamber stayed near constant temperature during the melting process for about 12 minutes. In this period, the encapsulated PCMs were working as heat sink. When the vapor chamber reached temperatures above the 65°C, the chiller was turned on.

In order to validate the thermal model, the predicted transient temperatures will be compared to the measured test data. The main parameter during the model correlation will be the heat transfer between the encapsulated PCMs and the working fluid.

Table 2. Thermal Model Input Parameters

Component or Parameters	Input Value
Copper Vapor Chamber OD	12.7cm
Copper Vapor Chamber Height	7.62cm
Vapor tube outer diameter	1.27cm
Evap Heat Transfer Coefficient	15,000 W/m^2-°C
Cond Heat Transfer Coefficient	22,500 W/m^2-°C
PCM	Paraffin Wax
PCM Melting Temperature	55 °C
PCM Heat of Fusion	184,000 J/kg
PCM Heat Capacity	2380 J/kg-°C
PCM Density	0.775 g/cc
Encapsulated Particle Size	250 micron
Porosity	0.30

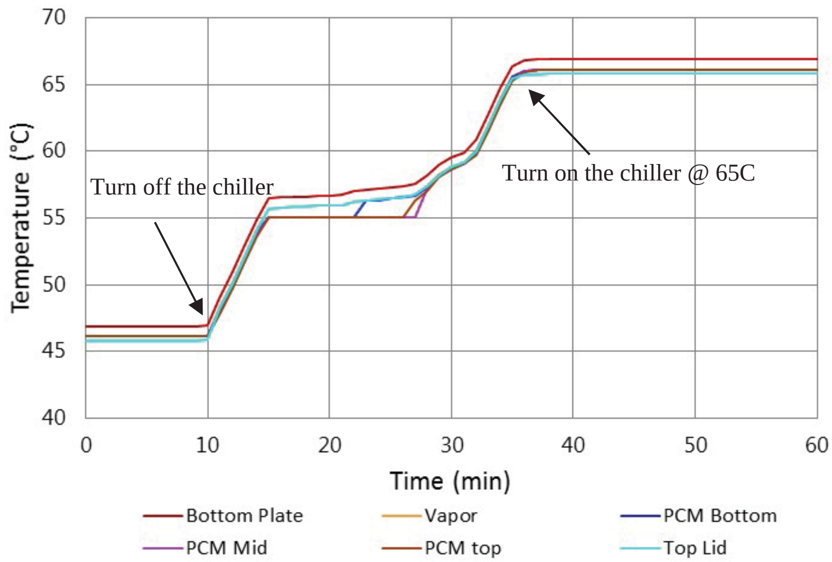

Figure 7. Predicted Transient Temperature Profile.

VI. Preliminary Characterization Testing

A. Capillary Wick Structure Validation

In order to determine the ideal microsphere particle size suitable for serving as a wick structure in the PCM vapor chamber, tests were performed to measure pore radius and permeability on four different particle sizes. Figure 8 shows the measured pore radius and permeability. As the particle size increased the measured pore radius and permeability also increased. In general, small pore size, resulting in high pumping capability, is very desirable in a wick. However, the capillary pumping capability of a wick is inversely proportional to its permeability (a measurement of the pressure drop during flow), which reduces the amount of power that can be transported. The design must balance the wick pumping capability against wick permeability when designing microencapsulated PCMs as a wick structure.

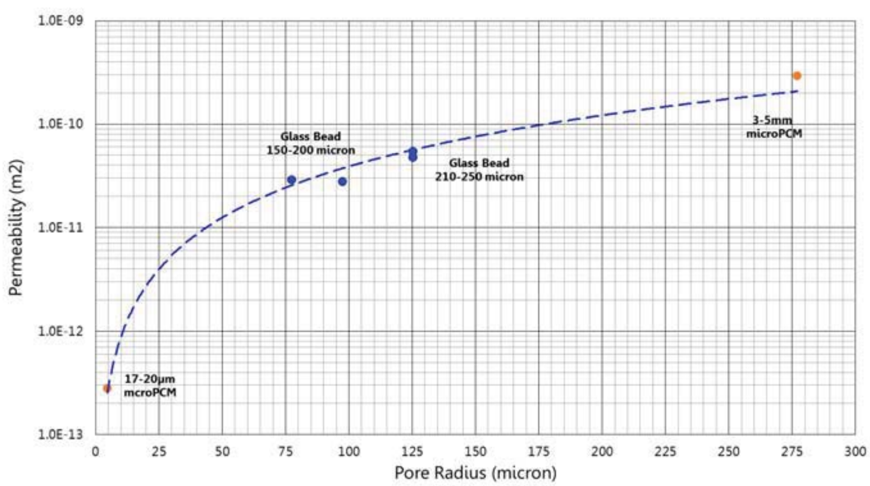

Figure 8. Measured Pore Radius and Permeability.

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B. Capillary Heat Transport Validation

A small-scale proof-of-concept prototype was preliminarily used to demonstrate the capillary two-phase operation of a packed bed of glass beads. As shown in Figure 9, the prototype consisted of 210-250 micron glass beads as a capillary wick structure, 4 layers of 100 mesh screens at top and bottom, and a copper tube (1.27cm OD) as vapor space in the middle. The glass beads were made from soda-lime glass with a density of 2.5 g/cc. A hermetic seal is achieved through a bolt pattern in the flange and an O-ring. The heat source and heat sink are integrated into the prototype, with cartridge heaters as the heat source and water as the coolant.

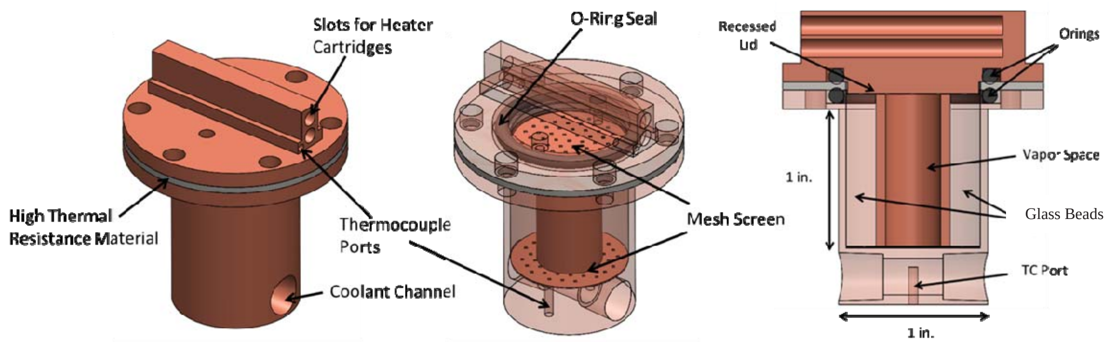

Figure 9. Reduced-scale Proof-of-concept Prototype.

Thermal performance tests were performed in both gravity aided and against gravity operation modes. Figure 10 shows a picture of the test set-up without insulation in against gravity. Each case was tested at three different powers and a chiller set-point of 40°C. Figure 11 shows a typical temperature profile as a function of time in against gravity with 3.5ml and 4.5 ml of water.

Figure 10. Test Set-up.

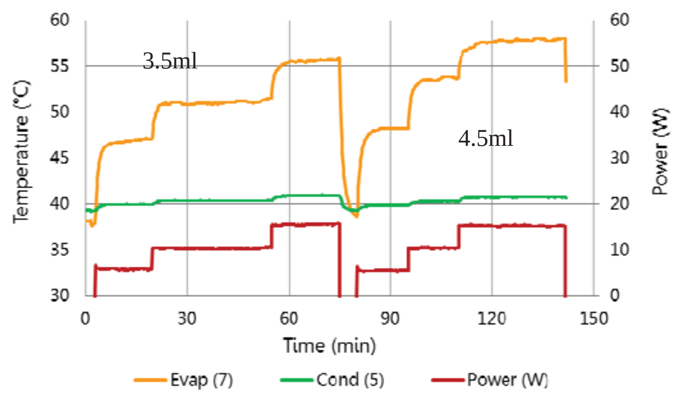

Figure 11. Typical Temperature Profile.

Table 3 summarizes the results of thermal performance tests. First test was performed without the working fluid to determine heat leaks through the copper wall. The measured back conductance was 0.34 W/°C. The conductance was calculated based on power applied to the vapor chamber divided by the temperature difference between the evaporator (T_e) and the condenser (T_c). When the vapor chamber was charged with 3 ml of water, the system conductance increased to 0.81 W/°C in gravity aided operation mode. The vapor chamber was also tested in against gravity operation mode with different water charges. In the against gravity mode, a system conductance of 0.96 W/°C was achieved when the vapor chamber was charged with 3.5 ml of water, which was slightly higher than the gravity aided operation mode. This demonstrated that a packed bed of microsphere particles could operate as wick structure within a two-phase heat transfer device.

Table 3. Thermal Performance Test Summary

Gravity Direction	Working Fluid Charge (ml)	Heat Load (W)	$\Delta T_{tot}=T_e-T_c$ (°C)	System Conductance (W/°C)	Avg. System Conductance (W/°C)
Aided	0	5.4	16.0	0.34	0.34
		10.7	32.2	0.33	
		15.3	45.1	0.34	
Aided	3	5.1	6.8	0.75	0.81
		10.2	12.6	0.81	
		15.7	18.0	0.87	
Against	2	5.1	7.8	0.66	0.63
		10.2	16.2	0.63	
		15.5	25.4	0.61	
Against	3.5	6.0	7.2	0.84	0.96
		10.7	11.1	0.96	
		15.9	14.9	1.07	
Against	4.5	5.8	8.4	0.69	0.79
		10.5	13.4	0.79	
		15.5	17.2	0.90	

As summarized in Table 4, the evaporation and condensation heat transfer coefficients are 15,000 W/m^2-°C and 22,500 W/m^2-°C, respectively, based on the measured back conductance and the system conductance with 3.5 ml of water. The evaporation active area was 0.697 cm^2.

Table 4. Measured Evaporation and Condensation Heat Transfer Coefficients.

Evaporation Heat Transfer Coefficient	15,000 W/m^2-°C
Condensation Heat Transfer Coefficient	22,500 W/m^2-°C
Evaporator Conductance	1.04 W/°C
Condenser Conductance	1.56 W/°C
Two-phase Loop Conductance	0.62 W/°C
Measured Back Conductance	0.34 W/°C
Measured System Conductance	0.96 W/°C

VII. Conclusion

A PCM vapor chamber concept was developed using microencapsulated PCM beads as the capillary wick structure to circulate the system's working fluid, which can operate as both thermal capacitor and two-phase heat exchanger. The microencapsulated PCM beads serves two functions. First, they act as a highly efficient thermal storage medium. Second, the packed bed microencapsulated PCM structure act as a wick structure for capillary pumping of the two-phase working fluid. Preliminary characterization tests indicated that microsphere particles could be used as a wick structure within a two-phase heat transfer device. In comparison to the traditional aluminum finned PCM heat exchanger, the PCM vapor chamber reduced the overall mass by more than half by eliminating the embedding high thermal conductivity metal fins.

A prototype copper PCM vapor chamber was designed and fabricated to demonstrate proof-of-concept of the PCM vapor chamber using microencapsulated PCM beads and water as the working fluid. The next step is the demonstration of capillary pumping and heat storage with relevant microencapsulated PCM beads (50°C melting point) using water as working fluid. The predicted transient temperatures will be compared to the measured test data to validate the thermal model developed using C&R Thermal Desktop software.

Acknowledgments

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References

[1]Kenisarin, M., and Mahkamov, K., "Solar energy storage using phase change materials." *Renewable & Sustainable Energy Reviews*, Vol 11, No. 9, 2006, pp. 1913-1965.

[2]Sharma, A., Tyagi, V.V., Chen, C.R., and Buddhi, D., "Review on thermal energy storage with phase change materials and applications." *Renewable & Suatainable Energy Reviews*, Vol 13, No. 2, 2009, pp. 318-345.

[3]Peyrou-Lauga, R., Collette, J., and Nutal, N., "Phase Change Material Heat Storage Device for Launchers and Orbiting Systems," 45th International Conference on Environmental Systems, Bellevue, Washington, July 2015.