Variable-View-Factor Two-Phase Radiator

Andrew Lutz[1], Calin Tarau[2], and Srujan Rokkam[3]
Advanced Cooling Technologies, Inc., Lancaster, PA, 17601

Essentially all manned spacecraft, satellites, planetary rovers and unmanned spacecraft need to reject waste heat through a radiator. While the waste heat load and the heat sink conditions can vary widely, the battery and electronics temperatures must be maintained within specified limits. Typically, the radiators are sized for the highest power at the hottest sink conditions, so they are oversized most of the time. Hence, there is a need to develop light-weight and efficient radiators for future spacecraft and satellites which offer the capability of significant turndown. Advanced Cooling Technologies, Inc. (ACT) has developed a novel vapor-pressure-driven variable-view-factor and deployable radiator that passively operates with variable geometry (i.e., form factor) and offers high turndown ratio. The device, utilizes two-phase heat transfer and novel geometric features that adaptively (and reversibly) adjust the view factor in response to internal pressure in the radiator. The radiator folds into a tear drop shape to minimize the view factor when cold, and opens up to maximize the view factor when hot. This is facilitated by a dynamic feedback between the internal pressure inside hollow curved panels of the radiator and the radiator structure itself, which permits a change of shape within the elastic limit of the material – thereby resulting in a passive, reversible, deployable and variable-view-factor radiator, which enables heat spreading via two-phase mechanism and further rejection via radiation.

Nomenclature

A	=	area
A_{inner}	=	internal radiator area
A_{outer}	=	external radiator area
ε	=	emissivity
$\varepsilon_{insulation}$	=	emissivity of external surface
$\varepsilon_{radiator}$	=	emissivity of internal radiator surface
η	=	radiator efficiency
F	=	view factor
Q	=	heat load
$Q(F)$	=	total heat radiated as a function of view factor
Q_{loss}	=	heat radiated from external insulated surfaces
R	=	major radius
SMA	=	shape memory alloy
σ	=	Stefan-Boltzmann constant
$T_{radiator}$	=	radiator temperature
T_{sink}	=	heat sink temperature
θ	=	external angle
$VVFTPR$	=	variable-view-factor two-phase radiator

[1] R&D Engineer, R&D, 1046 New Holland Ave.
[2] Principal Engineer, R&D, 1046 New Holland Ave.
[3] Lead Engineer, R&D, 1046 New Holland Ave.

I. Introduction

Typically, radiators for spacecrafts and satellites are sized for the highest power at the hottest sink conditions, so they are oversized most of the time[1],[2]. There is a need to develop light-weight and efficient radiators for future spacecraft and satellites which offers the capability of significant turndown[3],[4]. The 2015 NASA Thermal Roadmap says that NASA is looking for Variable Geometry Radiators[5], "The development goal is to provide radiators with a 6:1 (with a stretch goal of 12:1) heat rejection turndown capability." ACT has developed a passive, variable-geometry radiator that has the possibility of thermal turndown ratios greater than 40:1.

For spacecraft and planetary thermal control applications, it is essential to maintain survivable operational temperatures for onboard devices and minimize temperature fluctuation when the environmental temperature changes drastically. Under a Small Business Innovation Research (SBIR) project funded by NASA Marshall Space Flight Center, Advanced Cooling Technologies, Inc. (ACT) developed a novel *vapor-pressure-driven variable-view-factor and deployable radiator* that passively operates with variable geometry (i.e., form factor) and offers high turndown ratio. The proposed device, utilizes two-phase heat transfer and novel geometric features that adaptively (and reversibly) adjust the view factor in response to internal pressure (working fluid vapor pressure) in the radiator. The radiator folds into a tear drop shape to minimize the view factor when cold, and opens up to maximize the view factor when hot. This is facilitated by dynamic feedback between the internal pressure inside hollow curved panels of the radiator and the radiator structure itself, which permits a change of shape within the elastic limit of the material – thereby resulting in a passive, reversible, deployable and variable-view-factor radiator, which enables heat spreading via two-phase mechanism and further rejection via radiation. Investigation into the feasibility of the concept during development using structural and thermal simulation studies confirmed the viability of the concept.

II. Description of Morphing Radiator Concept

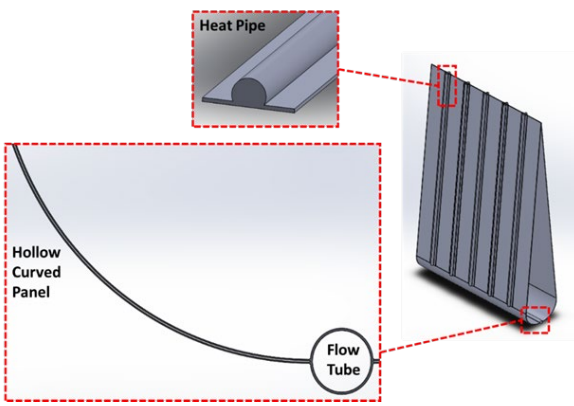

Figure 1. Conceptual schematic of the two-phase vapor pressure-driven variable-view-factor radiator

The basic concept of the variable-view-factor two-phase radiator (VVFTPR) is illustrated in Figure 1. The flexible actuator section of the VVFTPR consists of a hollow curved panel that is filled with a two-phase working fluid and sealed. An increase in fluid temperature, and therefore vapor pressure, results in pressurization of the hollow curved panel which causes the radiator structure to open, thus increasing the view factor of emissive surfaces.

Figure 2 shows a novel morphing radiator design which combines temperature dependent shape morphing behavior with high effective thermal conductivity via two-phase heat transfer. The radiator morphs continuously between a fully closed and fully open shape depending on the temperature of the curved, flexible vapor pressure-driven actuator section. If the heat sink environment temperature increases, the heat source temperature increases slightly to reject heat. Consequently, the working fluid vapor pressure in the internal cavity increases, causing the hollow curved panel to open and straighten out, leading to opening of the radiator (i.e. view factor increase). Due to the increase in view factor, thermal resistance to the environment decreases and the heat source temperature rise is minimized. When the heat sink temperature decreases the process is reversed as the vapor pressure inside the hollow panel decreases. When this occurs, the elastic properties of the envelope material force the structure to return to a closed position (view factor decreases and so thermal resistance with the environment increases minimizing the heat source temperature decrease). At intermediate temperatures, the radiator is partially open[4]. The sensitivity to vapor pressure can be optimized by adjusting geometric parameters such as wall thickness and cavity (gap) size.

[4] While this aspect is akin to the shape memory alloy (SMA)-based radiator concept. The SMA radiators do not really use or benefit from the two-phase heat transfer. However, the proposed deployable, variable-view-factor radiator has dynamic feedback from the internal pressure, is likely to be more efficient (as it uses two-phase heat transfer) and offers high turn down ratio.

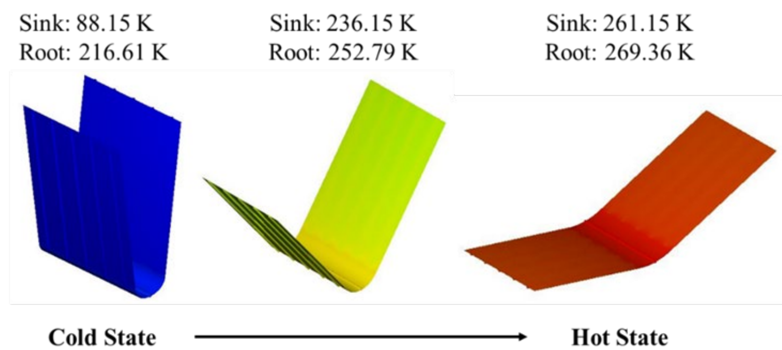

Figure 2. Illustration of thermal-structural analysis results showing varying radiator shape and temperature as heat sink temperature changes.

ACT demonstrated a vapor pressure-driven adaptive radiator capable of achieving a turndown ratio of 37:1. Figure 3 shows ACT's most recent prototype VVFTPR during an experiment where heat was applied to the exterior surface of the prototype along the centerline via a heat pipe transferring heat from a remote location.

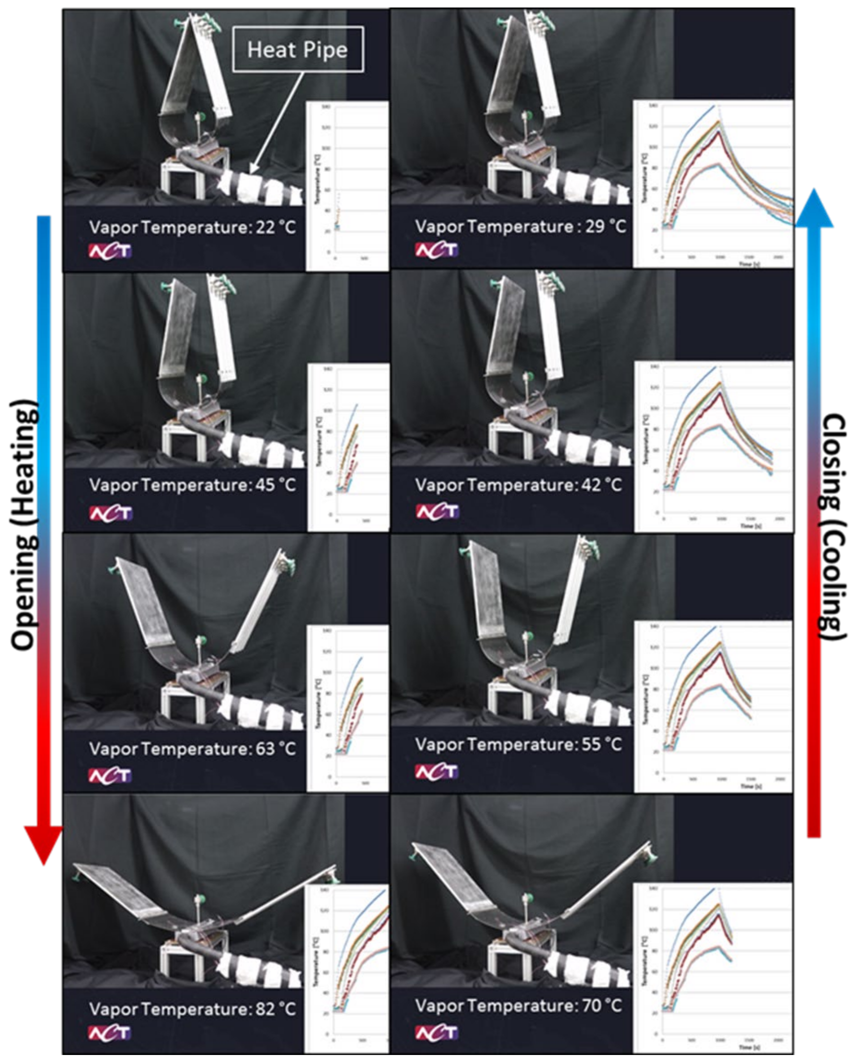

Figure 3. Images captured during experimental test of Prototype #5 showing temperature plot

The proposed vapor pressure driven variable-view-factor radiator has the following features:

- *High Thermal Turndown Ratio:* Modeling and experimental work shows that the geometry proposed can achieve a thermal turndown ratio of 37:1. Future designs can further increase the maximum turndown ratio, resulting in improved thermal control. Figure 4 shows a theoretical radiator design capable of achieving a 37:1 thermal turndown ratio.
- *Passive Thermal Control*: The proposed concept uses vapor pressure to passively change the shape of the radiator with no need for external power, equipment, or control mechanism.
- *Fast Response*: The proposed radiator morphs based on the vapor pressure inside the hollow curved panel. Experimental data proves that the variable-view-factor radiator morphing behavior is mainly temperature dependent. The time scale of morphing due to vapor pressure changes is nearly instantaneous relative to temperature changes of the wall material due to both conduction and thermal inertia.
- *Reversible and highly durable*: The proposed radiator morphs shape using the material deformation within the elastic domain and less than the fatigue limit. As such the deformation and resulting shape change is completely reversible.
- *High radiator efficiency*: The areas of the radiator containing two-phase fluids will be essentially isothermal. The VVFTPR has the potential to offer an efficiency improvement over heat pipe radiators from 0.85 to near one. In future work, the entire radiator panel can be constructed as a two-phase volume with ultra-high effective thermal conductivity. For the proposed baseline geometry, this efficiency improvement would allow an 18 % increase in heat rejection while maintaining a turndown ratio of 37:1.

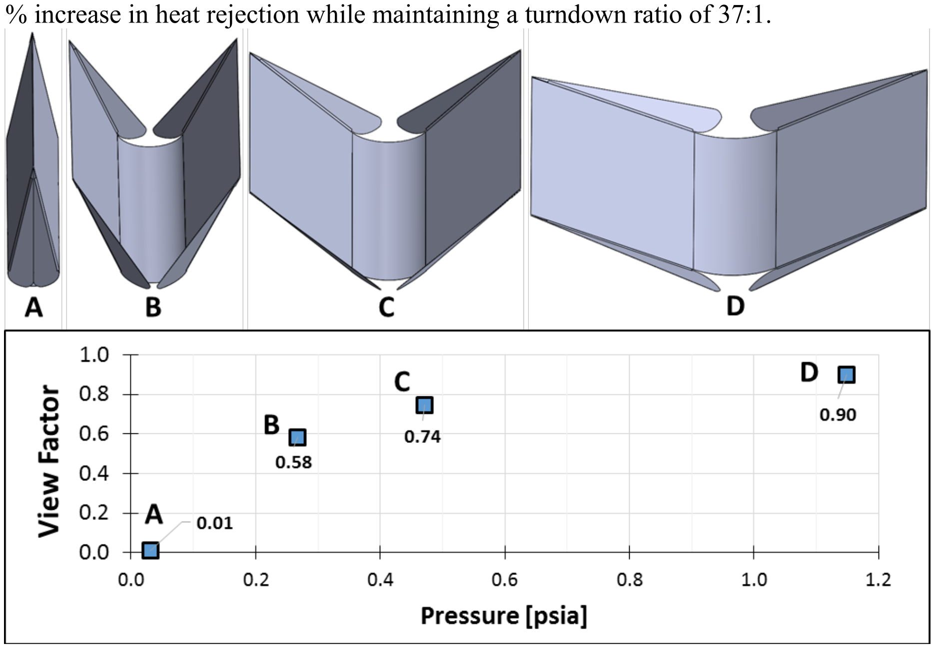

Figure 4. Images of VVFTPR with unfolding sections to allow near zero view factor at closed state showing view factor at corresponding internal pressure values

III. Design Method and Theoretical Analysis

A. Structural Study

To design a VVFTPR capable of maintaining radiator root temperatures within a desired range, a parametric structural study was completed to predict the effects of geometric design parameters on the relationship between internal pressure and opening behavior of a baseline VVFTPR. A two-dimensional (2D) structural model of a baseline VVFTPR was generated to investigate the feasibility of using various readily available materials for prototyping in Phase I. The 2D model was used to estimate deformation and the opening angle that can be achieved for a VVFTPR for given sets of design parameters. With an increase in pressure, a net force is generated in the direction normal to the outside wall which is balanced by the envelope material stiffness and resistance to bending.

The baseline model was used to investigate the relationship between internal pressure and opening angle for a simple VVFTPR geometry consisting of two concentric cylindrical walls which would be attached and sealed along all outer edges. Straight radiator panels would be attached to the ends of the VVFTPR, and the straight radiator sections would be tangent to the flexible variable-view-factor actuation section which consists of a cylindrical envelope with an external angle, θ, slightly greater than 360° in the closed configuration. Figure 5 shows the 2D view of the baseline geometry. To reduce model size, the straight section is omitted and the model is cut in half along the centerline of symmetry.

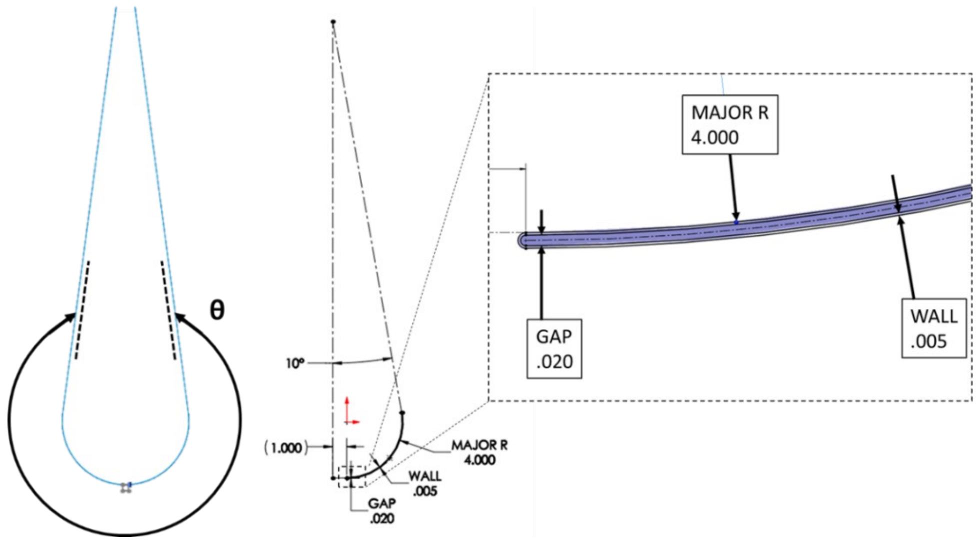

Figure 5. Left: View of a baseline VVFTPR geometry with angle θ shown, Right: Sketch of baseline geometry for structural study illustrating key parameters

ACT investigated the effect of various parameters of the geometry of the baseline VVFTPR on opening sensitivity to pressure via structural simulations in Abuqus Simulia. To investigate the effect of wall thickness, the wall thickness was varied from 0.010 inches (0.254 mm) to 0.020 inches (0.508 mm) with all other geometry constant. As expected, minimizing wall thickness maximizes sensitivity of opening the radiator when increasing internal pressure in the VVFTPR flexible envelope because the structure is less stiff. This relationship is shown in Figure 6. Opening sensitivity is a strong function of wall thickness.

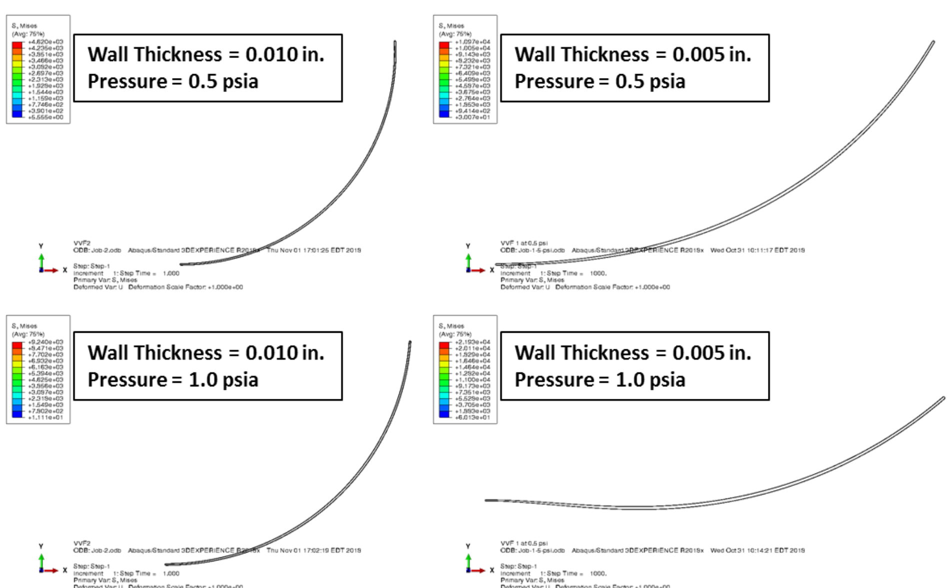

Figure 6. Resulting shapes of baseline VVFTPR design as a function of pressure and wall thickness

Figure 6 shows the opening angle of a baseline VVFTPR with an initial major radius of 4 inches (10.2 cm) pressurized to 5 psi (34.5 kPa) internal pressure. For each wall thickness there is a deformation limit where the stress in the wall material would exceed the yield strength, causing plastic deformation. Figure 7 shows the angular change of a 4 inch (10.2 cm) major radius VVFTPR with respect to internal pressure for varying wall thickness values. The results presented here only show cases where the yield strength is not exceeded and deformation is elastic.

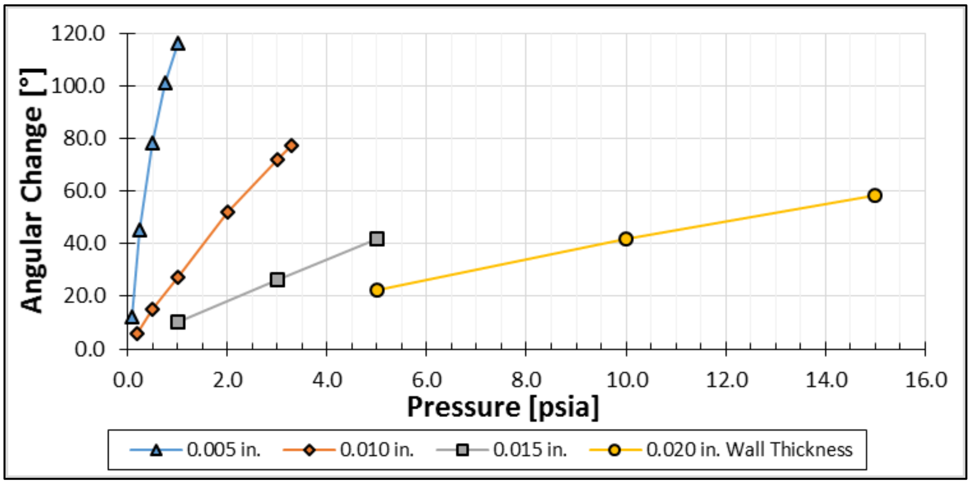

Figure 7. Angular change for varying wall thickness for a 4 inch (10.2 cm) major radius VVFTPR

During the structural study, the effect of major radius on morphing behavior was studied to provide insight about the scalability of the VVTPR to applications requiring smaller and larger radiators. With all other parameters held constant, the morphing sensitivity increases as major radius is increased. To maintain effective opening sensitivity as the major radius decreases, the wall thickness can be reduced. The structural study investigated major radius values ranging from 1 in. (2.54 cm) to 4 in. (10.16 cm). Scaling to larger major radii is straightforward because morphing sensitivity increases with an increaded major radius. However, as major radius is reduced toward 1 in. (2.54 cm) morphing sensitivity is diminished and the wall thickness may need to be reduced below a value capable of providing structural support and pressure containment.

B. Working Fluid Selection

The working fluid inside the hollow panels is selected based on the vapor pressure within the required temperature range for thermal control as well as its compatibility with the radiator material. First of all, the working fluid must be chosen so that the vapor pressure at the minimum temperature results in the closed radiator shape based on the force balance with the wall materials. The vapor pressure at the maximum temperature must be contained by the envelope materials at the maximum view factor shape configuration without inducing stress beyond the fatigue limit of the material. The opening behavior between these two points will be dependent on the working fluid saturation curve between the open and closed configurations, hence, working fluid selection can be used as a design parameter to optimize sensitivity or to limit the maximum opening range. During experiments so far, methanol was used as the working fluid so that experiments could be conducted in ambient atmospheric conditions. Working fluids that are compatible with elastic envelope materials such as stainless steel and titanium alloys are suitable candidate fluids. Depending on temperature control range, propylene, hydrofluorocarbons, ammonia, alcohols, acetone, or water could be working fluid choices.

C. Envelope Material Selection

A survey of materials that can be used to construct the envelope of the VVFTPR was initiated to select a candidate material for initial prototyping and to identify potential materials for future construction. The structural and thermal properties of each material are important factors because the material needs to tolerate a large degree of elastic deformation, demonstrate long life time, and readily allow heat transfer from the source to the radiator. In terms of thermal performance, the envelope material thermal conductivity should be as high as possible.

Conventionally, most springs are made of steel due to favorable elastic properties and low cost. Specifically, austenitic stainless steels such as 304 are commonly used for spring applications. Additionally, the yield strength of the envelope material must be high so that the most deformed regions of the flexible part may remain elastic throughout the lifetime of the part. Stainless steels and titanium alloys exhibit a fatigue limit where the number of deformation cycles before the part fails due to fatigue is practically infinite if the maximum stress is kept below a certain value. To achieve a long product life and allow the maximum opening sensitivity of the VVFTPR, the ratio of yield strength to elastic modulus should be as high as possible.

Another important criterion for envelope material selection is compatibility with working fluids. Over the years, ACT has tested heat pipe envelope and working fluid compatibility for numerous combinations of materials in order to qualify material compatibility. As a result, ACT has data proving or disproving the compatibility between certain working fluids and envelope materials.

D. Thermal Analysis

To determine the relationship between shape and radiation of the 3D radiator, computer-aided drafting (CAD) models were generated and Autodesk CFD software was used to calculate the view factor of the internal surfaces to the outside environment. Figure 8 shows some example CAD geometries used to calculate view factor as a function of VVFTPR shape where the surfaces with changing area (teardrop shaped face and top opening face) would be open to radiate to space. During this analysis, the minimum view factor when the shape is closed may still be relatively significant, but future development will involve closing the teardrop shaped face and minimizing the view factor to near zero.

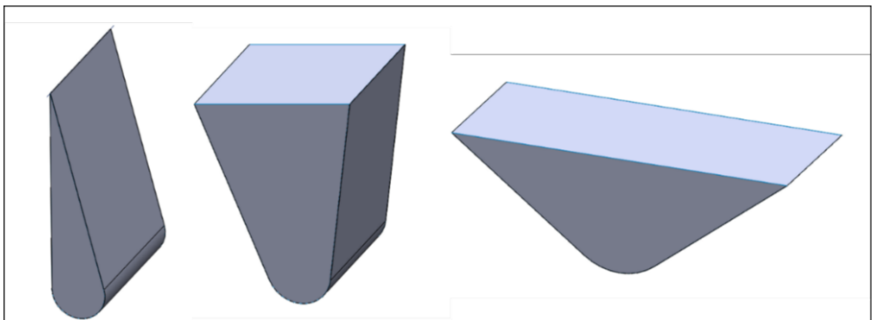

Figure 8. Example of CAD geometry for calculating view factor as a function of VVFTPR shape

To determine the turndown ratio of the VVFTPR, heat loads were calculated for a minimum and maximum view factor. In both cases radiation to space, the ultimate heat sink, was the heat transfer limiting phenomenon. That is, the operation of the two-phase cavity was capable of transferring a greater heat load without exceeding any heat pipe limits for a two-phase radiator than could be radiated (with ammonia as the working fluid). The minimum view factor for the emissive (interior) part of the VVFTPR was assumed to be zero when the VVFTPR is closed because insulating shielding will be incorporated to completely close the structure. The view factor of the reflective surface (exterior) of the radiator is assumed to be one in both the closed and open configuration, but emissivity of this surface is low. A heat loss from the radiator is calculated for a condition where the radiator is at a low temperature and is in a closed state. This calculation is shown in Equation 1,

$$\boldsymbol{Q_{loss}} = \boldsymbol{\varepsilon_{insulation} \cdot \eta \cdot \sigma \cdot A_{outer} \cdot \left(T_{radiator}{}^{4} - T_{sink}{}^{4}\right)} \tag{1}$$

where $\varepsilon_{insulation}$ is the emissivity of the exterior and is assumed to be 0.03. η is the radiator fin efficiency and is assumed to be 0.85 because heat pipes will be used to spread heat uniformly across the area of the radiator panels. σ is the Stefan-Boltzmann constant. A_{outer} is the area of the external surface of the VVFTPR. For this worst case cold state, the survival temperature of the radiator, $T_{radiator}$, is assumed to be 233 K (-40 °C) and the sink temperature is assumed to be 70 K (-203 °C). The Q_{loss} value calculated at these temperatures represents the minimum heat that must be generated for survival of the electronic components. To calculate the maximum heat dissipation of the radiator when the heat generation rate and heat sink temperature are greatest, Equation 2 is used,

$$\boldsymbol{Q(F)} = \boldsymbol{Q_{loss} + \varepsilon_{radiator} \cdot \eta \cdot \sigma \cdot A_{inner} \cdot F \cdot \left(T_{radiator}{}^{4} - T_{sink}{}^{4}\right)} \tag{2}$$

where Q_{loss} is calculated at new temperatures. The maximum allowable radiator temperature is assumed to be 293 K (20 °C), and the maximum sink temperature is assumed to be 230 K (-43 °C). The view factor used for this calculation is the maximum view factor achieved during structural simulations, which is 0.878.

$$\textbf{Turndown Ratio} = \frac{Q(F_{max})}{Q_{loss}} \tag{3}$$

From the minimum survival heat load and the maximum operational heat load, the turndown ratio is calculated.

Table 1 summarizes the temperatures used to calculate these heat loads and shows the minimum and maximum heat loads. This means that the VVFTPR can achieve a turndown ratio of 37:1 when designed based on the material and fabrication restraints imposed during the SBIR Phase I project. That is, the geometric parameters such as wall thickness used in this theoretical evaluation are limited within the scope of ACT's current manufacturing capabilities. With additional development and improved fabrication processes, the opening sensitivity and therefore turndown ratio can be improved. In addition, it has to be mentioned that the turndown ratio of 37:1 is calculated in a conservative manner since the temperature of the insulated side of the radiator is considered equal to the temperature of the emitting side of the radiator. If MLI is used on the non-emitting side then the outer surface of the MLI would be colder and therefore the losses will be further reduced.

Table 1. Mission Parameters for Determining Turndown Ratio

	$T_{radiator}$	T_{sink}	Q	Mission
	[K]	[K]	[W]	
Minimum	233	70	5.7	Survival
Maximum	293	230	211.4	Operation

The design of the VVFTPR can be changed to achieve different temperature control ranges with varying geometry, materials and working fluids. For example, the baseline design described here could utilize a different wall thickness or other geometric parameters and use the same working fluid which would result in a device with a different opening rate with respect to vapor pressure and a different maximum view factor. This would yield a different temperature control range. Alternatively, the same design could be used for different working fluids. All designs would require similar pressure ranges and result in similar view factor ranges, but the saturation temperature range of each fluid would be different. The VVFTPR design can be optimized to operate within a desired temperature and heat power range by selecting the appropriate working fluid and geometric parameters.

IV. Proof-of-Concept Prototyping

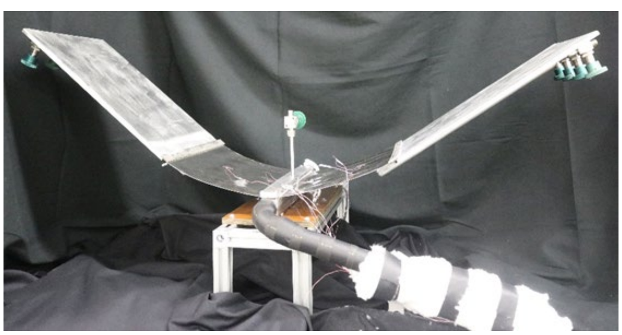

Figure 9. Picture of prototype at open position during experiment

A proof-of-concept benchtop demonstration was completed by fabricating prototype VVFTPRs and pressurizing the internal cavity to open the radiator shape, thus increasing view factor. Figure 10 shows a prototype VVFTPR in the open configuration during an experiment where heat was applied to the external surface of the flexible two-phase section along the axial center line via a heat pipe. Thermocouples were placed on the surface of the flexible two-phase section, and the wall temperatures were recorded during experiments. Displacement transducers were located at a position on the center plane of symmetry of the radiator and attached to points on the radiator so that deformation could be measured during experiments.

The recorded displacement values were translated to the corresponding angle between the flat radiator panel sections and used to calculate view factor. In experimental testing, radiator opening corresponding to the maximum predicted deformations via structural modeling were achieved, proving that view factor values up to 0.88 are achievable for currently manufacturable VVFTPR designs.

The prototype shown in Figure 10 was heated and cooled at varying rates while displacement was measured. Figure 11 shows a plot where the prototype was heated and cooled for 4 cycles. The heating rates were 100 W, then 125 W, then 175 W for the last two cycles. During the first 3 cycles, the prototype was cooled by forced convection with a fan, during the last cycle, the prototype was cooled by natural convection. Additional cycles were also run with 250 W, and reproducible morphing was demonstrated for 19 cycles.

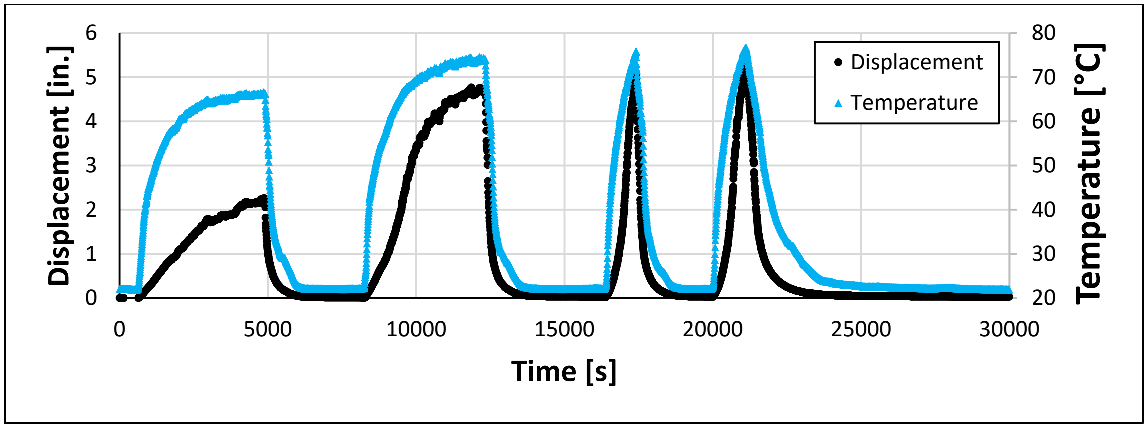

Figure 10. Plot of temperature and displacement of VVFTPR prototype at varying heating and cooling rates

Figure 3 shows images captured during an experiment using this prototype with the temperature plotted with respect to time during the experiment. The approximate fluid temperatures are indicated in the figure. The left column shows the radiator opening as temperature increases, then the right column shows the radiator closing as the temperature decreases. Figure 12 shows displacement with respect to temperature during these thermal cycling experiments. In all experiments there is some degree of hysteresis observed while cooling relative to heating. Every experiment where the VVFTPR is heated shows the same displacement for any given temperature despite varying heating rates. The data during the cooling portion of the cycles shows a wider range of displacement for any temperature, but this effect may not be related to cooling rate. Preliminary experiments show that the radiator shape is a function of temperature and is independent of time, showing no signs of lag or deadband.

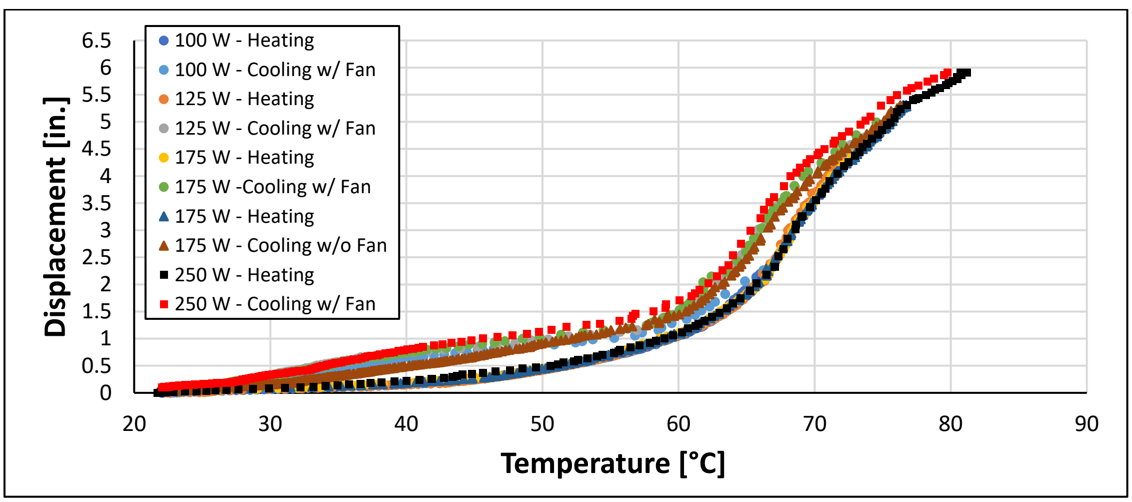

Figure 11. Plot of thermal pressurization experiments with different heating and cooling rates

V. Potential Future Steps for Development

The authors plan to continue developing the concept and fully maximize its benefits. At this point, reasonable feasibility has been demonstrated. Further steps into full development and optimization would consist of:

- Material/working fluid couple assessment
- Geometry optimization
- Pressure containment in the planar portion
    - Welding strategies
- Internal wick structure optimization

These steps would lead to increased sensitivity and therefore increased turndown ratio. Deployability increase would be also resulting from this development. At this stage multiple options open for radiator design based on the proposed concept and interesting configurations could be generated. For example, Figure 12 shows a potential radiator configuration/architecture that is fully based on the developed concept and consists of multiple radiator panels and joints mounted in series. Heat is transferred and spread by two-phase means if the straight portions are hollow with wick structure (in addition to the joints) or by an LHP condenser if the straight portions are solid. It is authors intention to develop a reduced scale version of such architecture in the near future.

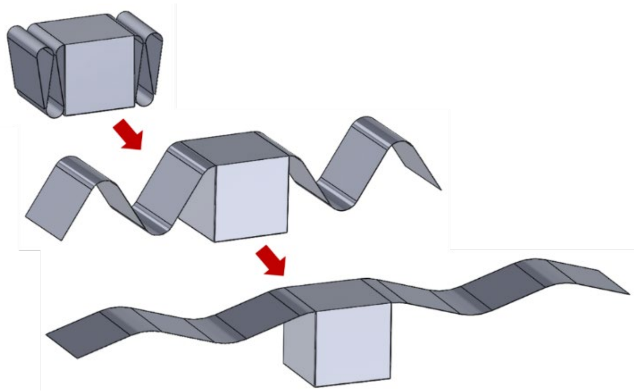

Figure 12. Variable view factor and deployable vapor pressure driven radiator with Multiple Panel Configuration.

VI. Conclusion

An innovative variable-view-factor and deployable two-phase radiator prototype was designed and fabricated by Advanced Cooling Technologies, Inc. Unlike previously developed variable-geometry radiator materials[6], the VVFTPR utilizes two-phase heat transfer to effectively transfer heat from the radiator root to the emissive surfaces maximizing their efficiency. The shape of the radiator continuously morphs to adjust view factor in response to changes in temperature. In this manner, passive thermal control is achieved as heat load or heat sink conditions change, and a thermal control range can be maintained. Thermal and structural analysis results were coupled to predict that the VVFTPR can achieve view factor values ranging from near zero to 0.90, corresponding to thermal turndown ratios of up to 37:1 based on current fabrication techniques. Prototypes were fabricated and experimentally tested to demonstrate the shape morphing behavior of the VVFTPR and proved that the maximum view factor configurations estimated during structural modeling are feasible.

Acknowledgments

This project is funded by NASA Marshall Space Flight Center under a SBIR Phase II program (Contract 80NSSC18P2187). The technical monitor is Jeff Farmer. Special appreciation to Phil Texter and Brent Bennyhoff for the prototype fabrication support.

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