proceedings 40 Years IHPC
17th international heat pipe conference
kanpur, india October 14 - 17, 2013

GROOVED AND SELF-VENTING ARTERIAL HEAT PIPES FOR SPACE FISSION POWER SYSTEMS

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ABSTRACT One design for a future space fission power system uses alkali metal heat pipes to transfer the reactor heat to a series of Stirling or thermoelectric converters for power generation. Artery de-priming by trapped vapor or non-condensable gas in an artery is a single point failure for traditional arterial heat pipes, which can be eliminated by using grooved or self-venting arterial heat pipe wicks. A self-venting arterial pipe has a screen artery that contains small venting pores in the evaporator section that allows any trapped vapor or non-condensable gas (NCG) to escape. A trade study found that the self-venting artery design had higher maximum transport and specific power, compared to arterial and grooved heat pipe designs for a given diameter. Two 1m-long, 1.91 cm O.D. sodium heat pipes were designed, fabricated, and tested; a self-venting arterial heat pipe and a grooved heat pipe. The self-venting arterial heat pipe is capable of carrying 2.6kW of power at adverse elevations of up to 7.62cm without drying out. The grooved heat pipe is capable of carrying 846W, 546W and 346W at adverse elevations of 0.25cm, 1.52cm, and 2.54cm, respectively.

KEY WORDS: Alkali metal heat pipes, arterial heat pipes, grooved heat pipes, space fission reactors

1. HEAT PIPE WICKS

NASA is examining small fission reactors for future space transportation and surface power applications (Mason and Carmichael, 2011). The proposed design would use 2-4 m long alkali metal heat pipes to transfer heat from the reactor to the Stirling or Thermoelectric (TE) converters for electrical energy generation.

There are five types of heat pipe wicks that could carry significant power over these distances in microgravity: 1. Arterial heat pipes with sintered powder (or screen) wicks, 2. Annular heat pipes, 3. Crescent wicks, 4. Grooved heat pipes, and 5. Self-venting arterial heat pipes; see Figure 1. Arterial, annular and crescent wicks have traditionally been the default designs for long alkali metal heat pipes in microgravity, due to their ability to carry significant power; however, they can suffer from de-priming of the artery due to NCG generation or the formation of a vapor bubble. If vapor or non-condensable gas is generated in these wicks, it will hinder liquid return flow through the wick and could de-prime the heat pipe. There is no method to remove the vapor or NCG from the wick once the artery is de-primed. Grooved and self-venting heat pipes offer potential benefits over the standard arterial heat pipes, in regards to the de-priming issue that may be experienced due to operation in a reactor. First, the grooves cannot be de-primed due to the liquid flow path being open to the vapor space. Second, the self-venting pipes are less susceptible to de-priming due to venting pores located in the evaporator that allow trapped NCG or vapor to escape into the vapor space.

1.1 Grooved Heat Pipes

The first alternate wick design considered in this program was the grooved wick, which is the standard wick used in spacecraft Constant Conductance Heat Pipes (CCHPs), Diodes, and Variable Conductance Heat Pipes (VCHPs). The benefit of the grooved wick is that it cannot be de-primed by vapor bubbles because they can vent directly into the vapor space. Typical aluminum grooved extrusions are shown in Figure 1d. These grooves have a very high permeability, allowing very long heat pipes for operation in zero-g, typically several meters long with ammonia or ethane as the working fluid. Their only flaw is that they are suitable

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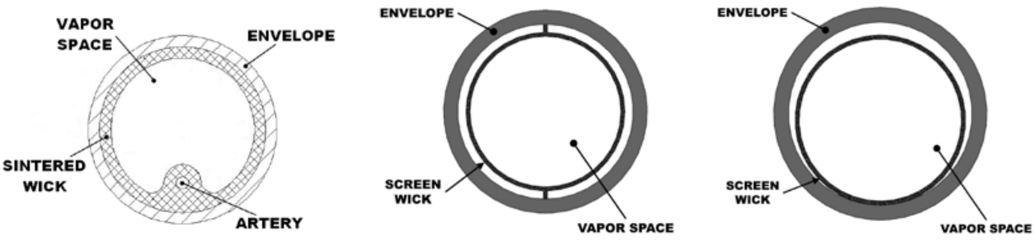
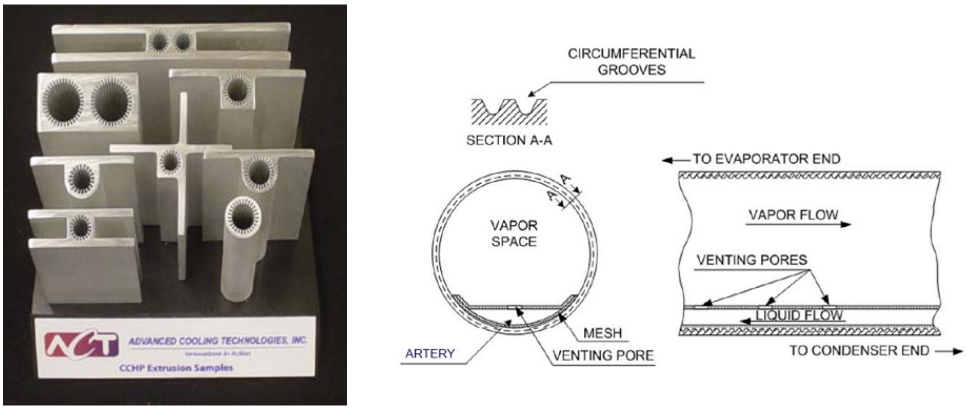


a) Sintered Arterial **b) Annular Screen Wick** **c) Crescent Wick**



d) Grooved Wick **e) Self-Venting Arterial Wick**

FIG 1: Heat pipe wicks suitable for long heat pipes in microgravity. a) Arterial heat pipe, b) Annular heat pipe, c) Crescent heat pipe, d) Grooved heat pipes, and e) Self-venting arterial heat pipe.

only for space or for gravity aided sections of a heat pipe. The reason is that the same large pore size responsible for the high permeability results in low pumping capability. The standard adverse elevation for testing grooved CCHPs on Earth is 2.54mm (0.1in) against gravity.

As shown in Figure 1d, aluminum heat pipes are typically extruded with very fine grooves. This is possible due to the relatively low yield strength, and high ductility of aluminum. The same process cannot be used with the heat pipe envelopes suitable for use with alkali metals, due to their higher yield strength and lower ductility. A new method was developed for non-aluminum grooved heat pipe fabrication that consists of electrical discharge machining (EDM) the internal grooved structure of the pipe from a solid rod in short sections, and then orbital welding the sections into a full length heat pipe.

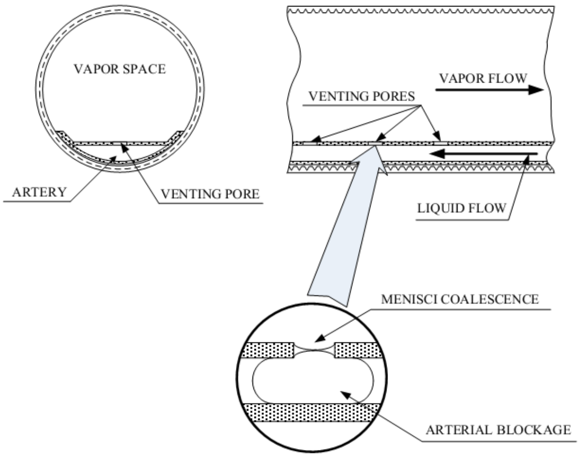


FIG 2: Self-Venting Arterial Heat Pipe has a series of vent holes in the artery to remove non-condensable gas trapped in the artery.

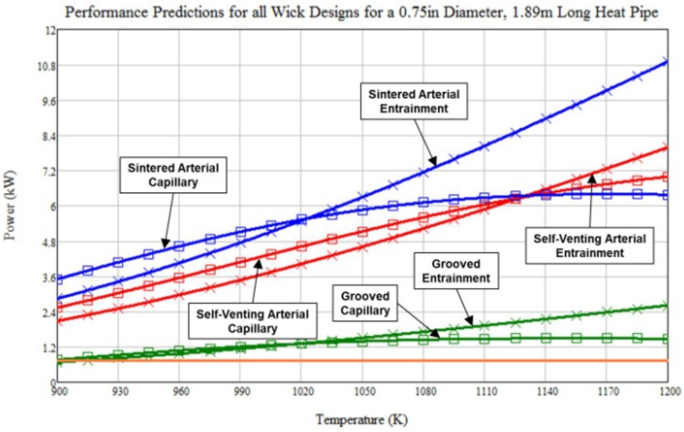


FIG 3: Capillary and entrainment limits for all wick designs for a 0.75in (1.91cm) OD, 74.4in (1.89m) long heat pipe.

1.2 Self-Venting Arterial Wicks

The second potential heat pipe wick considered is a self-venting arterial heat pipe that was first proposed by Eninger (1974). More recently, it was further developed by Goncharov et al. at Lavochkin in Russia (Goncharov et al., 1999, Kaya and Goncharov, 2010); see Figure 1e and Figure 2. The artery in this variation of heat pipe is created using a screen wick at the base of the heat pipe envelope that creates a single artery for the liquid return flow. The difference from conventional arterial pipes is the addition of small venting pores located on the top of the artery in the evaporator section. If vapor or NCG is introduced into the artery, the venting pores prevent the typical de-priming that would be experienced in a standard arterial heat pipe. Any vapor blockage will travel through the artery and into the evaporator where the venting pores are located. The vent pores are designed in a manner that when a blockage occurs the menisci formed on both sides of the venting pore will coalesce to allow the gas to be vented without de-priming the artery. Essentially, the venting pores provide an escape route for any trapped vapor or NCG in the artery; see Figure 2. The design eliminates the single point failure nature of standard arterial heat pipes.

The self-venting arterial heat pipe design has been validated in numerous Russian spacecraft, so the TRL level for ammonia, propylene and Freon heat pipes is 9. It is important to note that self-venting ammonia heat pipes have been built and tested in space. This contrasts with conventional arterial heat pipes, which will not work reliably with ammonia. Note that the wick designed used by Eninger and Goncharov et al. had circumferential grooves (screw threads) cut into the heat pipe I.D. The grooves collect the liquid in the condenser and deliver it to the artery. Similarly, the grooves distribute liquid from the artery in the evaporator. In our heat pipes, screen wraps are used instead.

2. FULL-LENGTH HEAT PIPE DESIGN TRADE STUDY

A trade study was conducted to compare powers and masses for arterial, self-venting arterial, and grooved heat pipes for the Stirling based system proposed by Mason and Carmichael. The heat pipes are required to carry a minimum of 725W of power, which is based on an 18 heat pipe thermal management design proposed by NASA Glenn (Mason & Carmichael, 2011). Two Outer Diameter (OD) sizes were compared in the Stirling trade study; 0.75in (1.91cm) and 0.50in (1.27cm). The 0.50in (1.27cm) OD is the desired size for system due to limited interfacing space between the Stirling engines and heat pipes, and an improvement in the reactor size.

The performance predictions for the 0.75in (1.91cm) diameter case can be seen in Figure 3. The limits for the self-venting arterial heat pipe are in red, the limits for the sintered arterial heat pipe are in blue and the limits for the grooved heat pipe are in green. The two arterial heat pipes are capable of transporting significantly more power than the grooved heat pipe. The self-venting arterial heat pipe is capable of transporting 2.3 to 7.0kW of power over the operating temperature range. The entrainment limit controls for the majority of the operating temperature range. The capillary limit controls from approximately 1115K to

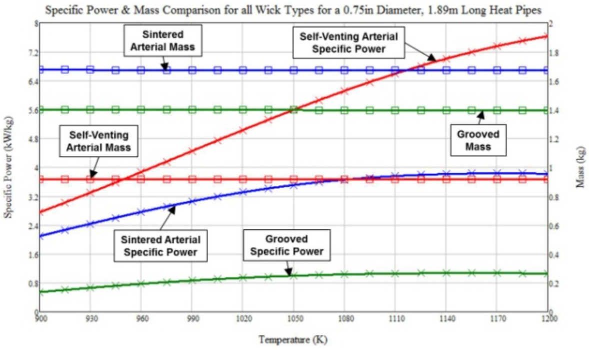


FIG 4: Specific power and mass of 0.75in (1.91cm) OD self-venting arterial, sintered arterial and grooved heat pipes for a Stirling based system.

1200K. The sintered arterial heat pipe is capable of transporting 3.0 to 6.3kW of power over the operating temperature range. The entrainment limit controls from 900K to approximately 1020K, while the capillary limit controls from 1020K to 1200K. The grooved heat pipe is capable of transporting 725W to 1.4kW of power over the operating temperature range. The capillary limit controls for the entire operating temperature range.

The specific power of the three heat pipe wicks was evaluated to determine the wick that provides the best specific power. Haynes 230 was used as the envelope material for the specific power analysis. Nickel powder was used for the sintered arterial wick and stainless steel screen was used for the self-venting arterial wick. Haynes 230 is the lone material used for the grooved heat pipe. The specific power as a function of temperature was calculated as the controlling heat pipe limit over the mass of the heat pipe. The results of the specific power trade study for the 0.75in (1.91cm) diameter case can be seen in Figure 4. The self-venting arterial heat pipe provides the largest specific power of the three wick designs. The self-venting arterial heat pipe is capable of specific powers ranging from 3.0 to 7.6kW/kg over the operating temperature range. The sintered arterial heat pipe is capable of specific powers ranging from 2.0 to 3.8kW/kg over the operating temperature range. The grooved heat pipe is capable of specific powers ranging from 0.6 to 1.0kW/kg over the operating temperature range. The self-venting arterial heat pipe is the lightest of the three wick designs, at 0.92kg. The sintered arterial heat pipe has a mass of 1.67kg, and the grooved heat pipe has a mass of 1.77kg.

3. GROOVED AND SELF-VENTED ARTERIAL HEAT PIPE FABRICATION AND TESTING

To the best of our knowledge, grooved and self-venting artery wicks have not previously been demonstrated with an alkali metal working fluid. One meter long versions of the grooved and self-venting arterial heat pipes were designed, fabricated and tested to provide experimental verification that these heat pipes could transfer the required power. To reduce expense, the heat pipes were fabricated from stainless steel with sodium as the working fluid and were operated at a reduced temperature of 725°C during experimental testing. The two heat pipes were tested at various adverse elevations to an evaporator dry out to determine their maximum transport capability. The sintered arterial heat pipe design was not fabricated since its design and performance are well understood. More details on the design and fabrication of these heat pipes can be found in Walker et al. (2013).

An outer diameter of 0.75in (1.91cm) was chosen for both the grooved and self-venting arterial heat pipes. An evaporator length of 10.0in (25.4cm) and a condenser length of 8.0in (20.3cm) were chosen for both the grooved and self-venting arterial heat pipes. While previous self-venting arterial heat pipes used a screw thread to collect and distribute liquid, the current pipe used two screen wraps around the entire heat pipe circumference.

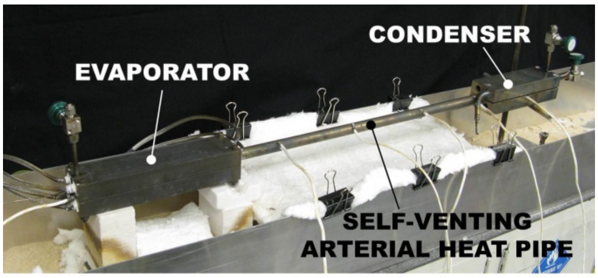


FIG 5: Self-venting arterial heat pipe on test stand.

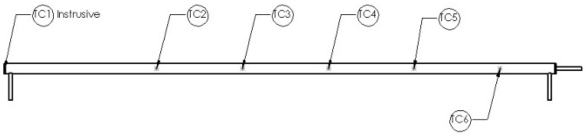
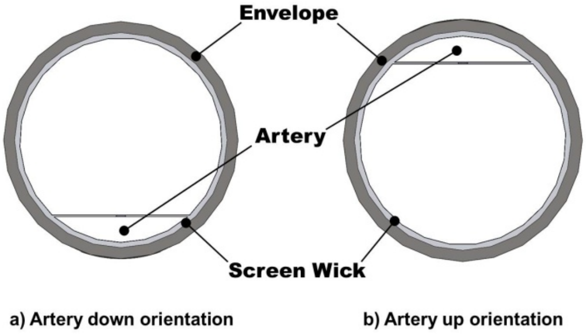


FIG 6: TC map for the grooved heat pipe and self-venting arterial heat pipes.



a) Artery down orientation

b) Artery up orientation

FIG 7: Self-venting arterial heat pipe artery orientation during testing.

3.1 Experimental Test Set-Up

Heat input to the grooved and self-venting arterial heat pipe was provided by a heater block. The heater block was machined from stainless steel accommodates eight, 750W embedded cartridge heaters. A condenser block, similar to the heater block, was machined from stainless steel. A Liquid Nitrogen (LN) Dewar was connected to the condenser block to provide cooling. The grooved heat pipe and the self-venting arterial heat pipe were tested separately using the same test assembly; see Figure 5. Both heat pipes were insulated (not shown in Figure 5) with multiple layers of Kaowool to reduce the overall heat losses from the system. The thermocouple map for both heat pipes is shown in Figure 6.

The heat pipe is operated until dry out occurs to determine the maximum transport capabilities. Dry out is indicated by a sudden spike in the evaporator or heater temperature. Thermal performance testing is performed at adverse elevations where the evaporator is positioned higher than the condenser, forcing the heat pipe to operate against gravity. The heat pipes were tested at a reduced operating temperature of 725ºC. The required operating temperature for the heat pipes in a nuclear reactor will be 827ºC (1100K); however, stainless steel was used as the envelope for these proof-of-concept tests at reduced temperature, due to the high cost of the superalloys that can operate at higher temperatures.

3.2 Self-Venting Arterial Heat Pipe Testing

The self-venting arterial heat pipe was tested in two orientations; artery up and artery down to determine if the artery location had an impact on heat pipe performance; see Figure 7. The heat pipe was tested in the artery-down orientation for only two adverse elevations because the artery-up condition provides the most

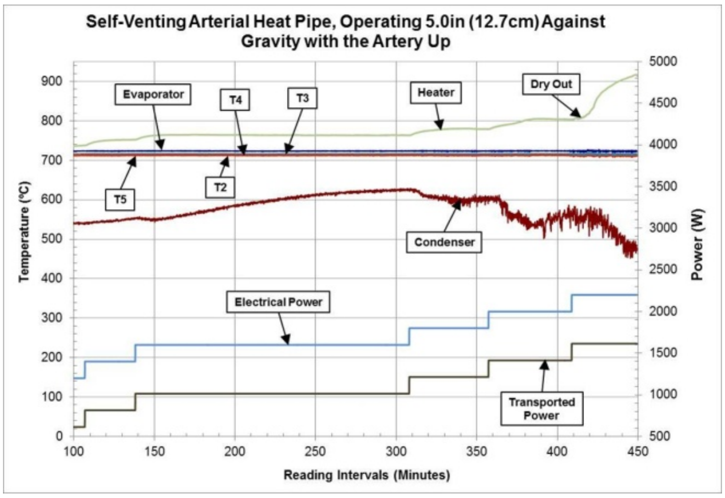


FIG 8: Self-venting arterial heat pipe performance, artery up with a 5.0in (12.7cm) adverse elevation. The maximum power was 1.4 kW.

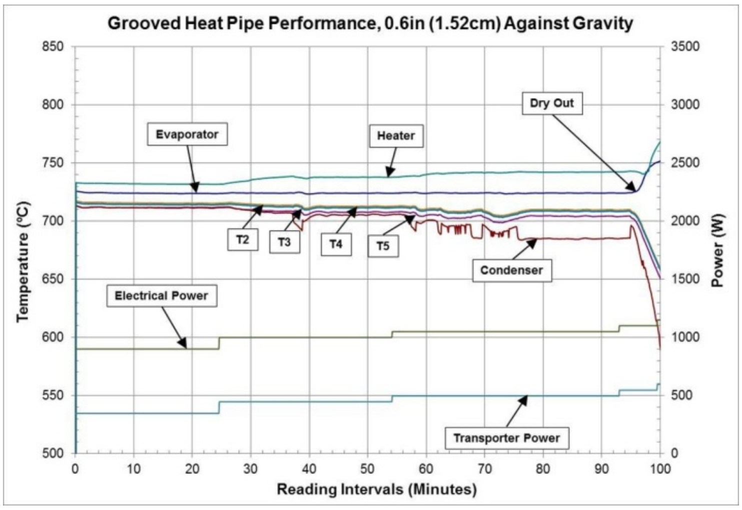


FIG 9: Grooved heat pipe performance, operating at 0.6in (1.52cm) against gravity.

difficult operating conditions for the heat pipe. Theoretically, if the heat pipe is capable of transporting a certain power in an artery-up condition, the performance will only improve if it is rotated to the artery-down condition. For this reason, testing of the artery down for the higher adverse elevations was deemed unnecessary.

For all tests, the evaporator was maintained at a steady operating temperature of 725ºC. The self-venting arterial heat pipe performed extremely well for all testing conditions. The artery orientation did not have a significant impact on heat pipe performance. The increased adverse elevations also did not have a significant impact on heat pipe performance, with the exception of the 5.0in (12.7cm) adverse elevation case. A transport power of 2.6kW was achieved for all testing conditions, with the exception of the 5.0in (12.7cm) case, where a maximum transport power of 1.4kW was determined.

Typical thermal performance results for the self-venting arterial heat pipe can be seen in Figure 8. The self-venting arterial heat pipe was capable of transporting 2.4kW to 2.6kW of power for the adverse elevations of 0.1in (0.25cm) to 3.0in (7.6cm). Dry out of the heat pipe was not achievable until 5.0in (12.7cm) adverse elevation due to insufficient cooling capabilities; see in Figure 8. The maximum power transport at that elevation was 1.4kW.

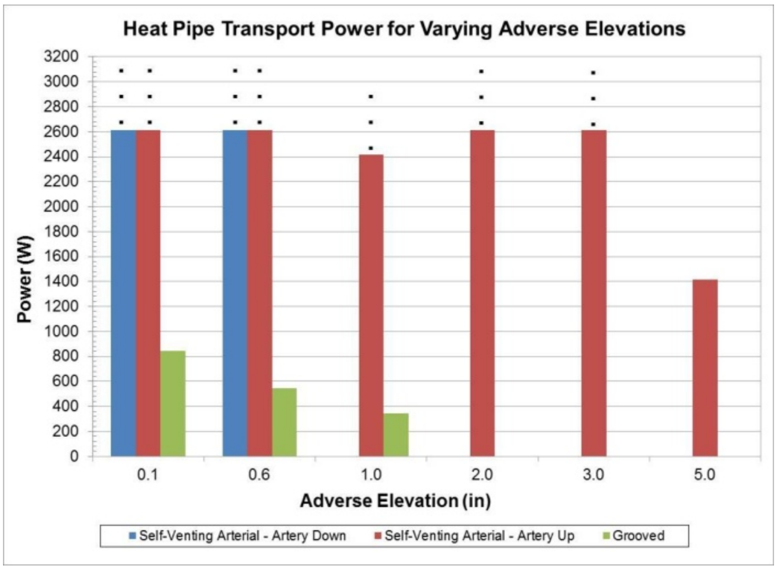


FIG 10: Summary of thermal performance results for the grooved and self-venting arterial heat pipes. The dots above the bars indicate that the power was limited by the test apparatus and not by the heat pipe. The reduced power for the artery at 2.0 inches is due to running out of coolant.

3.3 Grooved Heat Pipe Testing

An example of the thermal performance results for the grooved heat pipe can be seen in Figure 9. For all testing conditions, the evaporator was maintained at a steady operating temperature of 725ºC. The grooved heat pipe was operated until dry out for all testing conditions. At an adverse elevation of 0.1in (0.25cm), the grooved heat pipe was capable of transporting 846W of power, while it transported 546 W of power at an adverse elevation of 0.6in (1.52cm). The dry out is easily indicated in Figure 9 by the sudden increase in evaporator and heater temperatures and the sudden decrease in the condenser and remaining TCs. At an adverse elevation of 1.0in (2.5cm) against gravity, the grooved heat pipe was only capable of transporting 346W of power. The grooved heat pipe was significantly impacted by the increase adverse elevation. This tends to be true of grooved heat pipes as they are only suitable for zero-g or gravity-aided applications. The same large pore size responsible for the high permeability results in low pumping capability and therefore the maximum transport capability will be strongly affected by increasing adverse elevations.

3.4 Self-Venting Arterial and Grooved Heat Pipe Comparison

Thermal performance testing was conducted on both the self-venting arterial heat pipe and the grooved heat pipe to determine their maximum transport capability. The intention was to run each case until dry out. At the lower adverse elevations, dry out was not achievable for the self-venting arterial heat pipe due to insufficient cooling capacity. At a 5.0in (12.7cm) adverse elevation, dry out was experienced at 1.4kW. The self-venting arterial heat pipe was capable of at least 2.4 to 2.6kW of transported power for all testing conditions, except the 5.0in (12.7cm) adverse elevation. Its performance did not appear to be affected by the artery orientation. The grooved heat pipe was capable of transporting 846W of power for an adverse elevation of 0.1in (0.25cm), 546W of power for an adverse elevation of 0.6in (1.52cm) and 346W of power for an adverse elevation of 1.0in (2.5cm).

Dry out was achievable for all testing conditions of the grooved heat pipe and therefore the maximum transport capability has been determined. The grooved heat pipe was significantly affected by the increased adverse elevations. It had a decrease in maximum transport capability of 500W from 0.1in (0.25cm) to 1.0in (2.5cm) adverse elevations. A summary of the thermal performance results for both heat pipes for all testing conditions can be seen in Figure 10.

4. SUMMARY AND CONCLUSIONS

High temperature, alkali metal heat pipes have been developed to transfer the thermal energy generated by a spacecraft fission reactor to electrical convertors for power generation. Previously, three types of heat pipe wicks had been considered as suitable for long alkali metal heat pipes: arterial, annular and crescent. If non-condensable gas or vapor is generated in the artery or annulus of these designs, it could cause the heat pipe to de-prime and cease operating. This program examined an additional two wick designs: grooved and self-venting arterial. The advantage of these designs is that they are self-venting.

A trade study was conducted to compare the maximum transport and specific power for the self-vented artery, artery, and grooved heat pipe designs. In all cases for a given diameter, the self-vented artery design carried the highest power, and had the highest specific power.

A 1m (39.67in) long, 0.75in (1.91cm) outer diameter self-venting arterial heat pipe and a grooved heat pipe with similar dimensions were designed, fabricated and tested. Thermal performance testing of the two heat pipes was conducted at an operating temperature of 725°C and at adverse elevations ranging from 0.1in (0.25cm) to 5.0in (12.7cm). The self-venting arterial heat pipe was capable of transporting at least 2.6kW of power at all adverse elevations except 5.0in (12.7cm) where it transported 1.4kW. The grooved heat pipe was capable of transporting a maximum power of 846W at 0.1in (0.25cm) elevation and 346W at 1in (2.5cm).

ACKNOWLEDGMENTS

This research was sponsored by NASA Glenn Research Center under Contract No. NNX12CE07P. Any opinions, findings, and conclusions or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration. Mr. Marc Gibson was the contract technical monitor. Tim Wagner and James Bean were the laboratory technicians responsible for the fabrication and testing of the grooved heat pipe and self-venting arterial heat pipe.

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