INL/JOU-21-62106-Revision-0

Assessment of Screen-Covered Grooved Sodium Heat Pipes for Microreactor Applications

November 2021

Donna Post Guillen, Clayton G Turner

INL/JOU-21-62106-Revision-0

Assessment of Screen-Covered Grooved Sodium Heat Pipes for Microreactor Applications

Donna Post Guillen, Clayton G Turner

November 2021

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

ASSESSMENT OF SCREEN-COVERED GROOVED SODIUM HEAT PIPES FOR MICROREACTOR APPLICATIONS

Donna Post Guillen and Clayton G. Turner
Idaho National Laboratory
P.O. Box 1625, Idaho Falls, Idaho USA 83415

ABSTRACT

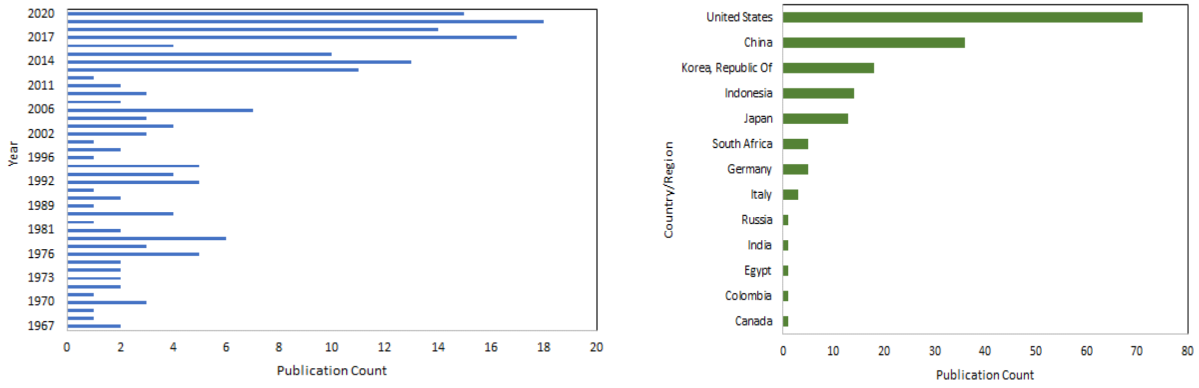
New nuclear reactor designs that incorporate heat pipes are being investigated for possible near-term deployment in terrestrial applications. This study explores the use of screen-covered axially grooved sodium heat pipes and their applicability for providing heat removal for microreactors. A sodium working fluid is appropriate for microreactors operating in the 5 to 20 MWt range at approximately 650ºC. HTPIPE, a legacy software code, was validated for the case of screen-covered grooves and used to perform steady-state analyses to determine the performance limits of a proposed heat pipe design. The performance limits of a sodium heat pipe with a screen-covered square grooved wick structure is compared to that of an equivalent heat pipe with an annular wick. In a horizontal orientation at an operating temperature of 650ºC, the performance limits for the heat pipe with an annular wick configuration are 15% higher than for the screen-covered groove wick. At operating temperatures below 777ºC the annular wick outperforms the screen-covered groove wick and at temperatures above 777ºC the screen-covered grooved wick outperforms the annular wick. However, the marginal performance gain at higher temperatures may not justify the use of heat pipes with a screen-covered groove wick structure due to increased manufacturing costs.

KEYWORDS
Sodium heat pipes, microreactors, screen-covered grooves, annular heat pipe, wick structure

1. INTRODUCTION

Microreactors, or very small transportable or mobile nuclear reactors with a capacity less than 20 MWt, are sought to provide heat and power for myriad applications in remote areas, military installations, emergency operations, humanitarian missions, and disaster relief zones [1]. Microreactors may someday sit beside larger nuclear reactors to provide emergency power to auxiliary cooling systems in the event of a situation where diesel generators cannot operate or be refueled. A wide variety of reactor types are under consideration, including sodium-cooled fast reactors, molten salt reactors, light water reactors, very high-temperature gas reactors, and heat pipe reactors. The focus of this report is on heat pipe technology as applied to microreactors.

Figure 1 shows the dramatic increase in interest in the use of heat pipes for cooling in nuclear reactors over the last decade. The publications originate mainly in the U.S. with contributions from at least a dozen other countries. An overview of alkali metal heat pipe cooled reactors is presented by Yan et al. [2]. Wang et al. [3] describes a design and analysis methodology for a 25 kWe reactor with potassium heat pipes wherein the performance and transient response are evaluated. Sun et al. [4] outlines a conceptual design for a 120 kWe nuclear reactor with lithium heat pipes to cool the core, six control drums, and tungsten and water radiation shields. There are several heat pipe cooled reactor concepts being designed [5]. Sterbentz et al. [6], Ahlfeld et al. [7], and Mueller and Tsvetkov [8] describe an integral fuel-element heat pipe with a central cavity containing the fuel with the heat pipe region directly surrounding the fuel in an annular configuration. Walker et al. [9] presented two sodium heat pipe designs for Kilopower, one of which consisted of a screen wick in the evaporator and open grooves in the adiabatic and condenser sections. However, there are no known cases of a sodium heat pipe operating with a screen-covered groove wick structure.



(a) (b)

Figure 1. **Publication count with the search terms "heat pipe" and "nuclear reactor" (a) by year, and (b) by country/region (source: Engineering Village).**

2. METHODOLOGY

Advanced, high-performance heat pipe designs are being considered for incorporation into 1 to 20 MWt microreactors. The function and performance of alkali metal heat pipes with a screen-covered groove wick structure for high-temperature thermal transport is investigated here to determine their feasibility for microreactors. A heat pipe is a device with very high thermal conductance that can transport large quantities of heat with a small temperature difference between its hot and cold ends. Heat pipes are passive devices with no moving parts, which makes them simple to operate, very reliable, and they have a long service life with minimal maintenance. These benefits make heat pipes desirable for transporting heat from micro-nuclear reactors to power conversion units or process heat applications. There are many different types of heat pipes, including constant or variable conductance, diode, oscillating, loop, or flat heat pipes [10]. Figure 2 shows the configuration of a typical constant conductance heat pipe with evaporator, adiabatic, and condenser sections enclosed by a sealed tube and an interior wick. Heat pipes function by condensing and vaporizing the working fluid inside of the heat pipe [11]. The working fluid inside the heat pipe is vaporized in the evaporator section and then condensed back to liquid in the condenser section. The working fluid circulates inside the heat pipe and is driven by capillary action in the wick. The capillary action functions due to the small pore size in the wick structure and the flow occurs due to the difference in pressure between the evaporator and condenser sections. Heat is transferred through the latent heat of vaporization of the working fluid. This process creates a very efficient transport of heat with minimal losses.

There are many different variables that affect heat pipe performance, such as orientation, wick structure, heat pipe size, heat pipe wall material, wick material, heat pipe working fluid, etc. The functional limits dictate how much heat transfer the heat pipe can handle at a given temperature before the heat pipe will stop functioning properly. Once a limit is reached, the heat pipe may fail to function properly [12].

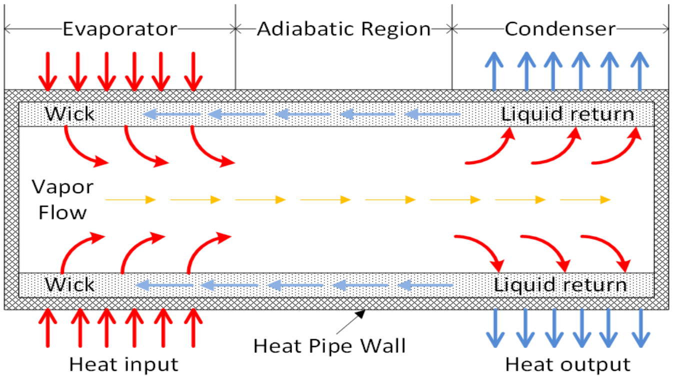


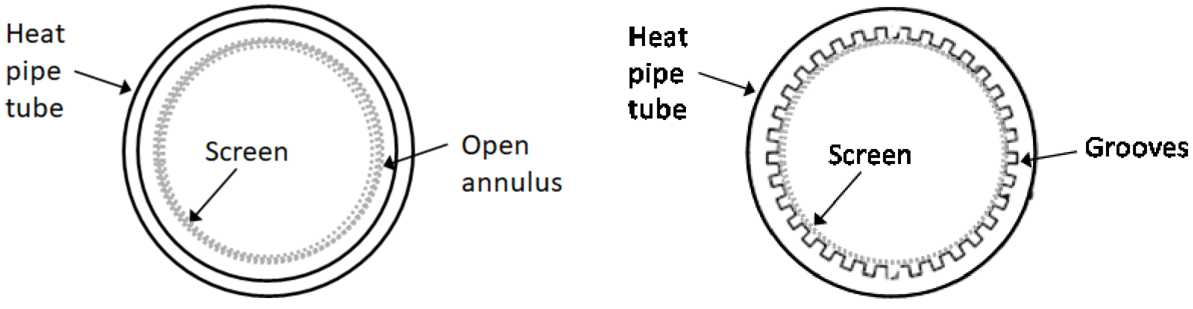
Figure 2. Basic operation of a heat pipe.

Designs for very small nuclear reactors featuring heat pipes are under development. The single primary heat extraction and removal emulator (SPHERE) testbed is being developed to support non-nuclear thermal and integrated systems tests to better understand the thermal performance of heat pipes under a wide range of heating flux and operating temperature. This will elucidate the behavior of heat pipe startup and transient operation. SPHERE offers an electrically heated testbed for the testing of a single heat pipe in a quartz tube for visualization of the temperature front as it travels along the heat pipe [13]. The Microreactor Agile Non-Nuclear Experimental Testbed (MAGNET) facility is a larger scale 250 kW electrically heated microreactor testbed constructed to enable experimental evaluation of a variety of microreactor concepts. The first article to be tested in MAGNET features sodium-filled heat pipes within a solid core block with positions to insert cartridge heaters that supply heat to the heat pipes. In the corresponding nuclear-fueled designs, the core block houses the nuclear fuel and the heat pipes. The heat pipes cool the core block and transfer the heat to a power conversion unit [14]. The proposed heat pipes for the MAGNET are 2.0 meters in length with an outside diameter of 1.5875 cm (5/8 inch). For this analysis, the core block is assumed to be 1-meter long which makes the evaporator section of the heat pipe 1-meter long. The other meter of the heat pipe comprises the adiabatic section and the condenser section. The condenser section is surrounded by a heat exchanger to transfer the heat to the power generation loop. Sodium is used as a working fluid inside the heat pipe for compatibility with the desired microreactor operating temperature between 650 ºC and 700ºC. According to Zohuri [10], the useful range of sodium is from 600 ºC to 1200 ºC. The sodium working fluid is in a frozen state prior to starting up the reactor and transitions through the free molecular flow regime to continuum flow during startup. Other alkali metal working fluids were not considered since their operating temperature ranges fall outside of this range or they react strongly with neutrons [15,16]. Compatible wick and wall materials are required to prevent corrosion, chemical or nuclear reactions. Corrosion will damage the materials and a chemical or nuclear reaction can produce non-condensable gas. Suitable materials of construction for the heat pipe tube and wick with a sodium working fluid include stainless steel, Inconel and Haynes alloys [17]. There is a precedent for using sodium heat pipes with nuclear fission systems. Sodium heat pipes were used to transfer thermal energy from the fission reactor to the Stirling engines in the Kilopower Reactor Using Stirling Technology (KRUSTY) demonstration reactor [18].

When incorporating heat pipes into a microreactor design, it is important to select an appropriate wick structure. Various types of wick structures described in heat pipe textbooks [16,22] can be categorized as either homogeneous or composite. Homogeneous wicks are isotropic structures with a uniform effective pore or channel sizes such that the permeability and the effective pore radius depend on the same characteristic property of the wick. Since high capillary pumping is achieved by small pore radii, whereas a low resistance to flow occurs with large pore sizes, the design of most homogeneous wicks requires a compromise between these conflicting requirements. Despite the performance limitations imposed by this compromise, homogeneous wick designs are widely used because of their reliability, good start-up characteristics, applicability to different applications, and low cost.

Homogeneous wicks including wrapped screens, sintered metal and axial grooves are commonly used in practice. Screen wicks can take the form of a wrapped screen consisting of several layers of a metal mesh in direct contact with the heat pipe wall or as an open annulus wick that leaves a gap for liquid flow between the wrapped screen and the heat pipe wall. Figure 3a shows the arrangement of an annular wick. Grooved heat pipes are the ideal choice for operation in space (microgravity). They are also a good choice in gravity environments when operating in a favorable orientation where the liquid return is assisted by a gravity component along all sections of the pipe. Axially grooved heat pipes have a circle of grooves along the interior heat pipe wall that efficiently pulls condensate back to the evaporator from the condenser. The grooves can be square, rectangular, triangular, trapezoidal, inverse trapezoidal, or nearly circular shaped [19]. Heat pipes with axially grooved inner walls are less sensitive to flow disruptions caused by non-condensable gas impurities and are generally easier to restart following such events. The liquid-vapor interface in a groove manifests as curvature across the groove width, rather than along two normal axes of the pores as is the case for a wick with a homogeneous capillary structure [11]. Grooved heat pipes must be operated in a gravity-aided or horizontal orientation, i.e., where the evaporator is at the same elevation as or below the condenser. The grooves provide high permeability and high thermal conductivity. Unfortunately, the groove dimensions tend to be much larger than the pores of a screen or sintered metal wick, which results in a smaller capillary pumping pressure. However, these constant conductance heat pipes can transport heat up to several meters, providing design flexibility. Grooved heat pipes allow a greater range of heat transport than sintered powder metal or screen wick heat pipes. They have been demonstrated to have long lifetimes with high reliability. Axially grooved heat pipes have been successfully used in many applications, such as satellites, spacecraft, space stations, electronics and permafrost preservation [20]. Water and ammonia working fluids have been commonly used for ambient temperature applications of grooved heat pipes [21].

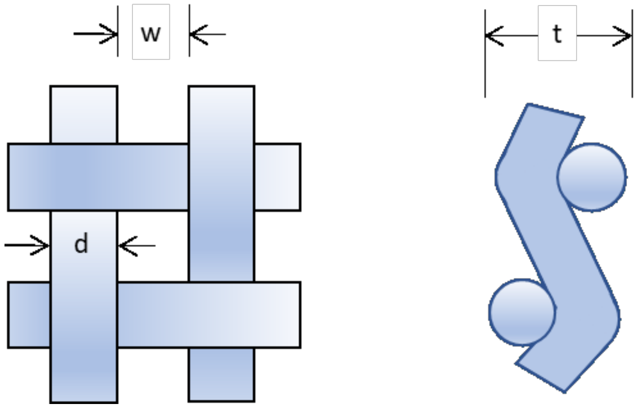
A screen-covered groove capillary is a type of composite wick (Figure 3b). A composite wick incorporates a combination of both small and large capillaries to avoid having to compromise between the requirement for small effective pore radii for high capillary pumping and large effective pore radii for high permeability. In this type of capillary structure, a single layer of mesh screen is used to improve the development of a large capillary pumping pressure where the grooves provide high permeability. The axial grooves ensure low resistance to the liquid flow and the highly conductive groove fins provide a low resistance to heat flow in the radial direction [22]. Heat is conducted through the heat pipe wall and the wick/liquid matrix to the liquid-vapor interface where evaporation occurs. Yilgor and Shi [23] report a 15.7% and 60.2% increase in the capillary limit for a potassium-filled heat pipe with screen-covered grooves compared to an annular or arterial wick, respectively.



(a) (b)

Figure 3. Cross-section of heat pipe with (a) annular wick, and (b) screen-covered grooves on inside of heat pipe.

Wick performance can be characterized by the pore size, permeability, porosity and equivalent thermal conductivity. The following expressions for a wick structure with screen-covered rectangular grooves are outlined by Faghri [17]. The effective pore radius of the metal screen illustrated in Figure 4 is given as



(a) (b)

Figure 4. Metal screen dimensions (a) front view, and (b) side view.

The number of openings per unit length (or mesh number) is given by

(1)

Figure 5 illustrates the nomenclature used in the following equations for a wick with screen-covered rectangular grooves. The permeability is given as

(2)

where the porosity is given by

(3)

the hydraulic diameter is given by

(4)

and

(5)

where

. (6)

The effective thermal conductivity is given by

(7)

where and are the thermal conductivity of the liquid working fluid and the wick material, respectively.

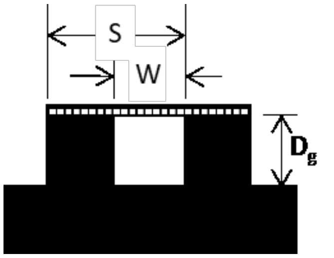


Figure 5. Nomenclature for wick structure with screen-covered rectangular grooves.

Despite detailed analytical expressions for this type of wick being available, this type of wick has not been commonly used [21]. However, there appears to be many benefits of this type of wick. Combining wick structures can result in heat pipes with high capillary pumping, thermal conductivity, and permeability. Capillary pumping refers to how well the liquid can return to the evaporator section. Permeability refers to the wick's resistance to liquid flow axially within the heat pipe to and from the evaporator and condenser sections. A high permeability decreases the liquid pressure drop and increases the thermal transport. The effective thermal conductivity controls the radial temperature drop through the wick structure between the inside and outside of the heat pipe with a small temperature difference desired. Screen-covered grooves have peak performance in capillary pumping and thermal conductivity and the permeability is rated at average to high [10].

In practice, bubble formation in the covered grooves may de-prime the heat pipe. However, since sodium requires a significant amount of superheat to boil (i.e., 879.05ºC [21]), the occurrence of bubbles in the grooves is unlikely. There are drainage and liquid pooling issues to be taken into account for vertical operation. Screen-covered grooved heat pipes for microreactors may work best in a horizontal orientation to avoid drainage and resultant pooling in the evaporator that can lead to instabilities and increased thermal resistance. However, the power is significantly decreased when operating in a horizontal versus vertical orientation. When the condenser is oriented vertically above the evaporator, working fluid will drain from the grooves and pool in the evaporator. A liquid pool in the evaporator may lead to a liquid superheat related instability. In the vertical orientation, condensate will collect on the screen interior surface and not readily flow into the groove. This creates a large thermal resistance between the condensate and the heat pipe outer wall. The problem of pooling can be addressed by including a reservoir below the evaporator, but the wick must be continuous between the reservoir and evaporator. The hydrostatic column that the wick can sustain needs to be enough to provide some liquid in the evaporator (although not necessarily for the entire height of the evaporator) so startup can be successful. Capillary height can be calculated from the relationship between surface tension of sodium , pore radius (hydraulic radius of the groove) and the hydrostatic pressure (where is liquid density and g is gravitational acceleration) and is given by [24]

(8)

which for a small contact angle as is the case for sodium [25]

(9)

Figure 6 shows the hydrostatic column that the capillary meniscus in the groove can sustain for sodium at 650ºC as a function of the equivalent groove size.

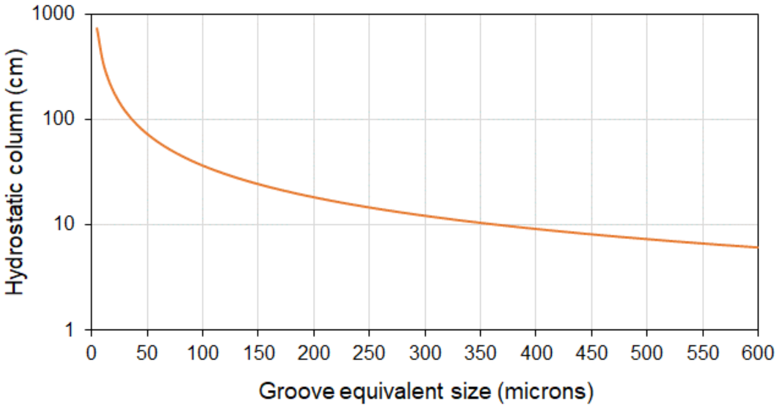


Figure 6. Capillary height for sodium at 650ºC.

There are some potential difficulties if this type of heat pipe is operated in a vertical gravity-aided orientation (i.e., with the condenser above the evaporator). Screen-covered grooves generally offer higher performance than open grooves. The screen-covered groove design uses the screen to protect liquid return from vapor shearing effects. The small pore radius of the screen is advantageous to avoid entrainment that can occur with open grooves, caused by the counterflowing vapor that shears the liquid preventing it from returning to the evaporator and a subsequent dry-out of the wick in the evaporator occurs. In a horizontal orientation, the screen would also increase the capillary pumping capability of the wick. In a gravity-aided orientation, the removal of the screen in the condenser section would be recommended since the presence of the screen in the condenser would impede the access of the vapor to the wall to condense and increase thermal resistance in the radial direction. Grooved heat pipes must not be allowed to drain and form a large liquid pool in the evaporator. If the capillary height of sodium in the groove is small, then the liquid will drain almost all the way to form a pool. The screen that covers the grooves (separating liquid from vapor space) would not impede the drainage. However, if the sodium charge is adequately chosen, then, at steady state the pool height can be minimized to very little, so phenomena related to the pool presence (pool boiling related instabilities and increased thermal resistance) may be diminished accordingly. Also, another way to decrease the pool formation would be to decrease the size of the grooves (and also to increase the number of grooves to put back some performance) in such a way that they will not drain. This type of wick needs to operate at inclinations below the hydrostatic column that the grooves can provide, which typically is small. A horizontal heat pipe orientation is recommended to avoid boiling instabilities that could lead to unsteady reactivity levels. A practical consideration to be noted is that grooved wall heat pipes tend to have higher thermal resistances during startup. This may not be much of an issue for microreactors since they are intended for continuous operation after startup, rather than undergoing repeated cycles of startup and shutdown.

A study was performed to investigate the feasibility of a sodium heat pipe design with screen-covered grooves using HTPIPE, a computer program developed by Los Alamos National Laboratory (LANL). HTPIPE has been extensively validated with experiments [26]. HTPIPE calculates a steady-state approximation of four limits within a heat pipe: capillary limit, sonic limit, entrainment limit, and the boiling limit [27]. The viscous limit is not a consideration here, since it is extremely high in the normal operating temperature range under steady-state conditions [16]. The capillary limit is reached when the wick structure cannot overcome gravitational, liquid, and vapor flow pressure drops. The sonic limit occurs when the vapor flow reaches sonic velocity as it leaves the evaporator and the flow becomes choked. The entrainment limit occurs when high velocity vapor flow strips liquid from the wick. The boiling limit occurs when the working fluid boils in the wick, preventing liquid return to the evaporator. These limits indicate the maximum heat flow into the heat pipe at a given temperature before the performance is degraded. The maximum heat transport ability of a heat pipe at a given temperature is determined by the most constraining limit [16].

3. RESULTS

Validation of the fidelity of the HTPIPE code to predict performance limits for screen-covered axially grooved heat pipes in a horizontal orientation was performed by comparison to the experiment performed by Krambeck et al. [28]. Table 1 lists the design parameters. Tests were performed with a heat load of 5W up to 30W without encountering any performance limits. HTPIPE successfully predicted the limits to be above the cases tested in the experiment as shown in Figure 7.

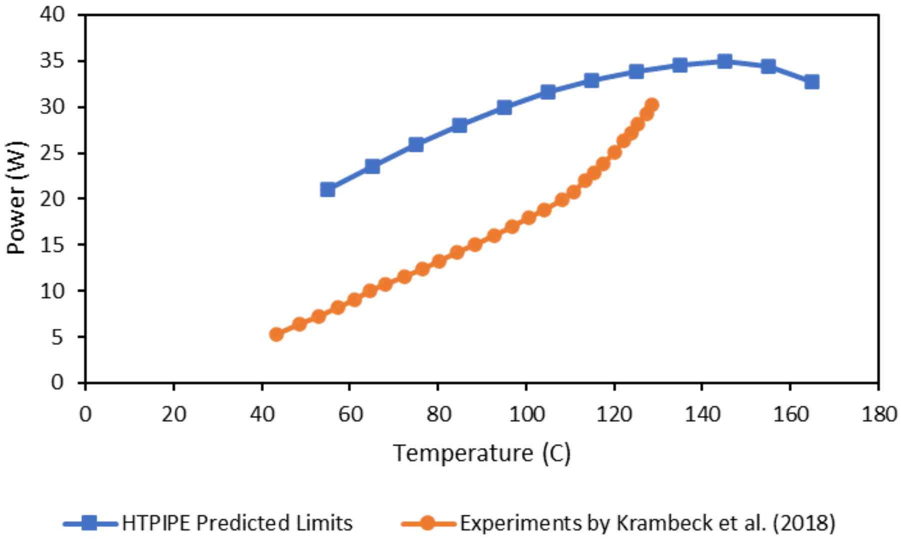


Figure 7. Comparison of HTPIPE predicted performance limits to experimental data for heat pipe with screen-covered grooves on inside of heat pipe.

Table 1. Heat pipe design variables for validation case.

Parameter	Value
Working fluid	Distilled water
Heat pipe envelope material	Copper
Mesh type	phosphor bronze mesh #100
Evaporator length (cm)	8
Adiabatic length (cm)	2
Condenser length (cm)	10
Tilt angle	0
Pipe inside radius (cm)	0.31
Distribution screen thickness (cm)	0.01
Half of wire diameter (cm)	0.006
Distance between grooves, S (cm)	0.0035
Depth of groove, D_g (cm)	0.003
Effective pore radius (cm)	0.0015
Number of grooves	32
Wick surface porosity	0.5
Thermal conductivity of pipe wick (W cm^{-1} K^{-1})	0.24

HTPIPE was used as a design and analysis tool to establish the feasibility of using a screen-covered groove wick structure with a sodium working fluid. There are a number of parameters used to describe the internal configuration of a heat pipe in HTPIPE. Many of the parameters characterizing the internal wick structure affect the heat pipe performance. Other parameters deal with the pipe diameter and the length of the main sections of the heat pipe (e.g., evaporator section, adiabatic section, and the condenser section). Another influential parameter is the orientation of the heat pipe. Heat pipes with wicks can in theory be operated either in a horizontal or vertical orientation. The results of a previous study were used to inform parameter selection when designing a heat pipe for microreactor applications [29]. Table 2 lists the design parameters that were input to HTPIPE to describe the heat pipe internal wick structure for a screen-covered grooved wick including the grooves and the porous wick material. The wick was selected from commercially available stainless steel 325 mesh manufactured by TWP, Inc. (Berkeley, CA) [30]. The designed heat pipe consists of microgroove square channels that are 0.05 cm deep on the interior pipe wall. Square channels were used since they provide the lowest liquid pressure drop for a given groove width [31]. The number of grooves was calculated to yield the maximum number of grooves subject to the constraint $S > D_g$. Since the calculated capillary height for this groove size is only ~7.2 cm, the heat pipe would need to be operated in a horizontal orientation.

Table 2. Heat pipe design variables.

Parameter	Value
Working fluid	Sodium
Heat pipe envelope material	Stainless steel
Mesh type	Stainless steel mesh #325
Evaporator length (cm)	100
Adiabatic length (cm)	10
Condenser length (cm)	90
Tilt angle	0
Pipe inside radius (cm)	0.705
Distribution screen thickness (cm)	0.00711
Half of wire diameter (cm)	0.00178
Distance between grooves, S (cm)	0.0509
Depth of groove, D_g (cm)	0.05
Effective pore radius (cm)	0.00356
Number of grooves	44
Wick surface porosity	0.495
Thermal conductivity of pipe wick (W cm^{-1} K^{-1})	0.34228

For comparison, simulations were executed for a heat pipe with an annular heat pipe wick with the same type of screen mesh. The inner radius of the pipe was increased to permit the same vapor flow area and the groove depth was split equally between the annulus and screen thicknesses. Simulation results for a 2 m long horizontally oriented heat pipe with screen-covered grooves versus an annular wick structure are shown in Figure 8. The results indicate that the heat flux limits for both wick types are in the 5 to 15 W/cm^2 range, which compares well with axial grooved heat pipes reported in the literature [32]. For both cases over the temperature range shown, the capillary limit is the most restrictive performance limit. At an operating temperature of 650ºC, the performance limits for the heat pipe with an annular wick configuration are 15% higher than for the screen-covered groove wick. A crossover point occurs at 777ºC where at temperatures below this value the annular wick outperforms the screen-covered groove wick and at temperatures above this value the screen-covered grooved wick outperforms the annular wick.

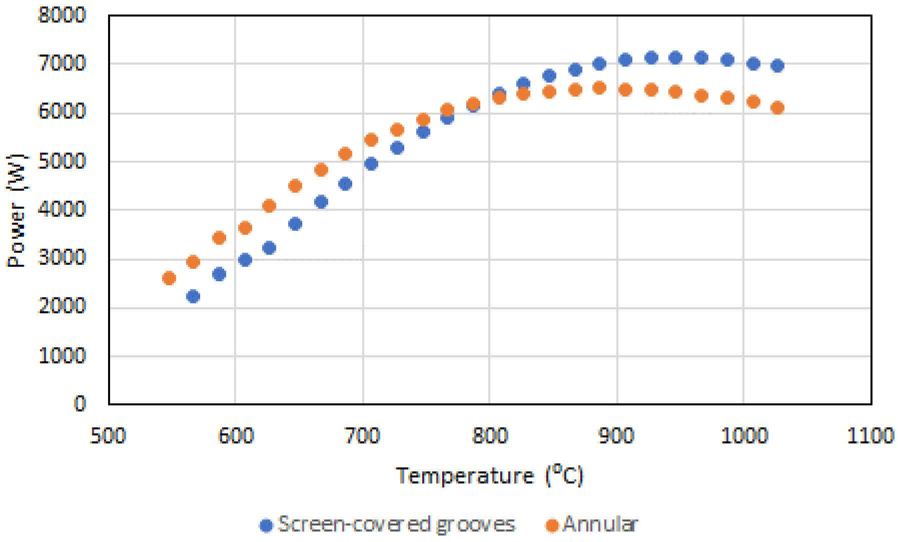


Figure 8. Performance limits for sodium heat pipe with screen-covered grooves (horizontal orientation).

Higher manufacturing costs may not justify the use of grooved heat pipes at temperatures above 777ºC. Grooved heat pipe wicks are traditionally manufactured using electrical discharge machining, extruding, mechanical notching, chemical etching, or ball spinning [33]. These techniques have been typically used for aluminum heat pipes for space applications. Extruding is not a viable technique for manufacturing grooved heat pipes for use with alkali metal working fluids, due to the higher yield strength and lower ductility of the compatible heat pipe materials [9]. Microgroove structures can also be fabricated by additive manufacturing (AM). Due to the limited build volumes of most 3D printers, the heat pipes could be manufactured in short sections, connected like a series of LEGOS®, and welded. Fabricating short heat pipes via additive manufacturing with subsequent testing and characterization would be the first step to be undertaken before pursuing the fabrication of very long heat pipes by this method. AM would not only be very useful to fabricate these types of configurations but would also be an enabling manufacturing technique to embed heat pipes within other structures, such as core blocks and heat exchangers, fabricated as an integral component.

4. CONCLUSIONS

Heat pipes are effective devices for passively transporting heat in thermal systems and are currently being incorporated into microreactor designs to provide heat removal. A study was performed to investigate the performance limits of a sodium heat pipe design with screen-covered grooves.

The key takeaways from this study are:

1. Wicks with screen-covered square grooves are a viable option for sodium heat pipes used in microreactor applications. Screen-covered grooved heat pipes for terrestrial applications work best in a horizontal orientation to avoid drainage and resultant pooling in the evaporator that can lead to instabilities and increased thermal resistance.
2. The capillary limit is the most constraining performance limit for steady state operation of the heat pipe. At an operating temperature of 650ºC, the performance limit for the heat pipe with an annular wick configuration is 15% higher than for the screen-covered groove wick. In this operating regime, annular wicks would be preferred.
3. At operating temperatures below 777ºC the annular wick still outperforms the screen-covered groove wick, whereas at temperatures above 777ºC the screen-covered grooved wick outperforms

the annular wick. However, the marginal performance gain at higher temperatures may not justify the use of heat pipes with a screen-covered groove wick structure due to increased manufacturing costs.

Future work is planned to research methods of producing complex internal wick structures to enhance the heat pipe performance. Simulations such as those performed here are valuable to provide insight into design trade-offs that can be used to guide (but not replace) experimental testing. The performance of new heat pipe designs can ultimately be tested in SPHERE or MAGNET. Single heat pipes can be tested in SPHERE and heat pipes integrated with components such as core blocks and heat exchanges can be tested in MAGNET.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, Office of Nuclear Energy under the Advanced Reactor Technology portfolio's Microreactor Program and authored by Battelle Energy Alliance, LLC, under Contract No. DE-AC07-05-ID14517 with the U.S. Department of Energy, Office of Nuclear Energy. The student internship for Clayton Turner was supported by the U.S. DOE Office of Science, Office of Workforce Development for Teachers and Scientists under the Science Undergraduate Laboratory Internship program. Dr. Calin Tarau provided helpful advice concerning heat pipe operation.

REFERENCES

[1] Guillen, D.P, et al. "Development of a Non-Nuclear Microreactor Test Bed," *Transactions of the American Nuclear Society*, *121*, November 2019, 1623-1626.
[2] Yan, B. H., Wang, C., Li, L.G. (2020) The Technology of Micro Heat Pipe Cooled Reactor: A Review. *Ann. Nucl. Energy* 135.
[3] Wang, C., Sun, H., Tang, S., Tian, W., Qiu, S., and Su, G. (2020). Thermal-hydraulic analysis of a new conceptual heat pipe cooled small nuclear reactor system. *Nuclear Engineering and Technology*, 52(1), 19-26.
[4] Sun, H., Ma, P., Liu, X., Tian, W., Qiu, S., and Su, G. (2018). Conceptual design and analysis of a multipurpose micro nuclear reactor power source. *Annals of Nuclear Energy*, *121*, 118-127.
[5] El-Genk, M. S., and Palomino, L. M. (2019). A walk-away safe, Very-Small, Long-LIfe, Modular (VSLLIM) reactor for portable and stationary power. *Annals of Nuclear Energy*, 129, 181-198.
[6] Sterbentz, J. W., Werner, J. E., Hummel, A. J., Kennedy, J. C., O'Brien, R. C., Dion, A. M., and Wright, R., Ananth, K. P. (2017). Preliminary Assessment of Two Alternative Core Design Concepts for the Special Purpose Reactor (No. INL/EXT-17-43212). Idaho National Laboratory (INL), Idaho Falls, ID (United States).
[7] Ahlfeld, C. E., Gilleland, J. R., Hyde, R. A., Ishikawa, M. Y., McAlees, D. G., Myhrvold, N. P., ... and Wood, L. L. (2009). U.S. Patent Application No. 12/152,904.
[8] Mueller, C., and Tsvetkov, P. (2020). Novel design integration for advanced nuclear heat-pipe systems. *Annals of Nuclear Energy*, 141, 107324.
[9] Walker, K. L., Tarau, C., and Anderson, W. G. (2014). Grooved and Self-Venting Arterial Heat Pipes for Space Fission Power Systems. *Heat Pipe Science and Technology*, An International Journal, 5(1-4).
[10] Guillen, D.P., Alternative Heat Removal Technologies for Microreactors: Novel Thermal Management Strategies for Nuclear Microreactors, Idaho National Laboratory Report, INL/EXT-20-57711, February 26, 2021.
[11] Zohuri, B., *Heat Pipe Design and Technology: a Practical Approach*. 1st ed., CRC Press, 2011.
[12] Silverstein, C.C. *Design and Technology of Heat Pipes for Cooling and Heat Exchange*. Hemisphere Pub. Corp., 1992.
[13] Sabharwall, P., Hartvigsen, J., Morton, T., Sellers, Z. and Yoo, J.S., SPHERE Assembly and Operation Demonstration, Idaho National Laboratory (INL) INL/EXT-20-60782, Revision 0, December 2020.

[14] Guillen, D. P., and Wendt, D. S. (2021). Technical feasibility of integrating a modified power

---

conversion unit into a non-nuclear microreactor testbed. *International Journal of Energy Research*.

[15] El-Genk, M.S. and Tournier, J.-M.P. (2011). Uses of Liquid-Metal and Water Heat Pipes in Space Reactor Power Systems, *Frontiers in Heat Pipes* 2, 013002. DOI: 10.5098/fhp.v2.1.3002.

[16] Beard, D., Anderson, W.G. and Tarau, C., "Self-Venting Arterial Heat Pipes for Spacecraft Applications," Proc. Joint 18th IHPC, 507-514.

[17] Faghri, A. *Heat Pipe Science and Technology*. 2nd ed., Global Digital Print, 2016.

[18] Poston, D., Gibson, M., Godfroy, T. and McClure, P. (2020). KRUSTY Reactor Design, Nuclear Technology, 206(sup), S13-S30.

[19] P.C. Stephan, C.A. Busse (1992). Analysis of the heat transfer coefficient of grooved heat pipe evaporator walls, *International Journal of Heat and Mass Transfer* 35(2), 383-391.

[20] Solomon, A. B., Kumar, A. R., Ramachandran, K., Pillai, B. C., Kumar, C. S., Sharifpur, M., and Meyer, J. P. (2017). Characterisation of a grooved heat pipe with an anodised surface. *Heat and Mass Transfer*, *53*(3), 753-763.

[21] Brennan, P.J., and Kroliczek, E.J., *Heat Pipe Design Handbook*, Vol. II, B&K Engineering, Towson, MD, June 1979.

[22] Reay, D. A., Kew, P. A., and McGlen, R. J. (2014). *Heat pipes: Theory, design and applications*. 6th ed. Waltham, MA: Butterworth-Heinemann: Elsevier, 65-94.

[23] Yilgor, I., and Shi, S., Modeling and Investigation of Three Types of Wick Structures in Heat Pipe Microreactor Applications, *Transactions of the American Nuclear Society* 124(1), June 2021.

]24] Wang, H. J., Tsai, H. C., Chen, H. K., and Shing, T. K. (2005). Capillarity of rectangular micro grooves and their application to heat pipes. *Journal of Applied Science and Engineering*, *8*(3), 249-255.

[25] Bader, M., and Busse, C. A. (1977). Wetting by sodium at high temperatures in pure vapour atmosphere. *Journal of Nuclear Materials*, 67(3), 295-300.

[26] Reid, R.S., Merrigan, M.A., and Sena, J.T. "Review of Liquid Metal Heat Pipe Work at Los Alamos," LA-UR-90-3721, Los Alamos National Laboratory (1991).

[27] Woloshun, K.A., Merrigan, M.A, Best, E.D., "HTPIPE: A Steady-State Heat Pipe Analysis Program", LA-11324-M, Los Alamos Scientific Laboratory, 1988.

[28] Krambeck, L., Bartmeyer, G. A., Santos, P. H. D., and Alves, T. A. (2018). Experimental Analysis of a Screen-Covered Groove Heat Pipe. *Revista de Engenharia Térmica*, 17(1), 58-62.

[29] Turner, C.G. Guillen, D.P., A Sensitivity Study of Sodium Heat Pipes for Microreactor Applications, Proceedings of the International Topical Meeting on Advances in Thermal Hydraulics 2020 (ATH'20), Palaiseau, France, October 20-23, 2020.

[30] TWP, Inc., Stainless Steel Wire Mesh, https://www.twpinc.com/wire-mesh-material/stainless-steel?material=20638. Accessed 7/21/2021.

[31] Chi, S.W., *Heat Pipe Theory and Practice*, Hemisphere (1976).

[32] Ababneh, M., Tarau, C., Anderson, W., Farmer, J., and Alvarez-Hernandez, A. (2016, July). Hybrid Heat Pipes for Lunar and Martian Surface and High Heat Flux Space Applications. Proceedings of the 46th International Conference on Environmental Systems.

[33] Yong, L., Hui, X., Bin, L., Yong, T., and Zhi-xin, Z. (2008). Forming method of axial micro grooves inside copper heat pipe. *Transactions of Nonferrous Metals Society of China*, 18(5), 1229-1233.