CAPÍTULO 1

TECHNOLOGY CHALLENGES USING ALKALI METALS IN HEAT PIPE-COOLED REACTORS

https://doi.org/10.22533/at.ed.135162517031

Data de aceite: 17/03/2025

Daniel de Souza Gomes
Instituo de Pesquisas Energética e Nucleares (IPEN-SP)

ABSTRACT: Shortly, the nuclear energy suppliers plan to decrease the size of the nuclear power units or power capacity due to many factors, including over-budgeted costs and a complex licensing process for new plants generating up to 5 GW. The Paris Agreement 2015 aimed to achieve net carbon zero emissions. As a result, the energy industry should explore cleaner and more efficient energy sources. The climate crisis and COVID-19 have significantly impacted society. They have also increased the costs of nuclear power construction, mainly when led by megaprojects showing budgets exceeding $ 1 billion. Nuclear power plants are megaprojects showing a budget of around $ 20 billion, such as Georgia's Vogtle plant, which is facing a significant overrun, and Hinkley Point C, which is experiencing a $26 billion cost overrun. These conditions raise questions about using small modular reactors for nuclear energy production. At the same time, microreactor designs are being developed using coolants like liquid metal, helium gas, or molten salt, with passive heat pipes for heat transfer and helium gas for high-temperature compatibility. Microreactors are highly efficient, cheap, and straightforward, producing power ranging from less than 1 MW to 20 MW. Westinghouse has designed VinciTM, which generates power from 200 kW to 5 MW using a high-temperature heat pipe and sodium as the working fluid. However, microreactors face challenges in enriched uranium fuel, heat pipes, passive cooling, and thermoelectric conversion efficiency. This way, we calculate a few parameters that describe a heat pipe-cooled reactor operating as alkali metals.

KEYWORDS: Heat pipe, kilopower, megapower, alkali metal, space reactors, Stirling thermoelectric converts.

INTRODUCTION

The nuclear sector increasingly considers small modular reactors (SMRs) as an alternative to civilian nuclear power for electricity generation. SMRs produce less waste, reduce volume and toxicity, offer flexibility, improve safety performance, and reduce construction time. However, actual operations must demonstrate these advantages. Megaprojects often fail due to over-optimistic forecasts and underestimated project risks. Large nuclear energy projects are fragile and susceptible to technical, operational, and political risks due to their complex supply chain and long construction times. Technological challenges encompass uncertainties in development costs, a lack of precise licensing requirements, and the need to maintain economic competitiveness in terms of cost per kWe. These challenges have affected new projects with budgets over $1 billion due to established licensing requirements and profit per kW/hour. Military installations and natural disaster recovery locations can quickly deploy microreactors, a subset of the SMR category. These reactors can operate independently from the electric grid and have a power output of up to 20 MWe. Microreactors can operate in microgrids for critical facilities like hospitals or military bases. Current microreactors operate with heat pipe designs, are portable, and produce electricity and heat without continuous refueling, which limits diesel generators in remote or critical areas.

R.S. Gaugler introduced the heat pipe in 1942, but its full disclosure occurred in the 1960s. In 1962, Trefethen introduced capillary pressure as a passive driving mechanism in a two-phase closed loop. In 1966, Grover filed a patent for the U.S. Atomic Energy Commission, defining the device as a "heat pipe" with a suitable capillary structure (Zouhri, 2019). The heat pipe operates in two phases, transferring heat between the evaporator and condenser (Wahlquist et al., 2023).

Los Alamos National Laboratory (LANL) has been planning heat pipe-cooled reactors (HPCRs) since 1960 (Walker et al., 2022). They are gaining popularity in fourth-generation nuclear power reactors due to their ability to reduce carbon emissions and avoid greenhouse gas production. Thus, HPCRs generate significant power output thanks to their compact design, eliminating the need for water pumps and other thermal-hydraulic components, such as intricate piping systems. Microreactors, small nuclear reactors, produce less than 30 MW of electricity and 100 MW of thermal power, making them ideal for strategic defense sites, remote communities, and space missions. Heat pipes (HPs), with their remarkable efficiency, absorb heat at the evaporator end of a cylinder, converting it into vapor and liquid (Lee et al., 2017). The vapor then moves to the condenser end, which rejects the heat and condenses back to the evaporator using capillary circulation. The Space Reactor Power Systems (SRPSs), sponsored by NASA, utilize heat pipes for efficient heat transfer, generating between 50 and 300 kW of electrical power. The Kilopower reactor project, initiated in 2015, includes a stainless-steel core, Haynes 230 sodium heat pipes, and Stirling power conversion (McClure et al., 2018). Heat pipes are also employed to cool various systems, such as heat pipe-fuel composite elements, Brayton energy conversion, and heat dissipation (Li et al., 2023). Larger diameters enhance capillary action and prevent the wick from boiling, making exploration more efficient and reliable. Today, heat pipes are recognized as one of the best devices for addressing heat dissipation challenges, utilizing a passive concept (Ma et al., 2021).

Furthermore, space microreactors are small nuclear reactors that can produce less than 30 MW of electricity and up to 100 MW. This versatility makes them ideal for mobile systems in crucial defense sites, combat zones, remote communities, and space exploration (Yan et al., 2020). Microreactors are efficient, cost-effective, and capable of producing power ranging from 1 MW to 20 MW. They offer flexibility, adaptability, mobility, resilience, and a free power grid capacity. NASA developed a heat pipe microreactor known as the Kilowatt Reactor Using Stirling Technology (KRUSTY), a prototype nuclear-powered test of a 5 kW thermal Kilopower space reactor (Poston et al., 2011). The NASA prototype, the KRUSTY, was tested and constructed for under $20 million, with the final testing completed in March 2018 at the Nevada National Security Site. Westinghouse designed eVinciTM, which uses a high-temperature heat pipe and sodium as the working fluid to generate power from 200 kW to 5 MW. However, microreactors face challenges in enriched uranium fuel, heat pipes, passive cooling, and thermoelectric conversion efficiency. Conversions like Stirling and AMTEC show a low-efficiency range of 15% to 30%.

In 2015, LANL built the MegaPower, a fast-spectrum reactor designed for space missions (Silverstein, 2011). The MegaPower is a typical 5 MWth heat pipe-cooled reactor (HPCR) intended to provide reliable power for long-duration missions to the Moon, Mars, or deep space exploration. In the 1950s, LANL began researching heat-pipe reactors that operate in a fast spectrum. The National Aeronautics and Space Administration (NASA) built several radioisotope thermoelectric generators (RTGs) designed for long-term operation without maintenance, instilling confidence in their reliability (Gusev et al., 2011). The MegaPower design incorporates 1,224 heat pipes, essential for creating a passive heat transfer system. These high-temperature alkali-metal heat pipes operate from 650 °C to over 1,000 °C, depending on the alkali metal used, such as potassium, sodium, or lithium, and function as a passive heat transfer mechanism. The fuel used is uranium dioxide (UO_2), with a U-235 enrichment of 19.75%. Reactivity control utilizes 12 control drums made of B_4C, each with a diameter of 22 cm. However, it is essential to note that heat pipes face thermodynamic limits, including dry-out, boiling, viscous flow, sonic limitations, entrainment, and flooding (Faghri, 2012)

TECHNOLOGY BACKGROUND

The U.S. and Russia engaged in a space race to showcase their superiority following World War II, which resulted in the U.S. government's establishment of NASA in 1958. Emerging from the Systems Nuclear Auxiliary Power (SNAP) program initiated by NASA in the 1960s, experimental radioisotope thermoelectric generators (RTGs) and space nuclear reactors were developed. Over the years, RTGs have been the primary power source for space exploration and satellite launches into Earth's orbit. Presently, plans are underway to visit Triton, Neptune's largest moon. However, RTGs rely on alpha emitters of particles and have a low efficiency of less than 8%. The size and weight of RTGs directly influence their power output, and the manufacturing process is intricate and costly. The first Radioisotope Thermoelectric Generator (RTG) was launched into space in 1961, powered by Pu-238, which requires 180 grams of Pu-238 to generate 5 watts. NASA has been at the forefront of developing these generators for over five decades. Kilopower is recognized as an experimental U.S. project led by NASA and the Department of Energy's National Nuclear Security Administration, which provides solutions up to 10 kW and marks a turning point in space reactors. The project was initiated in 2015.

Radioisotope Thermoelectric Generator

Public information indicates that NASA has developed over 40 RTGs for various missions since the 1960s. Galileo and Ulysses participated in deep space exploration, building two RTGs for Jupiter and Ulysses and one for the Sun. Galileo started orbiting Jupiter in December 1995, impacting Jupiter's surface in 2003. Ulysses orbited the Sun from 1994 to 2008. These generators convert thermal power into electrical power, making them adaptable to extreme conditions. Radioactive isotopes naturally decay, releasing heat that is converted to electricity. The thermoelectric process is based on the Seebeck effect, which converts heat into direct current (DC). In 1823, a German physicist, Thomas Johann Seebeck, discovered the impact resulting from a temperature gradient across the junction of two distinct metals or semiconductors. Pu-238 shows a half-life of about 87.7 years, ensuring steady heat energy for a long time. RTGs depend on alpha emitters, alpha decay, and disintegration. Nevertheless, their efficiency is low, usually between 3% and 8%.

Free-piston Stirling engine

Scottish minister Robert Stirling patented the engine; its applications have expanded since 1816. This hermetically sealed piston engine converts heat energy into electrical energy through repeated heat and cooling based on working gases like hydrogen or helium. Stirling engines generate power in the range of 10 kW at typical temperatures from 650 °C to 800 °C, achieving efficiencies of around 30% to 40%. The Stirling cycle is shown on the temperature-entropy (T–S) diagram. It has two isothermal compression phases and two isochoric heating phases. NASA attempted to develop the advanced Stirling radioisotope generator ASRG in 2013, but budget constraints led to its cancellation. Using a Stirling engine as a dynamic thermoelectric converter in RTGs could be a solution for future space missions because it works better at higher power levels (100 W and up). Since 1990, NASA has tried to develop a free-piston Stirling engine (FPSE) for a space dynamic power conversion system at the Lewis Field near Cleveland Hopkins Airport. The free-piston Stirling generator (FPSG) is a promising solution for small- or micro-scale applications (Dai et al., 2021).

Alkali-metal thermal-to-electric converter

Alkali-metal thermal-to-**electric converter (**AMTEC) is a thermally regenerative electrochemical device that transforms nuclear decay heat into electrical energy using alkali metals such as sodium or potassium. The working fluids, Na and K, evaporate through a Beta-alumina solid (BASE) ceramic electrolyte. This lets go of electrons and creates sodium ions. It is not just 238Pu that AMTEC can use; they can also use other isotopes because alkali sulfur evaporates and moves through the ceramic BASE, letting sodium ions pass but stopping electrons. The first two space reactors employed liquid metal heat pipes, such as sodium and potassium, as working fluids. Standard heat pipe-cooled reactors have incorporated Stirling engines and alkali metal thermal-to-electric conversion (AMTEC) units to convert heat energy to electricity.

Today, there are limited modes to convert heat into electric power, such as Stirling motors and the alkali-metal thermal-to-electric converter (AMTEC). A third idea for a spacecraft that will go close to the Sun uses a system based on infrared radiation. This system is called SiGe Thermo converters and is used in a sodium heat pipe-cooled liquid metal reactor.

Heat pipe technology

Due to their high thermal conductivity, heat pipes efficiently transfer energy, providing passive operation without external power and ensuring uniform temperature distribution. Over the years, industrial sectors have employed heat pipes to cool electronics, control heat in spacecraft, solar energy, and run nuclear space reactors. A heat pipe is an efficient device for heat transfer that operates based on the principles of phase change and thermal conductivity. It consists of three components: a sealed container, a working fluid, and a wick structure, which are divided into three main sections: the evaporator, the adiabatic section, and the condenser (Dunn and Reay., 1973).

A heat pipe system consists of an evaporator at the bottom, an adiabatic section in the middle, and a condenser at the top. The adiabatic section is insulated, allowing vapor to flow axially to the condenser. In practical cases, the evaporator length is smaller than the condenser, with a short adiabatic section. The container, the outer shell of a heat pipe, is made of materials with high thermal conductivity, such as copper, aluminum, or stainless steel. It is designed to be leak-proof and to withstand the internal pressure generated by the working fluid. Geometric parameters, like the shape and size of the container, alter based on the application. The evaporator section of a heat pipe absorbs heat from the heat source, causing the working fluid to transition from liquid to vapor. The vapor moves toward the condenser section because of the pressure difference created by this phase change. The adiabatic section is the central part of the heat pipe that links the evaporator and condenser

(Jouhara et al., 2016). It is thermally insulated to prevent significant heat transfer, and its primary function is to transport vapor without losing or gaining heat.

The working fluid evaporates due to heat absorption in the evaporator section. Subsequently, the vapor travels through the adiabatic section to the condenser. In the condenser, the vapor releases heat and condenses into a liquid. Gravity or capillary action (wick structure) completes the cycle when the liquid returns to the evaporator. Heat pipes strongly depend on the phase change of the working fluid, which contributes to their reliable thermal management.

At the same time, solar energy is a clean energy source that can meet thermal and electrical energy demands, but factors like radiation intermittency, lower efficiency, and capital requirements. The current challenge is improving solar collectors and collecting thermal energy from photovoltaic panels. Heat pipes show extensive application that enhances the performance of solar collectors and panels by transferring excess heat away from the solar cells.

Currently, there are numerous research plans for microreactors. Westinghouse Electric Company is making the eVinci™ microreactor, which can produce 200 kW to 5 MW of power and will use High-Assay Low-Enriched Uranium (HALEU) TRISO (TRi-structural ISOtropic) fuel. The eVinci™ can operate for over three years without needing refueling. Space microreactors have utilized alkali metals such as potassium, lithium, and sodium as working fluids. These metals are well-suited for high-temperature heat pipes because of their high thermal conductivity, low viscosity, and elevated surface tension. Kilopower has selected uranium molybdenum U-10Mo as fuel and sodium as a working fluid, achieving a heat pipe temperature of 749.85°C and a core average temperature of 799.85°C.

In contrast, the LANL project MegaPower generates 5 MWth, using UO_2 with enrichment of 19.2% as fuel and potassium as a working fluid. Advanced high-temperature systems, including interplanetary missions and high-power applications, employ lithium. However, these systems are highly chemically reactive and require compatible wick materials. Common materials like stainless steel, nickel, molybdenum, and tantalum resist alkali metal corrosion at high temperatures. The wick needs to keep its shape at high temperatures, stick to metal easily for capillary action to work, and have enough holes to hold the working fluid while letting enough fluid flow to keep the pressure drop to a minimum.

The container must protect the working fluid from external factors. It must maintain a consistent pressure differential, preventing leaks and shielding the working fluid from the outside environment (Dunn & Reay, 1973). Many metals are appropriate for heat pipes due to their substantial thermal conductivity, such as copper, aluminum, stainless steel, and titanium, which are typically used in applications in high-temperature and corrosive environments. Nickel (Ni) is a popular material due to its thermal conductivity, mechanical strength, and corrosion resistance. While working fluids depend on temperature operation, alkali metals are more suitable for temperatures above 500 °C. At temperatures where electronics operate, the high latent heat of vaporization significantly influences how heat pipes function. This value is much greater than the latent heat of other fluids. The container has high thermal conductivity to promote fast heat transfer.

Additionally, it minimizes the temperature drop between the heat source and the wick to prevent vapor diffusion, meaning the material cannot have pores. Heat pipe technology uses thermal concepts like effective thermal conductivity (keff) and thermal resistance (Rth) to determine heat transfer efficiency. A copper-water heat pipe, measuring 0.5 m in length and 12.7 mm in diameter, boasts a high effective thermal conductivity of approximately 10,000 W/mK. Consequently, copper-water heat pipes exhibit a temperature difference (ΔT) between 2 and 5 °C due to their low thermal resistance of about 0.3 K/W, indicating minimal heat loss.

Heat pipe types

Industrial heat pipes have a thermal conductivity of up to 100,000 W/m·K, while copper is around 390 W/m·K. Because of their high thermal conductivity, heat pipes efficiently transfer heat energy, supplying passive operation without external power distribution. Besides, there are different designs classified according to fluid motion mechanisms. Therefore, each heat pipe design offers specific benefits for typical applications. These categories include rotating heat pipes (RHP), wick heat pipes, pulsating heat pipes (PHP), loop heat pipes (LHP), heat pipes, variable conductance heat pipes (VCHP), and thermosyphons.

Conventional heat pipes are most commonly formed by metallic impenetrable tubes loaded with a working fluid and a porosity wick structure. Standard heat pipes utilize the capillary force for liquid return from the condenser to the evaporator without a dry-out effect. The evaporator end absorbs heat, causing the fluid to vaporize. The vapor then travels to the condenser through an adiabatic section, reaching the condenser, releasing the heat, and condensing it into a liquid while keeping it separate from the vapor traveling in the other direction. The wick structure aids in returning the liquid to the evaporator through capillary action.

RHP is planned to operate in rotating systems like turbines and engines. Reload centrifugal force transfers condensed fluid from the condenser to the evaporator. Because of the higher centrifugal speed force, the rotating system shows a more suitable thermal performance. The PHP idea, which is also called oscillating heat pipes (OHP), is for higher thermal flux and has used common materials like aluminum, copper, and titanium that do not expand or contract much when heated or cooled. High thermal flux applications such as electronic chip cooling have utilized LHP due to its high efficiency. LHPs have a gas line that connects the areas where water evaporates and condenses. Aerospace and electronics commonly use LHP for cooling applications.

In LANL, George Grover invented variable conductance heat pipes (VCHP) that included a specific amount of non-condensing gas (NCG) and working fluid in 1963. The working fluid and NCG form a gas plug in the condensation section, which can precisely control heat transfer. The selection of NCG and working fluid must be compatible with internal material and operating temperature, with the critical temperature below the minimum heat pipe's minimum operating temperature. Cryogenic heat pipes are designed to operate at extremely low temperatures, often using helium or nitrogen as the working fluid. They are used in applications such as space exploration and superconducting systems.

Heat pipe limits

Viscous, sonic, capillary, entrainment and boiling limits are some of the main things that limit the performance of a heat pipe. A distinct physical phenomenon causes each limit. The viscous limit is a significant decline in the vapor pressure in the heat pipe, making it hard for the fluid to move from the evaporator to the condenser. The vapor velocity reaches the sonic limit when it approaches the speed of sound, resulting in a choked flow. The capillary limit happens when the capillary pressure in the wick structure is inadequate to return enough working fluid to the evaporator. The entrainment limit arises when high-velocity vapor flow strips away liquid droplets, while the boiling limit is reached when nucleate boiling produces vapor bubbles. Therefore, extended limits can be created by factors like the condenser, material, and geometric limits. If the condenser cannot efficiently reject heat, its performance will be limited. The heat pipe's casing and wick materials must withstand temperature and pressure without degradation. The heat pipe's orientation and dimensions can also impose practical limits on its performance.

Theoretically, a critical limitation exists when exceeding max, leading to drying out, overheating, or reduced efficiency. Lumped heat pipe models show that the Qmax concept is the maximum heat transfer capacity a heat pipe can handle under optimal conditions, typically expressed in watts. It represents the maximum thermal energy transfer from the evaporator to the condenser without causing the pipe to fail or operate inefficiently. Many factors influence Qmax. The working fluid type, wick structure, temperature, diameter, length, and orientation influence the maximum temperature of a heat pipe. Variations in thermal conductivity, the latent heat of vaporization, and viscosity affect qmax. A well-designed wick can improve Qmax by facilitating efficient liquid return. Longer heat pipes or those operating against gravity may experience a lower Qmax due to increased pressure drop.

The first wick structure proposed was the screen mesh in 1964. Today, the most common wick structures are grooves, wire mesh, sintered powders, and fiber/spring. Research has used many wick structures to enhance heat pipes, including mesh screen wicks, grooved wicks, and sintered particle wicks. Metal foams fabricate porous steel, aluminum, nickel, or copper structures. Removable metal mandrels can mold them into arterial structures. Fibrous materials like ceramics have smaller pores but minor stiffness and require continuous support from a metal mesh. Ceramic fibers have the main disadvantage of having minor stiffness and requiring continuous support. Fibrous materials like ceramics have smaller pores but minor stiffness and require continuous support from a metal mesh.

Ceramic fibers have the main disadvantage of having minor stiffness and requiring continuous support. In a heat pipe, a sintered wick was made by sintering a mix of copper powder with particles between 100 µm and 200 µm in size, along with an agent that makes pores.

Wick structures made from screen mesh are low-cost, woven meshes made from stainless steel or nickel, offering excellent capillary pressure for alkali metals due to their high surface tension. However, they have limited permeability and can support high-temperature applications. Sintered Metal Powder Wick is a porous structure created by sintering metal powders. It has high capillary pressure, excellent thermal conductivity, and high mechanical strength but is more challenging to manufacture and has less permeability. Grooved wicks are grooves in heat pipes, offering high permeability, efficient liquid flow, simple design, and low cost. They have lower capillary pressure than screen mesh or sintered wicks. They may degrade in non-horizontal orientations, making them suitable for space applications or heat pipes with low to moderate heat loads. Arterial Wick is a device featuring a heated, sintered powder screen mesh and an arterial channel for liquid return. It offers high permeability and efficient flow but encounters challenges such as complex design, manufacturing issues, and the risk of vapor inducing a channel blockage. These properties make it suitable for high-performance heat pipes using alkali metals, particularly in high heat flux applications.

Composite Wick combines various wick structures (e.g., screen mesh with grooves or sintered powder with channels). Its benefits include balancing capillary pressure, permeability, and flexibility for specific applications. Composite wicks are perfect for high-temperature and heat-flux applications involving alkali metals. However, their complex design and drawbacks involve a complex manufacturing route, lower thermal conductivity, brittleness, and manufacturing difficulties. The capillary limit of the sintered wick material influences the process. It can be adjusted by varying the wick thickness and porosity/permeability. However, there is no universally applicable wick design.

Furthermore, it varies based on application requirements. The flow in a wick is similar to the sucking of water by a sponge, with microsized pores generating a meniscus at liquid-vapor interfaces, resulting in a capillary pressure gradient and liquid movement. The wick pump working fluid must be steady for heat pipe operation and fluid flow passage. Heat pipe optimization relies on wick structure, vapor space, and the evaporator’s and condenser’s geometry. Entrainment limits result in liquid droplets, particularly for potassium. The cooling system functions within the Brayton cycle, utilizing potassium at 675°C (Li et al., 2023). A heat-pipe reactor uses heat pipes to extract heat from a solid-block core during the liquid’s vaporization. The MegaPower project seeks to develop a thermal analysis of heat pipe-cooled reactors.

Calculations

Since the 1980s, computational simulations have analyzed the two-phase flow present in heat pipe fluid. Two-phase flow is associated with complex evaporation and condensation phenomena. Researchers have developed numerical schemes to accurately represent interface motion in multiphase flow simulations, addressing significant discontinuities and interface location tracking in engineering applications. The liquid volume of fluid (VOF) method keeps standard mass conservation. HPs exhibit ultra-high equivalent heat transfer coefficients (HTCs) due to vapor-liquid phase change heat transfer. Fig. 1 depicts the structure of the heat pipe.

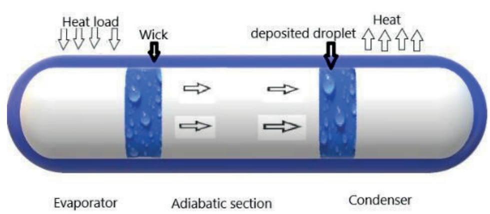

Fig. 1: Heat pipe section evaporator, adiabatic section, and condenser

The thermodynamic equilibrium occurs when molecules enter and leave a liquid phase. Standard formulations, like Hertz-Knudsen-Langmuir, operate mass flow rates in the Knudsen layer without solving the Boltzmann equation. Schrage, Lee, Tanasawa, and Wang models are references for multiphase flow modeling. The characteristics of heat pipe reactors cooled with sodium must define all usages. Tab 1 shows the parameters of heat pipes used in simulations. HPCRs have adopted similar dimensions but are capable of reaching high temperatures.

Properties	Parameters	Properties	Parameters
Envelop material	SS-316L	Adiabatic length (mm)	40
Wick section material	SS-316L	Pipe wall thickness (mm)	3
Outer diameter (mm)	20	Wick wall thickness (mm)	2
Heat pipe length (mm)	120	Wick porosity	0.5
Evaporation section (mm)	40	Quantity sodium contained (g)	16
Condensation section (mm)	40	Sodium vapor temperature(K)	300

Tab. 1: Heat pipe using sodium as fluid

The first model, derived from the Hertz-Knudsen equation, uses pressure and temperature to predict mass flux at the interface. However, the Lee model is relatively simple and computationally efficient compared to the Schrage equation. In the 1950s, Schrage proposed a model that could predict mass flux at the liquid/vapor interface using the pressure and temperature of both phases. Equation 1 illustrates the Hertz-Knudsen-Schrage (HKS) formulation.

$$\dot{m}_{flux(P,T)} = \left(\sigma_{evap}\frac{P_{sat}(T_{liq})}{\sqrt{T_{liq}}} - \sigma_{cond}\frac{P_{vap}}{\sqrt{T_{vap}}}\right)\frac{2}{2-\sigma_{cond}}\sqrt{\frac{M\,W}{2\pi R_u}} \quad (1)$$

RESULTS

The first model, derived from the Hertz-Knudsen equation, uses pressure and temperature to predict mass flux at the interface. However, the Lee model is relatively simple and computationally efficient compared to the Schrage equation. In the 1950s, Schrage proposed a model that could predict mass flux at the liquid/vapor interface using the pressure and temperature of both phases. Fig. 2 illustrates the merit figure for alkali metals used in heat pipes. Sodium shows excellent heat transfer properties, low neutron moderation, a high boiling point, and the ability to operate at low pressure. Fig. 3 depicts mass flow following the Schrage equation in heat pipe sections: evaporator, adiabatic, and condenser.

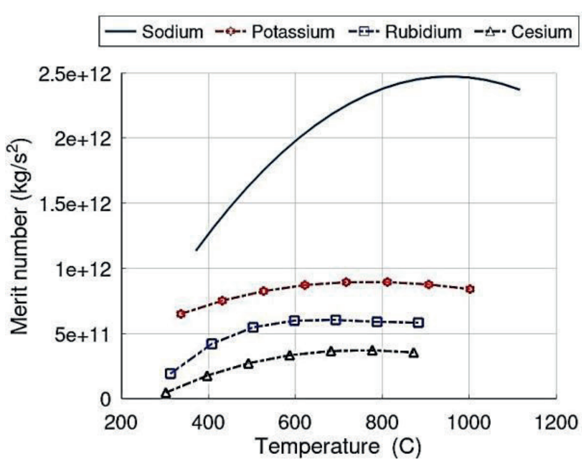

Fig. 2: Merith number for a few coolants of the heat pipe, sodium, potassium, rubidium, and cesium

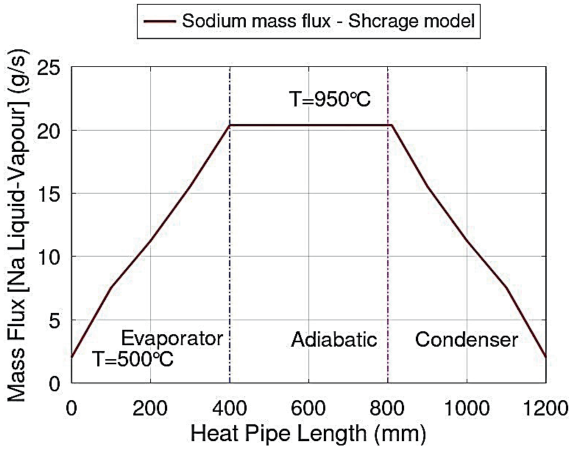

Fig. 3: Mass flux in the sections: evaporation, adiabatic and condenser, and temperature limits

Computational fluid dynamics uses the volume of fluid (VOF) technique to monitor the motion of fluid fronts, including bubble dynamics and flow in nuclear reactors. Comparatively, sodium shows better merit indices, which are the products of latent heat fusion, superficial tension, and liquid density divided by dynamic viscosity.

The Schrage equation yielded an overprediction of approximately 15% in heat/mass fluxes. Besides, mechanical statistics define the accommodation coefficients. The condensation coefficient measures the efficiency of condensation at the vapor-liquid interface in a heat pipe. The Maxwell-Boltzmann distribution, which describes the speed diffusion of molecules in a gas and represents a temperature function, forms the basis for this calculation. The condensation factor determines the fraction of vapor molecules that condense and stick to the surface. Fig. 4 illustrates the condensation coefficient.

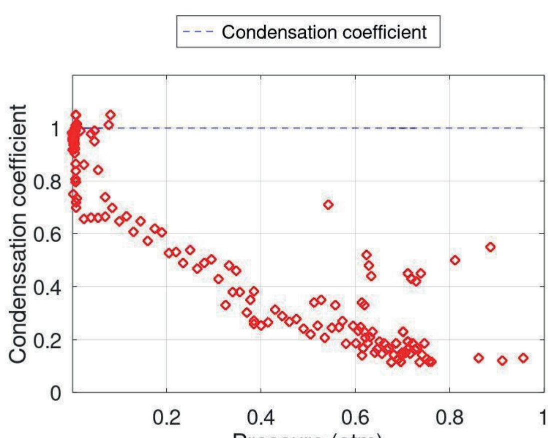

Fig. 4: Statistical distribution of the condensation coefficient given as a pressure function

CONCLUSIONS

The Knudsen layer indicates the point at which the interaction with the adjacent liquid dominates the gas's behavior. The Hertz-Knudsen-Schrage (HKS) equation estimates evaporation/condensation. Mass flow calculation is based on statistical mechanics and liquid and vapor thermodynamic states, but heat transfer is not considered. Today, a few numeric models, such as VOF, level-set, and particulate methods, are used for alkali metal heat pipes. HKS analyzes phase change statistically during simulation iterations to control evaporation and condensation coefficients.

ACKNOWLEDGEMENTS

The author sincerely thanks the Brazilian government and (IPEN/CNEN-SP).

REFERENCES

Bo, W., Shunhao, X., Bin, W., Weibing, W., Yongchao, L., Tong, L., & Mengyao, W. (2023). Review of recent research on heat pipe cooled reactor. Nuclear Engineering and Design

Dai, Z., Wang, C., Zhang, D., Tian, W., Qiu, S., & Su, G. H. (2021). Design and analysis of a free-piston Stirling engine for space nuclear power reactor. Nuclear Engineering and Technology, 53(2), 637-646.

Dunn, P. D., & Reay, D. A. (1973). The heat pipe. Physics in Technology, 4(3), 187.

Faghri, A. (2012). Review and advances in heat pipe science and technology. Journal of heat transfer, 134(12), 123001

Gusev, V. V., Pustovalov, A. A., Rybkin, N. N., Anatychuk, L. I., Demchuk, B. N., & Ludchak, I. Y. (2011). Milliwatt-power radioisotope thermoelectric generator (RTG) based on plutonium-238. Journal of electronic materials, 40(5), 807-811.

Jouhara, H., Chauhan, A., Nannou, T., Almahmoud, S., Delpech, B., & Wrobel, L. C. (2017). Heat pipe based systems-Advances and applications. Energy, 128, 729-754.

Lee, J. S., Lee, W. H., Chi, R. G., Chung, W. S., Lee, K. B., Rhi, S. H., ... & Park, J. C. (2017). Thermal behavior of heat-pipe-assisted alkali-metal thermoelectric converters. Heat and Mass Transfer, 53, 3373-3382.

Li, J., Hu, Z., Jiang, H., Guo, Y., Li, Z., Zhuge, W., ... & Ouyang, M. (2023). Coupled characteristics and performance of heat pipe cooled reactor with closed Brayton cycle. Energy, 280,

Ma, Y., Tian, C., Yu, H., Zhong, R., Zhang, Z., Huang, S., ... & Yang, Y. (2021). Transient heat pipe failure accident analysis of a megawatt heat pipe cooled reactor. Progress in Nuclear

McClure, P. R., Poston, D. I., Gibson, M. A., Mason, L. S., & Robinson, R. C. (2020). Kilopower project: the KRUSTY fission power experiment and potential missions. Nuclear

Poston, D. I., Gibson, M. A., Godfroy, T., & McClure, P. R. (2020). KRUSTY reactor design. Nuclear Technology, 206(sup1), S13-S30.

Silverstein, C. (2020). Design and technology of heat pipes for cooling and heat exchange. CRC press.
Wang, Y., Liang, L., Tian, J., Su, D., Li, H., & Jiang, N. (2024). Creep Fatigue Analysis of the 316SS Monolith in the MegaPower Heat Pipe Reactor. Nuclear Technology, 210(11), 2115-2132."

Walker, E., Skutnik, S., Wieselquist, W., Shaw, A., & Bostelmann, F. (2022). SCALE Modeling of the Fast Spectrum Heat Pipe Reactor (No. ORNL/TM-2021/2021). Oak Ridge National

Zohuri, B. (2019). *Heat pipe applications in fission driven nuclear power plants*. Springer International Publishing.