Nuclear Energy and Advanced Thermal Technologies

1. Abstract

A higher demand for safe clean energy to replace fossil fuel leads to new innovations in nuclear reactor designs and thermal management techniques. Many Small Modular Reactors (SMRs) and Micro-reactors leverage heat pipe technology to passively pull heat from the reactor core to the heat exchanger for the power conversion system. Advanced Cooling Technologies, Inc. has been working to develop the high-temperature heat pipes used in these reactors for both space and terrestrial applications. The space applications require a heat pipe with wicks to enable liquid return through capillary pumping. Terrestrial applications can take advantage of gravity and use lighter, more cost-effective thermosyphons to transport the heat, which rely on gravity to return the liquid to the evaporator. Heat pipes allow nuclear reactors to adapt to changing temperatures dynamically. They can transfer heat at high rates over long distances with minimal temperature drops. This autonomous operation, combined with high performance and built-in redundancy, makes heat pipes an ideal passive cooling solution for nuclear applications.

2. Introduction

The United States is heavily dependent on fossil fuels as an energy conversion source. Over 60% (2,553 billion kWh) of the US total energy consumption in 2022 was provided by fossil fuels[1], while only 18.2% (772 billion kWh) was from nuclear energy[1]. The US officially started working on Nuclear Energy in 1942 and commissioned the first commercial nuclear reactor, Shippingport Atomic Power Station, in 1958[2]. In the 60s and 70s, 79 plants in total began the build process in what was the nuclear power growth period. However, due to the partial meltdown of the nuclear power plant Three Mile Island in 1979, only one power plant has been commissioned in nearly 30 years. Westinghouse's AP1000, that was commissioned at the Vogtle power plant site in July of 2023, marks a new epoch in Nuclear Power that brings with it innovative reactor designs and the advanced thermal technology to support them.

The AP1000 design is a Pressurized Water Reactor (PWR)[3] used in many of the U.S. reactors built in the 60s and 70s. This established design leverages two coolant loops. The first loop interacts with the nuclear reactor and absorbs the heat released. This loop is pumped under high pressure to keep the coolant in a single phase. It then transfers the heat to a second, low-pressure loop that produces the steam to drive the turbine. Generation III and IV reactors have improved the PWR design by adapting the size and enhancing the thermal management of the core. Many of the improvements were developed for applications in space and defense that will apply to terrestrial and commercial use.

Advanced Cooling Technologies, Inc. (ACT), an expert thermal engineering company, has over 15 years of experience developing innovative thermal management solutions for nuclear energy systems used in space exploration. These technologies help regulate extremely high and low temperatures within systems like Nuclear Electric Propulsion, Fission Surface Power, and Stirling Radioisotope Generators. Specifically, ACT has created specialized heat pipes, radiators, pumped loops, heat exchangers, and other technology for thermal management. This allows nuclear energy to be harnessed safely and effectively in space and can be applied to terrestrial reactor innovations.

Unlike active cooling methods that require pumps or blowers – like in the PWR design – passive heat pipes can remove heat from reactors without any moving parts. This simplicity enables more compact and modular nuclear designs, perfect for space, Small Modular Reactors (SMR), and Micro-reactors. Heat pipes allow nuclear reactors to adapt to changing temperatures dynamically. They can transfer heat at high rates over long distances with minimal temperature drops. This autonomous operation, combined with high performance and built-in redundancy, makes heat pipes an ideal passive cooling solution for nuclear applications.

Both on Earth and in space, heat pipes have proven invaluable in cooling reactors, efficiently and reliably without active components.

3. Heat Pipe Reactors

Heat pipe reactors are a type of small modular reactor that uses embedded heat pipes to passively extract heat from the nuclear core, as seen in Fig. 1 from LANL. The heat pipes' cold ends can then transfer the heat through an exchanger to power conversion systems. High-temperature alkali metals, like potassium and sodium, are required as the heat pipe working fluids.

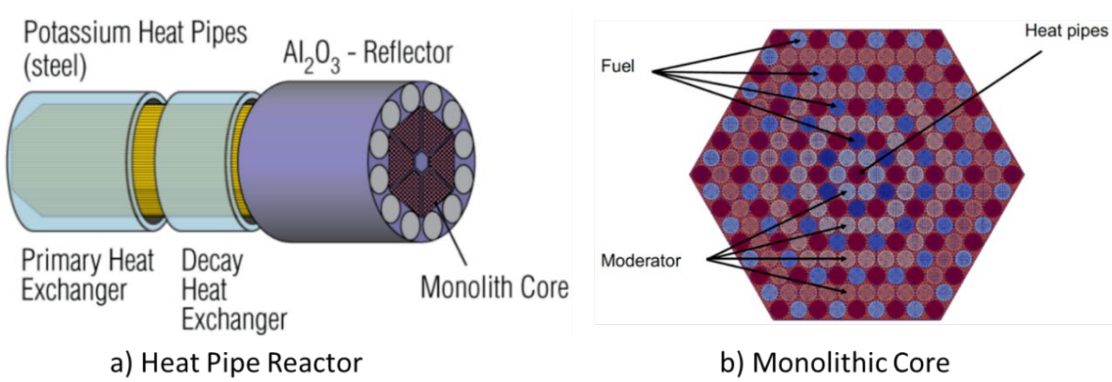

Figure 1 - Heat pipe reactor design proposed by LANL, b) Pattern of fuel rods and heat pipes in a heat pipe reactor's monolithic core.

Heat pipe reactors have several key advantages:

- **Reduced Size:** More compact than other designs due to the monolithic core with integrated fuel and heat pipes, and no pumps/auxiliary equipment.

- **Simplicity:** Heat pipes are passive, solid-state devices with no moving parts, enabling reliable operation with less maintenance.
- **Safety and Redundancy:** Unlike pumped coolants that can fail, hundreds of independent heat pipes provide redundancy. The lack of high-pressure systems also increases damage resilience.

Heat pipe reactors have diverse applications on Earth and in space. NASA's Kilopower program demonstrated a 10 kWe sodium heat pipe reactor for lunar/Martian use [4,5]. On Earth, they can provide power to remote DoD bases, villages, mining sites, and hybrid renewable systems needing <10 MWe.

Scaling heat pipe reactors to higher power requires maximizing individual heat pipes' transfer capacity, which depends on the wick design, geometry, fluid, and temperature. Increasing pipe diameter boosts capacity, but may not be viable due to core constraints. Advanced wicks that improve capacity for a given diameter enable higher total reactor power, increased safety margins, and more onboard power for space nuclear systems. This reliable scaling into the MW range expands heat pipe reactors' potential.

3.2 Heat Pipes for Microgravity (Space) Operation

Heat pipes are necessary passive devices for thermal management in microgravity nuclear systems. They use fluid evaporation and condensation to efficiently transfer heat over long distances with minimal temperature drop.

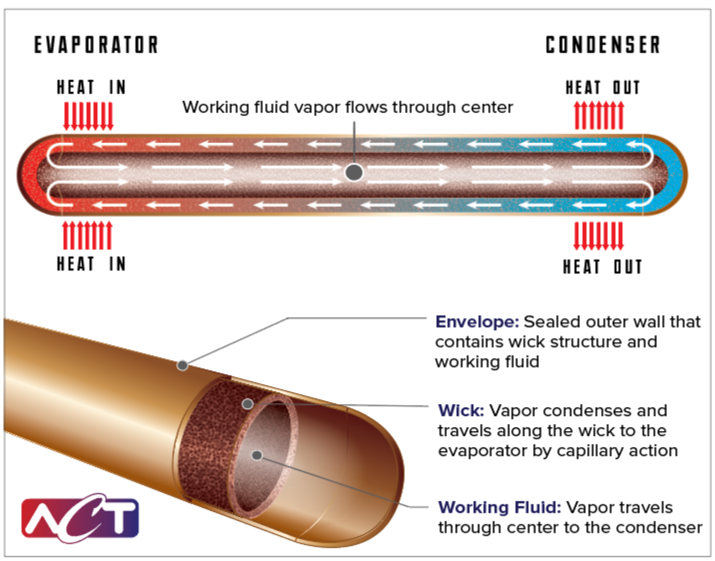

Figure 2 - Basic heat pipe internal structure and its operation.

As shown in Fig. 2, a heat pipe contains a sealed envelope with saturated working fluid and a capillary wick. Heat input in the evaporator vaporizes the fluid, which flows to the cooler condenser, condenses, and returns via the wick. This two-phase process gives heat pipes extremely high equivalent thermal conductivity.

In space applications, heat pipes require wicks to enable liquid return through capillary pumping without gravity. ACT has extensive experience developing high-temperature alkali metal heat pipes with various metal envelopes for both space and terrestrial nuclear applications.

3.3 Heat Pipes for Gravity Assisted (Planetary Surface) Operation – Thermosyphons

A thermosyphon relies on gravity, not capillary action, for liquid return. As shown in Fig. 3, heat entering the evaporator vaporizes the working fluid. The vapor's pressure rise propels it to the condenser where it condenses and falls back down via gravity.

Compared to wicked heat pipes, thermosyphons have lower mass and cost since they lack an integrated wick. Some designs add basic wicks, just in evaporator areas, to aid liquid distribution and startup. Special wicks can also optimize thermosyphon performance. However, their reliance on gravity makes thermosyphons unsuitable for space applications.

Studies of thermosyphons show several operating limits that depend on heat input, geometry, fluid fill, and fluid properties:

- **Dry-out limit** - Inadequate fluid causes a break in circulation and leads to evaporator dry-out and temperature spike
- **Boiling/critical heat flux limit** - Similar to the pool boiling critical heat flux, this also leads to a sharp increase in the evaporator wall temperature
- **Viscous limit** - At low temperatures, there is insufficient pressure to drive vapor mass flow for heat transfer
- **Sonic limit** – The vapor velocity approaches the speed of sound and can no longer carry more power, resulting in a rise in evaporator and vapor temperature until the sonic limit matches the heat input

- **Entrainment** – The high-speed upward vapor flow disrupts the falling liquid return from the wick, decreasing the liquid return flow rate to the evaporator, drying it out. **Flooding limit** – Similar to entrainment, the vapor flow impacts the counter-current liquid return flow, but only in the wickless zones where the vapor flow "shears" the falling liquid, which can flood the condenser and dry out the evaporator.

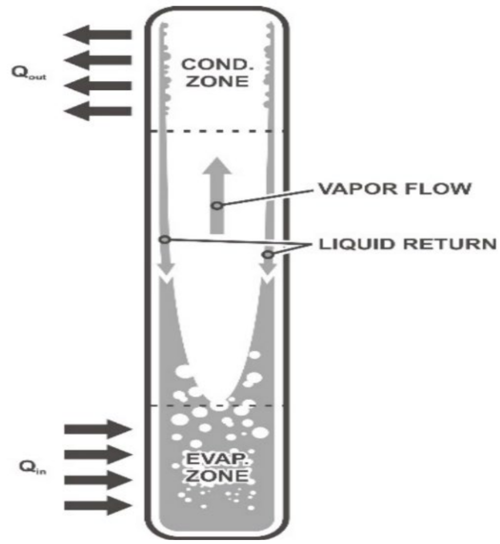

Figure 3 - Illustration of thermosyphon.

For traditional long thermosyphons, the flooding limit is often the main concern, especially with large liquid fills and axial heat fluxes. The sonic limit can also dominate at low temperatures during startup for alkali metals. Under normal conditions, other limits are much higher than flooding.

In nuclear reactors, relatively long pipes (~2m) with high axial fluxes make flooding the key limit. Increasing pipe diameter can raise the flooding limit, but may not be feasible.

To eliminate flooding and greatly boost performance, ACT developed innovative internal wick structures. These separate vapor and liquid flows, overcoming flooding and increasing maximum power to the next much higher limit.

4. Conclusion

Heat pipes allow nuclear reactors to adapt to changing temperatures dynamically. ACT has applied and further developed Heat Pipe technology for several notable NASA programs including:

- NASA's Prometheus – Space Radiator Demonstration Unit (RDU)
- NASA's Kilopower Program (Hot and Cold End)
- NASA's Fission Surface Power (FSP) Program
- NASA's Nuclear Electric Propulsion (NEP)
- NASA's Stirling Radioisotope Power Systems for Space

By leveraging the technology developed for space, ACT has and continues to innovate unique and advanced approaches to the terrestrial world. The development of Advanced Nuclear Reactors and thermal management solutions will lead to the ability to replace the United States' dependency on Fossil Fuels and continue the new era of nuclear power.

5. About the Authors

Kimberly Mankosa, Lead Sales Engineer

Kimberly routinely solves complex military and industrial applications with innovative, custom thermal designs. She has a B.S. in Energy Engineering from Penn State University, which plays a large role in her ability to find the most efficient and long-lasting solution for a given thermal challenge. After working several years as a consultant for NAVSEA, she joined ACT to help bring top end thermal solutions to a diverse group of industry leading partners across the globe.

Calin Tarau, Principal Engineer, R&D

Calin has his Ph.D. in Aerospace Engineering from the Polytechnic Institute of New York University. Since 2006 most of Calin's work has been dedicated to the advancement of spacecraft and planetary thermal control applications. His most notable accomplishment is his work on the NASA Europa ice melting project. He is the leading engineer on much of ACT's work with NASA and has collaborated on 3 patents with many still pending.

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