INL/RPT-24-76309
Revision 1

Analyses Supporting Heat Pipe Experiments

August 2023

Summer Internship Report

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Idaho National Laboratory

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

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ABSTRACT

This internship report presents thermal analysis support aiding the development efforts of advanced reactor systems as a part of the Department of Energy Microreactor Program. The heat pipe microreactor (HPMR) is one such reactor concept where the heat from the reactor core is removed via passively operating heat pipes. Heat pipes have found numerous applications in many fields due to their simplicity, effectiveness, and reliability. The present work includes a review of heat pipe experiments and experimental techniques, ideation on experiments using the SPHERE test bed, identification of heat pipe phenomena of interest, and suggestions for future directions on heat pipe experiments. Hence, it directly supports the development of heat pipe microreactors (HPMRs).

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ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy–Office of Nuclear Energy (DOE-NE) under the Idaho National Laboratory (INL) Advanced Reactor Technology (ART) portfolio's Microreactor Program. The authors credit Carolina Dutra and Joshua Hansel for their efforts on the Sockeye simulations presented in this report.

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Analyses Supporting Heat Pipe Experiments

1. INTRODUCTION

Advanced reactor development efforts include many proposed designs and thus a variety of great challenges which must be tackled. Heat pipe microreactors (HPMRs) are one such concept that utilize heat pipes to transfer heat from the reactor core to the power conversion system. The present internship focused on HPMR development by (1) conducting a systematic review on existing heat pipe experiments, (2) proposing experiments, (3) aiding Sockeye validation efforts via experimental data, and (4) providing suggestions for future testing in the SPHERE facility along with potential modification to test setup and instrumentation.

2. BACKGROUND

Microreactors are crucial in satisfying the need for compact, portable, and safe carbon-free power generation in applications ranging from disaster relief, remote military operations, space power, and backup power [1]. They are characterized by their compact form factor, rapid deployment capabilities, and low power outputs in the kilowatt to lower megawatt range. Microreactors are expected to be initially utilized in remote or off-grid locations [2]. A recent study by Aumeier et al. on the U.S. markets for microreactors specified potential markets in the states of Alaska and Wyoming [3], the two most scarcely populated states in the country, where compact or mobile microreactors could provide great utility in civic, commercial, and emergency response applications. The identified commercial opportunities included niche markets with high energy costs, energy-intensive industries, value added materials manufacturing, process heat generation, and decarbonization policy driven markets. Applications in these markets include mining operations, seafood processing plants, deep water ports, and data centers. Separate economic analyses identified the cost drivers [4], and showed that microreactors are cost competitive with systems of similar size such as diesel generators and renewable sources in microgrids [5].

Amongst other small modular reactors and microreactors, the Heat Pipe MicroReactor (HPMR) concept in particular offers unique advantages compared to conventional light water reactors [6] and other advanced reactor designs by utilizing heat pipes with liquid alkali metal working fluids to harvest the heat generated in the reactor core. Heat pipes can be classified as high-efficiency passive two-phase heat transfer devices which operate through the cyclic evaporation and condensation of a working fluid [7]. A schematic describing the operating principle of heat pipes can be seen in Figure 1. They have diverse range of applications that include nuclear microreactors [8, 9], electronics [10], solar thermal plants [11, 12], furnaces [13], heat exchangers [14], and turbines [15]. The advantages of HPMRs mainly arise from their compact size, the passive operation of heat pipes, and the elimination of intricate coolant pumping systems, which also enables increased passive safety.

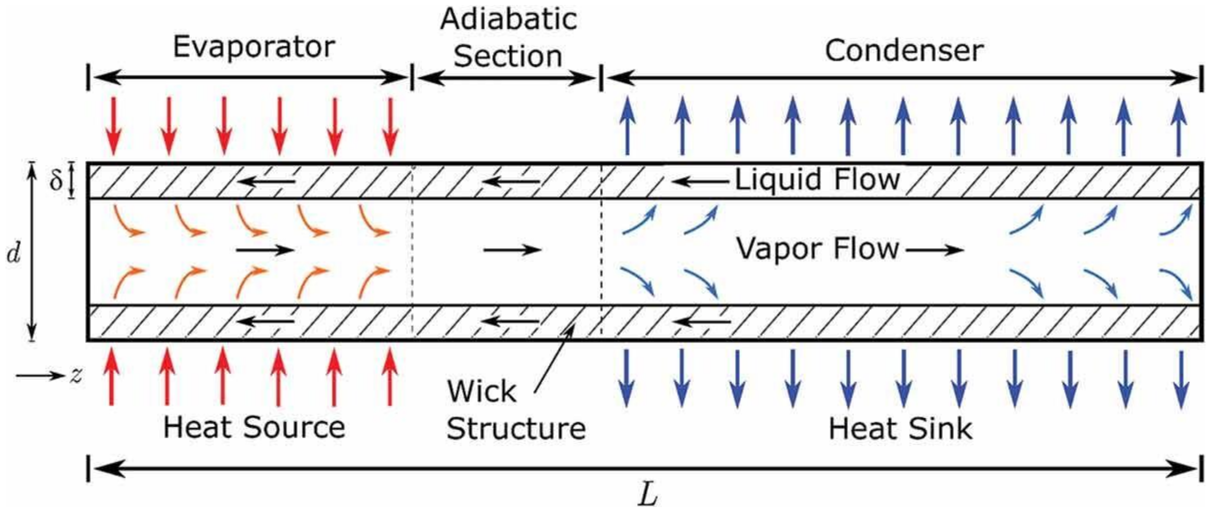

Figure 1. A schematic describing heat pipe operation [16].

Numerous governmental, commercial, and academic institutions from multiple countries aid the deployment of HPMRs. In particular, HPMR development for civilian applications is being spearheaded by the U.S. Department of Energy (DOE) Microreactor Program (MRP) [1, 17-21]. The program involves DOE national laboratories as well as academic and commercial partners and builds on the work which was initiated at Los Alamos National Laboratory (LANL) in the 20th century [22-26]. On the commercial front, the eVinci™ Microreactor is under development by Westinghouse Electric Company [27, 28].

The research and development efforts for HPMRs include a variety of studies using analytical, numerical, and experimental methods [14, 29-32]. In particular, there has been a recent acceleration in experimental work related to heat pipes for microreactor applications, due to the fact that detailed high-fidelity experimental data is lacking in literature. Experimental work is needed to better understand heat pipe operation including transients and accident scenarios. The data can then be utilized for the verification and validation of models, development of high-performance wick structures, and the establishment of regulatory requirements. Therefore, experiments utilizing state-of-the-art methods and instrumentation are a necessary step on the path to HPMR deployment.

3. HEAT PIPE EXPERIMENTAL METHODS

Heat pipe experiments usually focus on the investigation of operating limits [33-38], wick development and performance [39], startup transients [40, 41], inclination angles [42-44], novel instrumentation [16, 40, 45], two-phase flow characteristics [46], and motion conditions [47]. This subsection discusses some of these different experimental approaches. Readers may refer to Wahlquist et al. [29] for a comprehensive review of previous heat pipe experiments in nuclear energy applications.

3.1 Operating Limits

Conventional heat pipe analysis considers multiple limits that include the viscous, sonic, entrainment, capillary, and boiling limits. The limit for a particular case depends on the heat pipe geometry, wick structure, working fluid, and operating conditions. For instance, viscous and solid limits are significant at lower heat pipe operating temperatures, as opposed to the boiling limit, which is significant at much higher temperatures especially for liquid metal working fluids. Although the performance of a heat pipe must be characterized holistically based on the particular application, the concept of operating limits provides a practical means of evaluating heat pipe performance. Therefore, many existing works in literature have focused on the experimental evaluation of operating limits and the development of limit models [7, 37, 48].

Due to the different physical phenomena that are in effect for the different operating limits, indirect methods must often be used to determine which limit is reached. The operating limits are usually characterized by an abrupt increase in the overall thermal resistance of the heat pipe [24, 35]. The power at which the limit is reached can usually be determined based on temperature measurements. Analytical estimates and physics-based reasoning can then be employed to determine the limiting factor based on the evaporator exit temperature and the experimental context. However, it should be noted that operating limits can change both in the short-term during transients, as well as in the long-term due to effects such as corrosion and the introduction of non-condensable gases.

3.2 Wick Investigations

A well-designed wick structure is a crucial component of a heat pipe that has a great influence on its overall performance. Therefore, many researchers have previously investigated the performance and fabrication methods of both conventional and novel wick designs [39, 49-51]. In general, the type of wick structure must be chosen specifically based on the application. For instance, HPMR applications typically utilize heat pipes with high length to diameter ratios [2, 8], this dictates the use of wicks with relatively high permeabilities rather than capillary pumping abilities. The annulus-screen wick is commonly used for such applications as it provides a low resistance flow path to the liquid [51]. In addition, efforts exist on the utilization of additive manufacturing technologies for heat pipe and wick fabrication [52, 53]. This technology enables the free-form production of heat pipe wick structures and the tailoring of wick properties such as pore size and permeability [54].

Investigations of novel wick designs or manufacturing techniques usually involve the characterization of wick properties which are significant for heat transfer applications. These properties may include the permeability, effective pore radius, effective thermal conductivity, porosity, wettability, and surface morphology [55, 56]. Most of these properties can be measured utilizing an array of methods and instruments, ranging from test rigs utilizing simple physical phenomena to cutting-edge equipment [53, 57]. After the wick is characterized, conclusions can be drawn on its applicability in heat pipe applications based on the measured parameters. The wick's performance during operation can then be examined within a heat pipe, and the properties can later be used in model development or validation.

3.3 Steady State and Transients

Operating limits and wick investigations described in the preceding sections are usually characterized by steady state experiments. However, it is particularly important in nuclear applications to understand and predict startup, shutdown, and power transients as well as accident scenarios. Examples of transients include liquid metal heat pipe frozen startup, power transients during normal operation, recovery from heat pipe limit, the cascading failure of multiple heat pipes, and system level transients. Many works have investigated heat pipe response to changes in evaporator input power or condenser cooling rates [58-60], to transients in systems with heat pipes as components [61, 62], and heat pipe startup [40, 42, 63-65].

3.4 Instrumentation

High temperature operation and the presence of liquid metals create a multitude of challenges for the integration of instruments to test facilities. Therefore, liquid metal heat pipe experiments have mostly utilized wall temperature measurements via thermocouples or other types of temperature sensors [29], as well as systems to monitor and regulate the evaporator power input or temperature. In addition, some have utilized a calorimeter at the condenser to calculate the power removed and estimate heat losses. However, these techniques fail to give crucial information on heat pipe two-phase flow dynamics such as pressures, liquid/vapor flow velocities, stresses, and flow visuals. Experiments which aid the R&D of advanced reactors should also exploit cutting-edge technologies and techniques. Hence, advanced measurement and visualization techniques are currently being developed by multiple institutions [66]. These include fiber optic temperature and strain sensors [16, 40, 45, 67, 68], Infrared (IR) thermography, digital image correlation (DIC) [69], high-speed camera flow visualization and pressure measurements of a surrogate fluid [16, 45, 70, 71], radiation based tomography [60], and laser spectroscopy techniques [72].

4. IDEATION ON EXPERIMENTS UTILIZING SPHERE

This section compiles three ideas for experiments which can be conducted in SPHERE, and which are relevant for the research and development of heat pipe microreactors, especially on the verification and validation of heat pipe modeling tools. These experiments require no significant change to the SPHERE facility.

4.1 Cascading Heat Pipe Failure

Cascading heat pipe failures are designated as a mode of failure for recent heat pipe microreactor designs. Figure 2 shows a visualization of a cascading heat pipe failure in an HPMR core [73]. A cascading heat pipe failure can be simulated in SPHERE by increasing the heater power in multiple heaters by a certain percentage. The number of heaters that would have increased power, the percent increase, and the duration of the increase, are some parameters that must be determined to run such an experiment. These parameters should be determined based on a prototypical core design, considering its geometry and nominal operating conditions. Multiple cases can be investigated based on the number of heat pipes failed in the core. The data from the experiment can be utilized to develop models for the cascading failure of heat pipes, and to verify Sockeye models.

Having an asymmetrical heater power input into the block and thus the heat pipe could create thermal stresses that might damage the heat pipe and/or the block. Thus, finite element simulations of thermal stresses should be conducted to prevent damage to the test articles. Strain sensor can also be integrated to monitor the deformation of the block or the heat pipe.

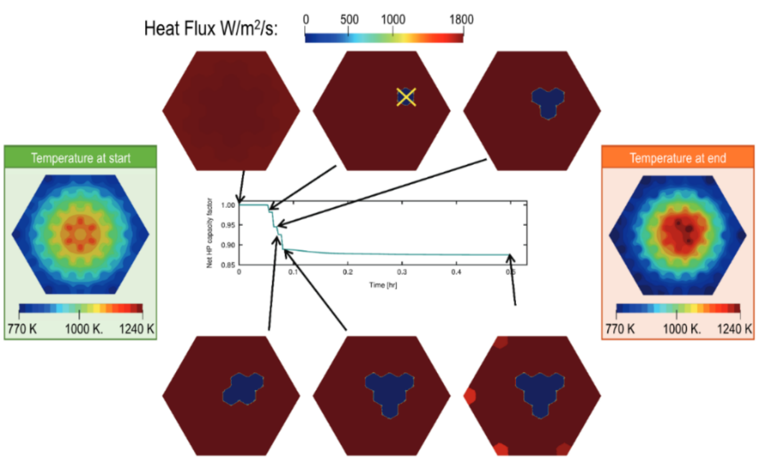

Figure 2. Visualization of SOCKEYE results on cascading heat pipe failure in an HPMR core as a result of a 19% over-power transient [73].

4.2 Power Transients

The ability of heat pipes to withstand power transients could govern the operating flexibility of heat pipes and heat pipe microreactors. Figure 3 shows the numerical simulation of a power transient for an HPMR. Transients in the form of multiple cycles of over-power, and under-power conditions could be investigated. The data can be used to benchmark models predicting heat pipe temperature response. The investigation of both fast and slow power transients could be valuable. The transients would be characterized by the input power, the frequency, and overall duration. The evaporator input powers for these experiments must be reasonable considering the heat pipe operating limits and the nominal operating conditions. The investigation of ± 20% power transients are expected to be valuable. The transients could be characterized by scaled values, similarity groups from Yilgor and Shi [70] which could be utilized to characterize the experiments.

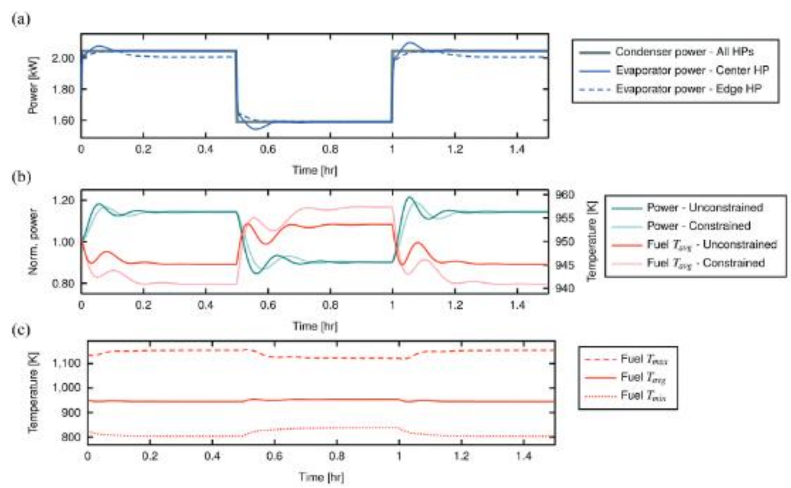

Figure 3. Power input for a ±15% power transient [73].

4.3 Long-term performance tests

The long-term performance and reliability of heat pipes is crucial for their deployment in future microreactors. Various factors could degrade heat pipe performance over time during normal operation. Certain transients could expedite this performance degradation. Potentially quantifying the effects of long-term generation of non-condensable gasses through the oxidation of the heat pipe inner wall and/or the wick structure could be highly beneficial. Furthermore, tests in the order of ~3,000 hours could demonstrate capabilities to run such long-term experiments.

5. HEAT PIPE PHENOMENA OF INTEREST

Although they are seemingly simple systems, heat pipe operation involves numerous physical phenomena of great complexity. To make effective use of the available experimental capabilities, it is necessary to rigorously evaluate the phenomena of interest within heat pipes. For liquid alkali metal heat pipes with microreactor applications, the possible operating states can be identified as follows:

- **Startup or frozen startup:** The working fluid, which is initially at a fully or partially frozen state, gradually melts and then evaporates to later travel towards the condenser section.

- **Normal operation:** A heat pipe which is under normal operating conditions exhibits nearly isothermal operation across its active length.

- **Operating limits:** The power throughput is bound by heat pipe operating limits that include frozen startup, viscous, sonic, capillary, entrainment, and boiling limits.

- **Degraded performance:** Heat pipe performance may degrade over its operating life due to internal or external corrosion and wick damage, gradually decreasing its heat transfer efficiency

- **Acute mechanical failure:** Mechanical failure of the heat pipe casing or the wick may cause total failure of the heat pipe

- **Shutdown:** The shutdown process must consider the future startup of the heat pipe for optimum startup performance

These states and possible parameters and phenomena of interest that can be measured or observed is described in the following subsections.

5.1 Startup

Startup of a heat pipe involves various physical phenomena described as follows. The working fluid can initially be in fully or partially frozen state based on the ambient conditions. As the heat is input to the heat pipe evaporator, the frozen working fluid melts and wets the wick. The melt front moves to wet the entire wick region. The evaporated vapor simultaneously flows towards the condenser section. Full vacuum conditions may exist starting from the condenser endcap within the heat pipe if it is not gas loaded. The vapor molecules then slowly diffuse towards the condenser section. A visualization of this process is shown in Figure 4. The ramp rate of the evaporator input power during the startup process must consider the viscous, sonic, and frozen startup limits which are significant at lower operating temperatures observed during startup. Once continuous circulation of the working fluid is established and the heat pipe is under isothermal conditions, the startup process is complete.

5.1.1 Melt, Temperature, and Vapor Fronts

Any form of flow visualization is helpful in understanding and communicating two-phase flow physics. The three so-called “fronts” representing the presence of an interface can be identified. These are melt, temperature, and vapor fronts. The melt front designates the solid/liquid interface that represents the boundary of the melted region. Next, the temperature front can be described as the boundary of the region where the heat pipe temperature is approximately isothermal. Lastly, the vapor front can be used to separate the region where the vapor phase of the working fluid exists as opposed to vacuum or non-condensable gasses. The location of the vapor front cannot be identified with current methods; however, it can be treated somewhat analogous to the temperature front, which can be observed with temperature measurements. The temperature front moves from the evaporator to the condenser during startup, and it is a practical and efficient way of characterizing the startup of a heat pipe. The temperature front can clearly be seen from Figure 5, which show steady state vapor core temperature measurements using a fiber optic distributed temperature sensor.

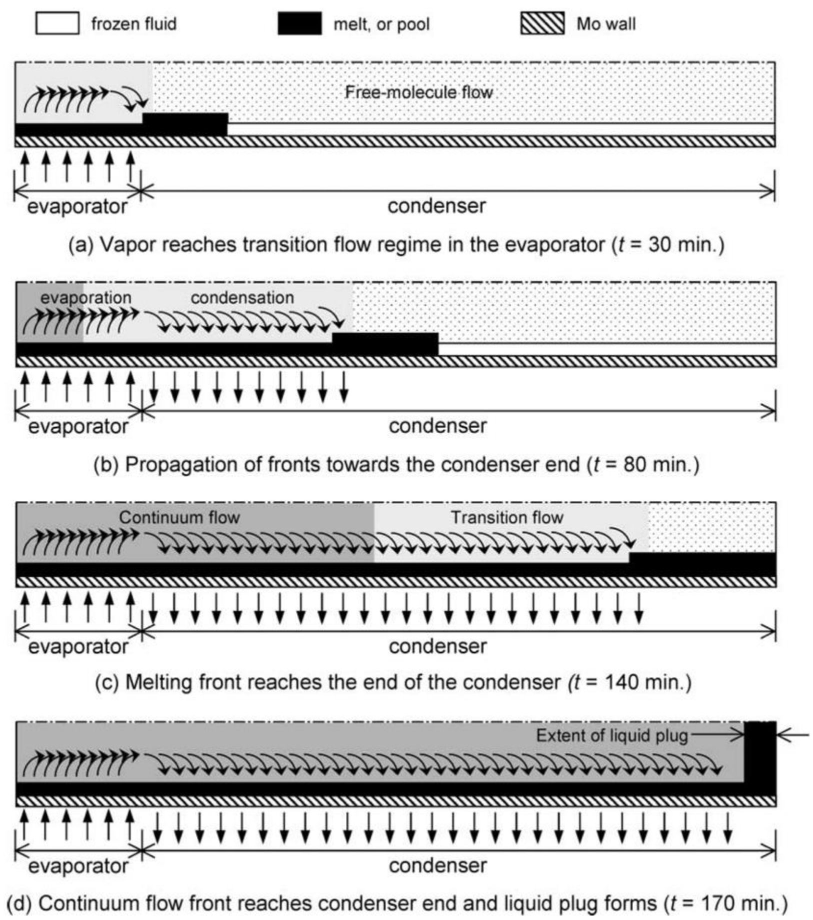

Figure 4. A visualization of the frozen startup process of a lithium heat pipe from Tournier and El-Genk [64].

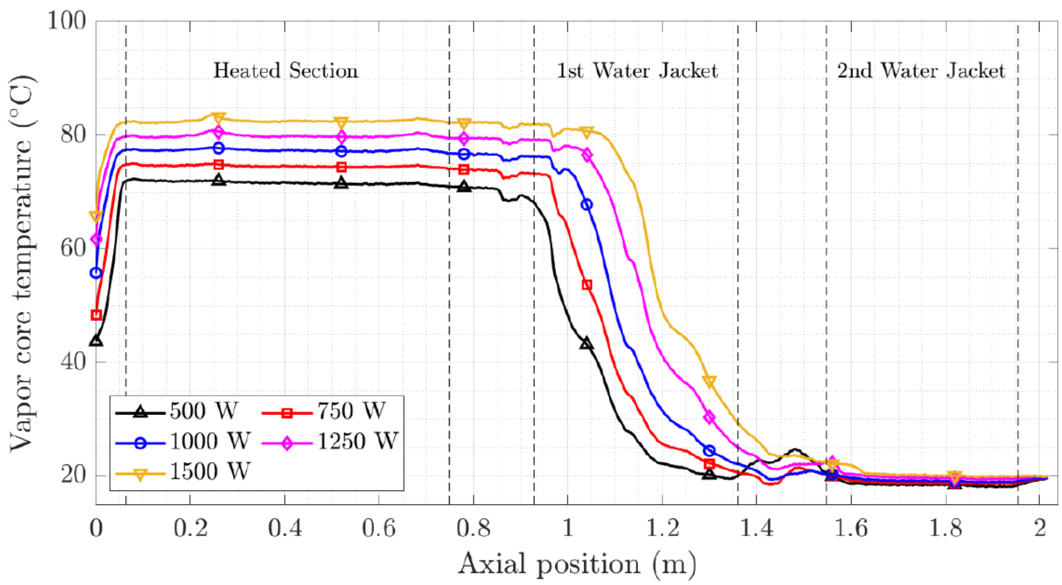

Figure 5. Axial vapor core temperature profiles from Yilgor and Shi [45].

The melt front may be challenging to study with x-ray tomography since one may not be able to distinguish the liquid from the solid. However, under certain conditions, the movement of the liquid pool towards the condenser section may be observed with x-ray tomography, given that the test facility is posed to such technique. Observing the liquid pool as it moves towards the condenser endcap has benefits in characterizing the wick performance during startup. The pool may also form a plug of excess liquid as it reaches the condenser endcap, which can also be recorded with x-ray tomography. The advancement of the liquid pool can be seen in Figure 6.

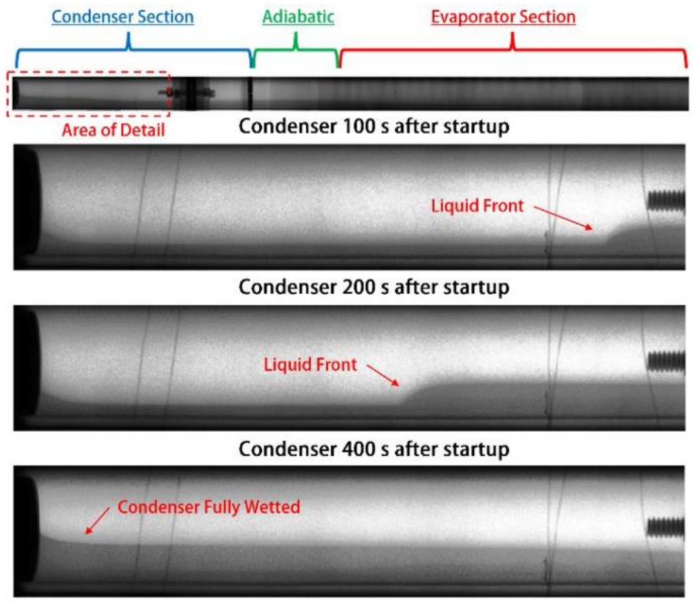

Figure 6. Liquid pool advancement during startup from Tillman et al. [74].

5.1.2 Time Constant

Rapid response of heat pipes during startup may be required for certain reactor designs, in which case it becomes important to characterize the heat pipe's time constant, which is not a strictly defined parameter in literature. However, the heat pipe temperature and the location of the temperature front would be practical ways of defining a time constant. Additional time constants using different parameters could also be identified based on the phenomena of interest.

5.1.3 Working Fluid Inventory in the Evaporator

There needs to be an adequate amount of working fluid present in the evaporator section for the proper startup of a heat pipe. The working fluid amount has to be sufficient for the liquid to wet the wick structure within the design operating range of the heat pipe. Low working fluid inventory in the evaporator may occur after an improper shutdown of the heat pipe, where the working fluid can accumulate and freeze in the condenser. In the case of low working fluid inventory in the evaporator prior to startup, large temperature gradients will be seen in the heat pipe wall since the frozen working fluid can only melt after the heat is conducted through the heat pipe wall. This could cause high stresses which might damage the heat pipe and could also induce the frozen startup limit. The working fluid inventory in the evaporator can be observed and its amount measured via x-ray tomography.

5.1.4 Stress/Strain

Greater thermal gradients are more likely to be observed during heat pipe startup as the heat pipe's heat transfer efficiency may not be as high as in normal operation. Furthermore, the interface between the heat source and the heat pipe may cause additional stresses due to the difference in the thermal expansion of different materials. Both stress and strain can be measured with conventional or distributed sensors.

5.2 Normal Operation

Heat pipes under normal operating conditions operate passively and without any operator action. However, heat pipes need to be monitored continuously to detect any degradation in performance or failures, both for the heat pipes themselves and for the system at large.

5.2.1 Overall Thermal Resistance

One of the simplest ways to quantify heat pipe performance is to investigate the overall thermal resistance of the heat pipe, i.e., the thermal resistance between the heat source (fuel or heater block) and the heat sink (coolant at the condenser). The overall effective conductivity is also used for similar purposes. The thermal resistance can be computed from temperature measurements at multiple locations. It may increase due to a heat pipe limit being reached, which usually transpires as an abrupt increase in evaporator temperature. In addition, the contact resistance at the evaporator or condenser interface might increase due to corrosion or other mechanical degradation, which will in turn increase the overall thermal resistance.

5.2.2 Axial Temperature Profile

The axial temperature profile can be used to clearly visualize heat pipe isothermal operation, while also allowing the identification of the active region of the heat pipe. Furthermore, it is a simple way of observing transients, and of determining if steady state is reached. The effectiveness of the heat pipe in a particular application can often be judged using axial temperature profiles. The measurements are usually taken at the wall or the vapor core. The wall measurements often involve thermocouples that are welded or mechanically secured on the heat pipe or in grooves machined along the heat pipe. Vapor core measurements can be taken within integrated thermowells in the heat pipe. Advanced instrumentation such as fiber optic distributed temperature sensors and ultrasonic temperature sensors can provide very high spatial resolution axial temperature profile measurements.

5.2.3 Location of the Wet Point

The wet point is defined as the axial location where the liquid and vapor pressures are equal. It can also be described as the point where the wick is flooded, i.e., the liquid-vapor interface is flat. Its location depends on numerous factors that include heat pipe orientation and pressure drops. Knowing the exact location of the wet point allows better characterization of the length of the liquid flow path, which is important for the modeling of liquid/vapor flow and pressure drops. The wet point can also be observed with x-ray tomography.

5.2.4 Quantification of Heat Losses

Knowledge of the actual power input/output to and from the heat pipe enables the calculation of heat losses, which tend to be significant particularly for high temperature heat pipe experiments due to both radiative and convective losses. Without rigorous quantification of heat losses, the obtained data may not be effectively used for model verification and validation. The losses can be quantified by comparing heating power to cooling power; for non-nuclear high temperature test beds this is usually achieved via watt transducers and gas gap calorimeters, respectively. The measurements could be supported by analytical estimates of radiative and convective losses from the insulation. Gas-gap calorimeters may also be placed on each heat pipe section, which allows a more rigorous quantification of heat losses [7].

5.3 Degraded Performance

Performance degradation in heat pipes over long-term operation can occur due to numerous effects such as internal/external corrosion, introduction of non-condensable gasses due to oxidation or leakage, wick degradation, and creep at high temperatures.

5.3.1 Overall Thermal Resistance

Performance degradation can usually be identified from temperature measurements. For instance, depending on the conditions, the heat pipe may transfer the expected power at a higher evaporator temperature, which indicates that the overall thermal resistance of the heat pipe has increased from designed levels. This could occur due to oxidation at the heater or coolant interface, or by internal means.

5.3.2 Introduction of Non-Condensable Gasses

Non-condensable gasses may be introduced in the heat pipe due to corrosion or leakage. Their presence can be indirectly observed from axial temperature profiles, given that the measurements have sufficient spatial resolution, since their presence will shorten the isothermal length of the heat pipe as they accumulate at the condenser end. They may also have a detrimental effect on the heat pipe's operation by increasing the pressure within the heat pipe and thus the heat pipe operating temperature. They will, at the least, cause changes in the heat pipe's normal operating conditions.

5.3.3 Wick Damage or Degradation

The wick could get altered or damaged during normal operation due to factors such as corrosion, clogging, or mechanical degradation, which can diminish the performance of the heat pipe. Depending on its type and thickness, corrosion can cause significant damage to the wick structure. Any break in the continuity of the wick structure could limit the capillary pumping ability of the wick. Similarly, any clogs in the wick structure due to corrosion or other contaminants will increase the pressure drop in the wick and could also limit its capillary pumping ability. Other forms of mechanical degradation may occur due to the thermal expansion of the wick, the heat pipe endcaps, and casing. Wick degradation can be investigated via x-ray tomography during operation, and via higher resolution computerized tomography (CT) scans post-operation.

5.3.4 Stresses During Long-Term Operation

Thermal and mechanical stresses in the long-term can result in the creep failure of the heat pipe or other system components which might cause catastrophic failure or otherwise degrade performance. These stresses can be measured with conventional and distributed stress/strain sensors, however other forms of inspection may be needed for their accurate characterization.

5.4 Shutdown

Heat pipe shutdown, similar to startup, involves a multitude of physical phenomena. During shutdown, the working fluid transitions from being in its liquid and vapor states to its solid state under standard atmospheric conditions. The shutdown mechanics depend highly on the power ramp down rate at the evaporator, and the cooling conditions at the condenser.

5.4.1 Solidification Front and Solid Accumulation Region

The solidification front can be defined as the solid/liquid interface that represents the boundary of the frozen solid region. How the solidification front behaves depends on the evaporator and condenser conditions during shutdown and the heat pipe orientation. Most importantly, if the solid accumulation region is largely outside of the evaporator, there may not be enough working fluid inventory in the evaporator for the proper startup of the heat pipe. Both the solidification front and the solid accumulation region may be observed with x-ray tomography images.

5.4.2 Temperature Front

Conversely to startup, the temperature front will move gradually from the condenser endcap to the evaporator during heat pipe shutdown. It reflects the active heat transfer region during shutdown and can be used to determine when shutdown is complete, i.e., when heat is no longer transferred via the phase change of the working fluid. The temperature front can be investigated with axial temperature profile measurements.

5.4.3 Shutdown Time Constant

Similar to the startup time constant, the shutdown time constant can be used to characterize the timescale for heat pipe shutdown for both normal operating conditions and accident scenarios. It could be defined using various parameters depending on the phenomena of interest to determine its time response during shutdown. A simple definition could be through temperature measurements as described previously for the startup time constant. The shutdown time constant may be particularly important if the experiment simulates reactor shutdown or decay heat scenarios.

5.4.4 Stress/Strain

Greater thermal gradients can also be significant during shutdown, resulting in higher stresses. These stresses could be due to varying evaporator and condenser conditions, as well as changing geometric dimensions due to thermal expansion. They can be measured with both conventional and distributed stress/strain sensors.

6. SOCKEYE VALIDATION

Facility information and experimental data were provided to the Sockeye team from recently published data in [45] for the validation of vapor core temperature profiles using the code [31]. The provided data included the facility dimensions, vapor core temperatures, evaporator power inputs, condenser coolant mass flow rates, and coolant inlet/outlet temperatures. The simulations were conducted by Carolina da Silva Bourdot Dutra under the supervision of Joshua Hansel. Figure 7 shows a schematic of the simulation which considers the heaters, heater blocks, adiabatic section visualization port, and insulation in the evaporator section.

Figure 7. A schematic of the Sockeye simulation.

A comparison between experimental and simulation results is shown in Figure 8. It can be seen that the Sockeye results closely match experiments. However, an artificial inactive length, which is normally used to model non-condensable gases, was introduced into the heat pipe in an attempt to reconcile the initial discrepancy with the data. A detailed description of this modeling approach can be found in Tano et al. [75]. The discrepancy between experimental and numerical results is thought to be due to the combined effect of non-condensable gases present during the experiments and liquid pooling at the condenser. Future experiments will include additional tests in order to evaluate the effects of the presence of non-condensable gases in the test section. The experimental procedure will then be modified based on the findings.

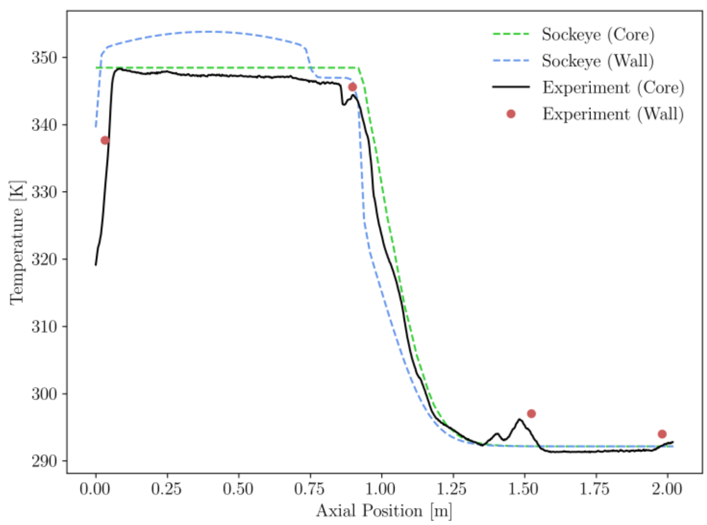

Figure 8. Comparison of Sockeye simulations by Dutra and Hansel with experimental data from Yilgor and Shi [45].

7. FUTURE DIRECTIONS FOR EXPERIMENTS

As heat pipe microreactors mature as a technology, it will become increasingly necessary to utilize advanced instrumentation for the detailed analysis of heat pipes. Presently, temperature, strain, and x-ray tomography techniques are the only available options for high temperature heat pipe experiments. Some types of measurements that could be revolutionary in heat pipe experimentation may include:

- **Liquid/vapor mass flow rates:** Measurements of the mass flow rates, and/or the velocities for high-temperature heat pipes could be a giant leap in the field. These parameters can be utilized in numerous ways: (1) calculation of actual power throughput, (2) compressible flow analysis for vapor, (3) wick and interfacial stress calculations for entrainment, (4) characterization of the transient response of flow rate changes with evaporator power input, condenser cooling power, and limit conditions, (5) better identification of steady state conditions, (6) back-calculation of liquid/vapor flow areas. There are currently no robust method for measuring the liquid and vapor flow rates or velocities within a high-temperature heat pipe, however methods such as laser spectroscopy were proposed [66].

- **Pressures and pressure drops:** It is challenging to effectively measure pressure within any type of heat pipe, but the difficulties are amplified with the presence of high temperatures and liquid metals for heat pipes in microreactor applications. In addition, any pressure taps would not only be intrusive to the two-phase flow dynamics, but they would also present new safety risks since the heat pipe would seize to be a closed system. Another concern would be that the pressure tap might be exposed intermittently to liquid or vapor, which would affect how the data should be interpreted. Furthermore, the locations of the pressure taps must be carefully determined, and exactly what pressure is being measured should be conclusively shown. In particular, measurements of capillary pressure would be extremely valuable in assessing wick performance, and aiding wick development and modeling efforts. Lastly, effective measurements of liquid or vapor pressure drops would be very beneficial in pressure drop model validation.

- **Liquid, vapor, non-condensable, and vacuum fractions:** Knowing the mass or volume fractions of the liquid, vapor, non-condensable gasses, or vacuum within a heat pipe enable the direct calculation of additional parameters. One such parameter is interfacial heat flux, which can be used as an additional parameter to characterize transients when compared to the evaporator power input. Knowing the gas composition could also aid in the identification of corrosion and leakage within the heat pipe.

Besides the development of advanced instrumentation, another challenge HPMR developers face is on the regulatory front. The safe operation of heat pipe and heat pipe assemblies must be demonstrated via well-scaled experiments and validated modeling and simulation data for the licensing of a particular design. Literature is lacking in work related to the scaling of heat pipes using nuclear engineering scaling methodologies [70]. However, scaling analysis must be conducted and verified for the extension of the results from scaled-down facilities to prototypes. Scaling could be conducted on the heat pipe level [70], or on the system level. Besides the practical implications, development of robust scaling methods on the heat pipe level and the quantifications of scaling distortions would be a valuable tool in improving the understanding of heat pipe physics. Scaling analysis could focus on specific phenomena within a heat pipe, such as pressure drops, compressible flow dynamics, vapor diffusion during startup, response to power transients, etc.

Lastly, the reliability and predictability of heat pipes and heat pipe systems over long term need to be established, particularly to advance wick fabrication and heat pipe assembly methods [76]. These efforts could be supplemented by failure detection and prevention techniques which could include autonomous approaches.

8. CONCLUSIONS

The heat pipe work conducted during the internship period was geared towards identifying possible avenues to pursue regarding heat pipe experimentation, and to allow the intern to think critically about heat pipe technology. The work included a thorough review of recent heat pipe experiments from U.S. institutions, ideation on experiments utilizing the SPHERE facility, identification of phenomena of interest within heat pipes, and proposing some future work related to heat pipe experiments. As a direct result of this internship, foundations of two journal articles related to heat pipe experiments were laid.

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