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ABSTRACT

The engineering-scale heat pipe application Sockeye, being developed through the U.S. DOE Nuclear Energy Advanced Modeling and Simulation (NEAMS) program, is concurrently undergoing code development and verification and validation activities. One such validation activity is part of a larger collaboration between the NEAMS program and the U.S. DOE MicroReactor Program (MRP). This activity involves using Sockeye to model one of the numerous sodium heat pipe experiments from the MRP's Single Primary Heat Extraction and Removal Emulator (SPHERE) facility at Idaho National Laboratory for validation purposes.

Heat pipe data produced by the SPHERE facility was used to create a useful validation case for Sockeye. Sockeye's conduction model was used to simulate an experimental run at SPHERE. The steady-state temperature distribution was accurately reproduced, but discrepancies with experimental data were found in the transient behavior after the power shutoff. This effort also revealed a number of challenges of modeling an experimental setup such as SPHERE. For example, the simulation results are strongly dependent on many experimental parameters that were not described or characterized at the time, such as possible gaps in insulation.

KEYWORDS: Sockeye; SPHERE; heat pipe

1. INTRODUCTION

Microreactors are a class of nuclear reactors that generate relatively small amounts of power, up to 20 MW of thermal energy, which can be used to generate electricity or be used for heat in industrial applications. These reactors also typically boast a high degree of portability, which makes them suitable for unique applications such as electricity generation in remote areas, military bases, and areas devastated by natural disasters. One class of such reactors are termed "heat pipe microreactors" since they utilize heat pipe technology to achieve heat transfer from the core. Heat pipes are very efficient, passive, compact, and reliable heat transfer devices operating on a two-phase flow with phase change, which have been used in a variety of applications, such as electronics cooling, oil pipelines, air conditioning, and space exploration [1,2].

The Department of Energy (DOE) Nuclear Energy Advanced Modeling and Simulation (NEAMS) program is currently developing Sockeye, an engineering-scale heat pipe application [3]. Sockeye features both design and simulation capabilities, which require verification and validation before being fully utilized in design and analysis activities. Ample experimental data exists for low-temperature heat pipes, such as copper-water heat pipes, but high-temperature heat pipes are largely lacking in experimental data due to several experimental challenges associated with the high-temperature range and the selection of working fluids. The Single Primary Heat Extraction and Removal Emulator (SPHERE) facility, designed and implemented by the DOE Microreactor Program, was designed to measure the heat flows and temperature distribution in systems approximating subsections of heat-pipe-cooled reactors [4] and thus offers the capability to support Sockeye validation.

This paper is organized as follows. Section 2 gives a brief overview of Sockeye's simulation capabilities, Section 4 gives an overview of Sockeye's current validation plan, Section 3 gives an overview of the SPHERE facility, Section 5 demonstrates some initial validation work performed using data from SPHERE, and Section 6 gives some conclusions and discusses future work.

2. SOCKEYE MODELS

Sockeye has two simulation models. The first, termed the "flow model," actually simulates the working fluid flow inside the heat pipe [3]. The second, termed the "conduction model," approximates the heat pipe interior using the heat conduction equation with thermal properties that attempt to mimic heat pipe performance. Here we only outline the conduction model, since the results shown in this paper were generated using this model.

2.1. Conduction Model

Sockeye's "conduction model" is based on a common modeling approach in heat pipe modeling that approximates a heat pipe as a superconducting rod [5,6]. When a heat pipe has reached its operating temperature, this is a reasonable approximation, since the heat pipe operates nearly isothermally. With this approximation, instead of modeling the fluid flow inside the heat pipe, the heat conduction equation is solved over the entire heat pipe:

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = 0 \,, \tag{1}$$

where ρ is density, c_p is specific heat capacity, k is thermal conductivity, and T is temperature.

The main distinguishing characteristic of superconduction heat pipe models is how they behave for non-isothermal conditions. Sockeye divides the heat pipe into three radial regions: the cladding, the liquid/wick, and the vapor core. Each region has its own definitions of the thermal properties ρ, c_p, and k. The cladding region just uses thermal properties of the cladding material, the liquid/wick region uses some average of the liquid and wick thermal properties, and the vapor core region uses vapor thermal properties for ρ and c_p, but k is changed dynamically to obey analytic approximations of various heat pipe limits. For details on this strategy, see [7].

This work introduces an extension of this dynamic thermal conductivity model to include heat pipes with non-condensable gases (NCGs). This model is based on the steady flat front model introduced in [8]. In this model, a sharp interface is assumed between the "active" length of the heat pipe, where the working fluid operates, and an "inactive" length, where NCGs reside. In Sockeye's conduction model, the thermal conductivity in the vapor core is set to be a high value for the active length and a low value for the inactive length.

3. SPHERE FACILITY

The SPHERE facility is designed for the operation and characterization of heat pipes. The main function of the test bed is to provide electric power to heaters for the simulating the fuel for the heat pipe. Watt transducers provide an accurate measurement for input power. Multiple temperature measurement systems are used, including IR, thermocouples, and other advanced methods. Additionally, a differential temperature sensor and flow meter are used to provide calorimetry on the heat rejection end of the heat pipe. The measurement of energy into and out of the system, along with temperature distribution measurements, provides details regarding the heat flow through the test articles. Additionally, the test bed, which consists of an 88-inch quartz tube with an interior diameter of 6 inches, is able to have various internal gas compositions, including any mixture of argon, helium, and nitrogen, or a vacuum can be created via a vacuum pump. The control of the gas composition provides the ability to reduce oxidation during testing and create different heat transfer conditions. An absolute pressure gauge is used to measure the level of vacuum and control gas mixtures by a partial pressure addition to the tube. Fig. 1 shows a cross section of the heated region of the setup, including the cross section of the heat pipe itself, which includes a central thermowell in which thermocouples are installed, which allow measurement of the axial temperature profile.

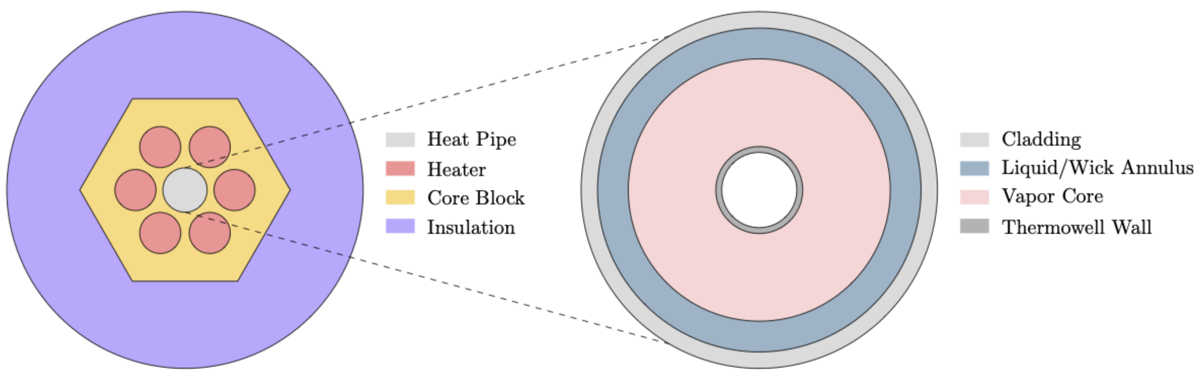

Figure 1: Cross Section of Evaporator Section.

Thermocouples were installed both outside the heat pipe and inside the interior thermowell. These positions are shown in Fig. 2, where the exterior cladding thermocouples are numbered with the "C" prefix, and the interior thermowell thermocouples are numbered with the "TW" prefix. Note that the axial dimension is reduced by a factor of 2 for visibility.

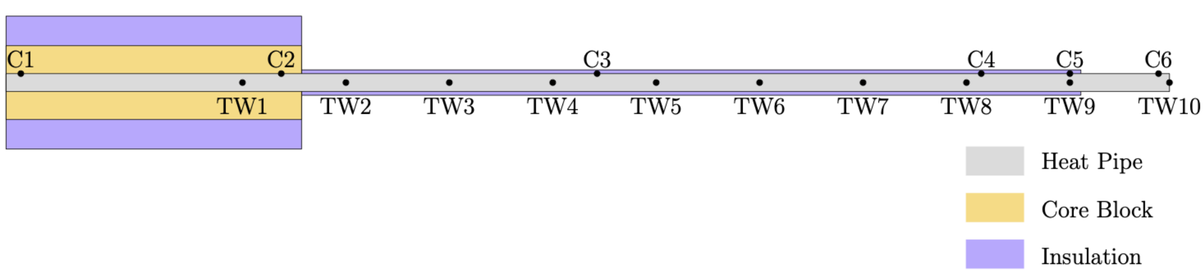

Figure 2: Thermocouple Axial Positions.

4. SOCKEYE VALIDATION PLAN

Determining the suitability of Sockeye in evaluating heat pipe safety performance and in calculating operational limits requires a comprehensive set of validation cases against which code results are compared. A demonstration of the Sockeye numerical models validity and applicability ranges depends upon the ability of the software to reproduce experimental results and quantify the software intrinsic model uncertainties.

This exercise requires experimental data that covers the entirety of the operating conditions of the heat pipe Sockeye is modeling.

The use of existing heat pipe experimental data is challenging for use of software validation. The collection of experimental data for high-temperature heat pipes is challenging. Instrumentation precision, accuracy of the measurements, and experimental processes need to be well documented for a rigorous validation. Additionally, instrumentation operational limitations and precision need to be characterized. Furthermore, the majority of the experimental data for high-temperature heat pipes is limited to externally mounted thermocouples. Instrumentation must be able to withstand these high temperatures, and the installation of instrumentation on the inside of a heat pipe potentially affects the flow field. This limits the quantification of physical properties within the pipe to indirect evaluations. A few experiments have measured internal data, such as vapor temperature, but documentation on the details and uncertainties of these measurements is lacking.

Recent efforts in designing and conducting experiments with high-precision instrumentation and with the ability to quantify complex phenomena within heat pipes provides an opportunity to obtain high-quality data for software validation. The Sockeye development team is working closely with the facility's experimentalists to obtain high-resolution spatial and temporal data to be able to capture smaller scale phenomena as well as the analysis of the interactions between the various components in the experimental rig. This can be achieved through a combination of separate effect tests and integral effect tests. The validation of numerical models at characterizing physical phenomena is achieved by separate effect tests experiments, while in the Sockeye model overall uncertainty is likely to be best quantified through qualification analyses of larger experiments, such as integral effect tests.

Data provided by SPHERE corresponds to a sodium heat pipe with a screen wick and annular gap, and the heat pipe contains NCGs. Operational regimes included frozen startup, normal operation, and shutdown. Temperature measurements included thermocouples mounted both in the interior thermowell and on the exterior of the cladding, as shown in Fig. 2. The thermowell thermocouples offer a decent axial resolution so that the vapor temperature distribution in Sockeye can be validated directly, and data is acquired at 1-second intervals so that that the transient processes of startup and shutdown can be examined in sufficient detail. The exterior cladding thermocouples are more sparse but provide data to validate radial temperature changes when compared against thermowell data.

5. RESULTS

Currently, the only data produced using the SPHERE facility corresponds to a heat pipe containing NCGs, and Sockeye's flow model mentioned in Section 2 has not yet developed support for NCGs, so the validation studies performed so far are only valid for the conduction model described in Section 2.1. Nevertheless, these studies demonstrate how data produced using SPHERE can be applied to the flow model after implementation of NCG support or when SPHERE utilizes heat pipes without NCGs.

5.1. Startup and Shutdown of a Sodium Heat Pipe

Many runs have been performed at the SPHERE facility under various conditions. In this section we describe a run performed on February 3, 2021, which featured a sodium heat pipe starting from a frozen state at room temperature, operating in a steady state, and shut down afterward. A constant electric power of 750 W was supplied to the heaters for approximately 51.5 hours, followed by a drop to near-zero power for the remainder of the experiment, approximately another 39 hours.

The Sockeye model used for this run was two-dimensional and included the heat pipe, core block, and insulation covering the core block and adiabatic section. The actual core block geometry lacks azimuthal symmetry since its cross section is hexagonal, not circular, and has the six heater tubes. The core block was transformed into a cylindrical shell region with the same heat capacity and outer surface area of the actual core block, with no heater holes. Heat was applied uniformly throughout the core block as a volumetric source, using the electrical power data from the experiment. This run was performed in vacuum conditions, so radiation was the only heat transfer mechanism at the system boundary. The system was assumed to exchange radiation with a constant temperature environment using a boundary condition of the following form:

$$q = \sigma\epsilon(T^4 - T_\infty^4) \,, \tag{2}$$

where q is the heat flux *out* of the system, σ is the Stefan-Boltzmann constant, ϵ is the emissivity of the outer surface of the system, T is the surface temperature of the system, and T_∞ is the ambient temperature. In the evaporator and adiabatic sections, the outer surface corresponds to an insulation layer, whereas the condenser section surface is the heat pipe surface itself.

Fig. 3 shows the Sockeye temperature transient solution at the thermowell thermocouple positions, compared against the measured data. In the steady portion of the transient, Sockeye's model matches measured data fairly well. Fig. 4 shows the spatial temperature profiles in the middle of this steady section. Sockeye's solutions show almost no difference in the centerline and cladding temperature profiles. The centerline temperatures match very well with measured data, but the cladding temperatures have some discrepancies with measured data. Particularly, the thermocouple close to the evaporator end cap, C1, exceeds Sockeye's prediction by 25 K, and there is a significant temperature dip at C2 that is not captured in Sockeye's prediction. The reason for this dip is not known with certainty, but possible explanations are the following:

- C2 may be adjacent to a gap in the insulation.
- C2 may be in contact with one of the structural supports that may draw heat away.

After the steady portion of the transient, when the electrical power is shut off, Sockeye's solution shows significant discrepancies with the measured data; all temperatures appear to decay faster than the measured data. The reason for this discrepancy is most likely an inaccurate description of the boundary conditions, such as inaccuracy of the emissivities and/or the ambient temperature, or that radiation exchange is occurring with additional surfaces, such as the table supporting the setup.

It should be noted that this conduction model requires several quantities to be adjusted to attempt to replicate measured data. There were several unknown quantities, such as the mass of non-condensable gas in the heat pipe, the emissivities of the cladding and insulation. Additionally, there are tunable parameters that are inherent to the model itself, namely, the thermal conductivity used for the vapor core, both for the active and inactive regions. Thermal properties (ρ, c_p, and k) of the various materials also play a large role in these setups; however, of these, only thermal conductivity plays a role for the determination of steady conditions. The volumetric heat capacity ρc_p obviously plays a role in heat retention; an underestimation could be a factor in the overestimated temperature fall rate after power shutoff, for example.

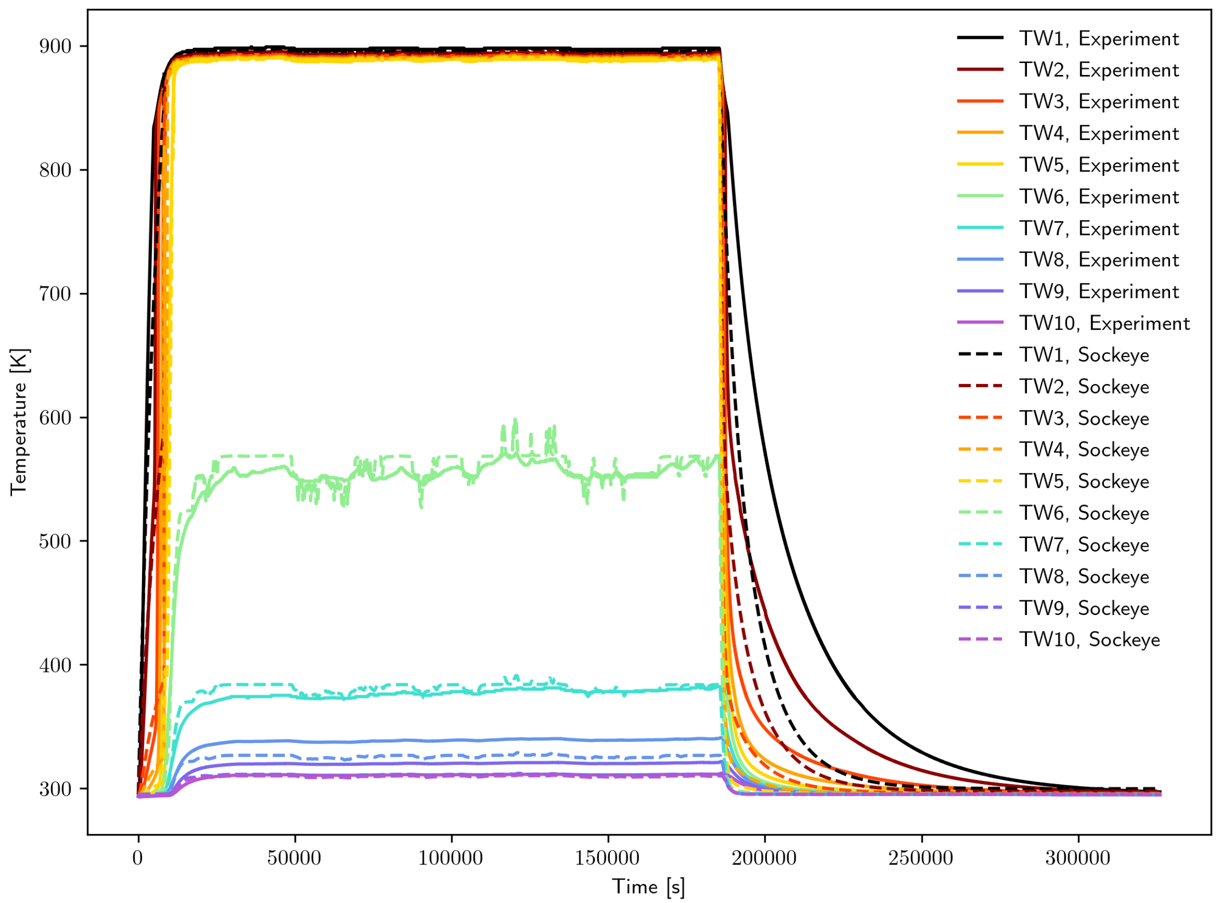

Figure 3: Comparison of Thermowell Temperature Transient Between Sockeye and Experimental Data.

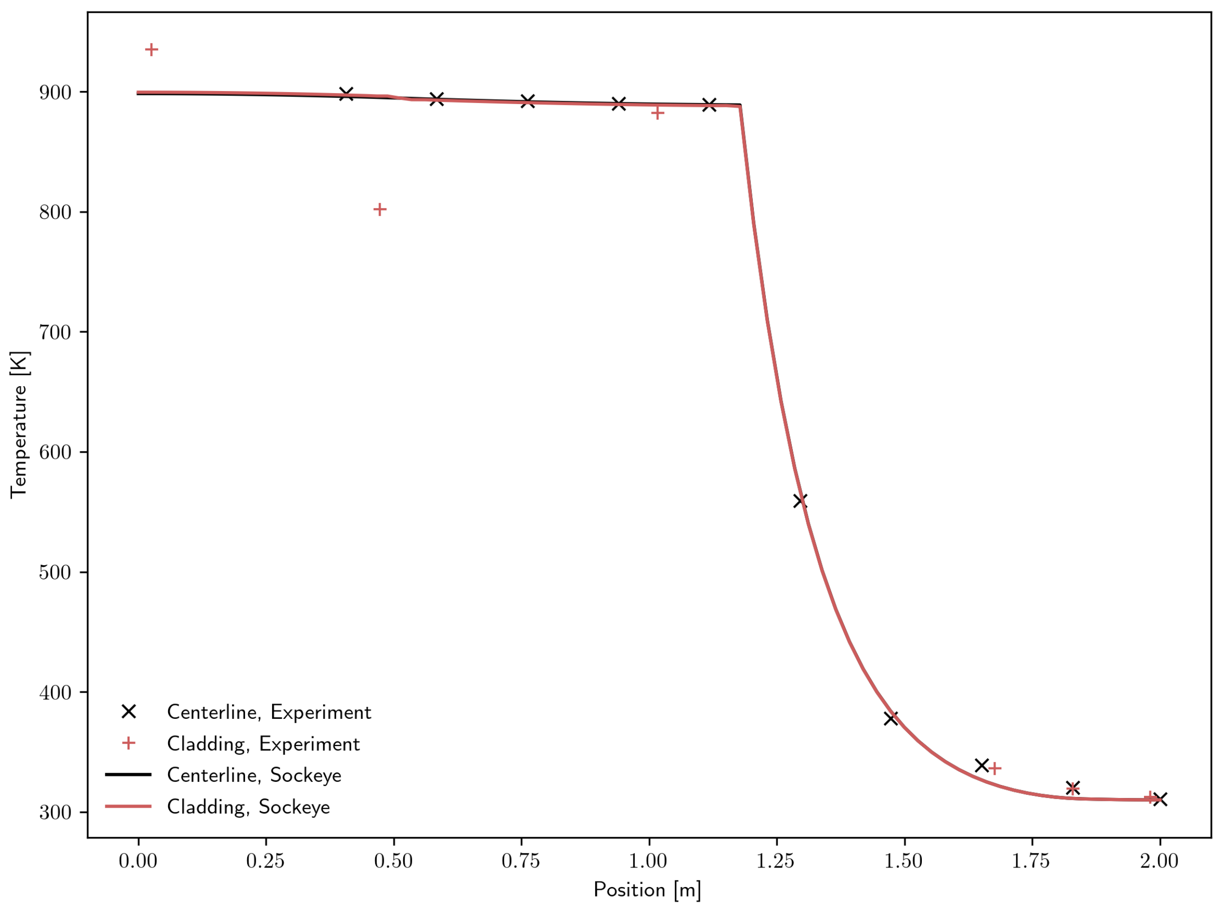

Figure 4: Comparison of Centerline and Cladding Temperature Profiles Between Sockeye and Experimental Data at 100,000 s.

6. CONCLUSIONS

Heat pipe data produced by the SPHERE facility was used to create a useful validation case for Sockeye. Sockeye's conduction model was used to simulate an experimental run at SPHERE. The steady-state temperature distribution was accurately reproduced, but discrepancies with experimental data were found in the transient behavior after the power shutoff. This effort also revealed a number of challenges of modeling an experimental setup such as SPHERE. For example, the simulation results are strongly dependent on many experimental parameters that were not described or characterized at the time, such as possible gaps in insulation.

The NEAMS and MicroReactor programs will continue to collaborate in the area of microreactor modeling, simulation, and validation, including continued use of new and refined data from experiments such as SPHERE to validate NEAMS tools like Sockeye. In particular, updated measurements and additional descriptions of the SPHERE experiments will be used to update and expand on the Sockeye validation work reported in this paper.

Future work for Sockeye includes concurrent code development and verification and validation activities. The flow model referenced in Section 2 is planned to be extended to allow the inclusion of non-condensable gases, which will allow it to take advantage of data produced using SPHERE and data from other facilities, as well as filling a necessary gap for heat pipe simulation. Experiments at Texas A&M University [9] and the University of Michigan [10] have produced data for sodium heat pipes that can further support verification and validation efforts. Additionally, existing validation studies, such as the test problem presented in this work, can be improved with more sophisticated models; for example, the temperature dependence of thermal properties can be considered, as well as more accurate boundary conditions.

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