Validation of the transient heat pipe code with the SAFE-30 experiment

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1. Introduction

As interest in decarbonization increases, there is a movement towards using nuclear power in forms other than conventional baseload power, such as load following, off-grid, propulsion, etc. Consequently, the development of SMRs and microreactors has been initiated. Among these, Heat Pipe Microreactors have been the subject of much research, particularly since the success of the KRUSTY experiment[1], focusing on passive heat removal capacity, safety, and compact design.

To simulate the heat pipe reactor, a heat pipe code is required for simulating the heat pipe itself. Therefore, through past research efforts, a sodium heat pipe analysis code based on a thermal network model was developed in the previous research[2]. However, the existing analysis results had the issue of not matching the experiments under start-up and shut-down conditions. To address this, improvements were made to the code to simulate start-up and shut-down operations. Through these enhancements, validation of the SAFE-30[3] experiment was conducted.

2. Methods and Results

2.1 SAFE-30 experiment

The SAFE-30 experiment conducted at LANL involved testing the full operational conditions of a single heat pipe from start-up to shut-down. The performance of the heat pipe in this experiment was as Figure 1. The experimental apparatus was inserted into a vacuum chamber and cooled by water.

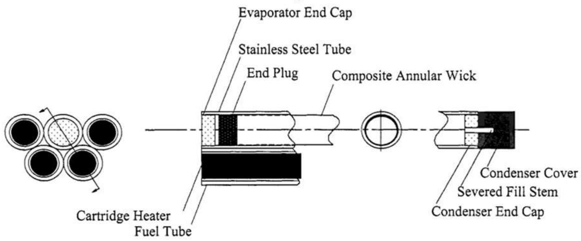

Fig. 1. SAFE-30 Experimental apparatus[3]

All of the heat from the heat pipe is removed by radiative heat transfer. At the evaporator section, the uncovered top side of the heat pipe wall can be observed. During the experimental process, the uncovered evaporator section releases the heat by the radiation.

The sodium heat pipe is used for the SAFE-30 experiments. The composite wick structure is used, consisting of the screen mesh and artery. Before the experiment, the oxide layer formed on the outside of the heat pipe was removed by bead blasting. The design values for the heat pipe are listed in Table I.

Table I: Heat pipe design values[3]

Parameter	**Value**
Heat pipe length (m)	1.20
Evaporator length (m)	0.43
Condenser length (m)	0.77
Heat pipe outer diameter (cm)	2.54
Heat pipe inner diameter (cm)	2.21
Wick type	Screen + Artery
Wick outer diameter (cm)	2.07
Wick inner diameter (cm)	1.74
Effective pore radius (μm)	47
Ambient Temperature (°C)	20.75

2.2 Implementation of start-up/shut-down model

To predict the start-up/shut-down of the heat pipe, we implemented two different models: the solid-liquid phase change model and the wick-vapor interface thermal resistance model. For the solid-liquid phase change model, we used the mushy zone method, which accounts for latent heat in the working fluid heat capacity[4].

In previous research, the thermal resistance of the wick-vapor interface was neglected. To predict start-up/shut-down, we incorporated phase change thermal resistance and radiative thermal resistance into the transient heat pipe code. For the phase change thermal resistance, we utilized a model based on the Clausius-Clapeyron equation[5], and for radiative heat transfer, we employed a modified model considering the Knudsen number. Using these models, the code calculates phase change thermal resistance and radiative thermal resistance using Eq. (1) and Eq. (2) with wick-vapor interface temperature $\boldsymbol{T_{wi}}$ and vapor temperature $\boldsymbol{T_v}$.

$$\boldsymbol{R_{pc} = \frac{\sqrt{2\pi}R^{1.5}T_v^{2.5}}{P_{sat}h_{fg}^2A}} \qquad (1)$$

$$R_{rad} = \frac{Kn}{\sigma_{rad}\epsilon(T_{wi}+T_v)(T_{wi}^2+T_v^2)A} \quad (2)$$

With the modified code, we simulated the SAFE-30 experiment, applying radiative boundary conditions to the condenser and experimental temperature data to the evaporator to assess model agreement. Figure 2. depicts the simulation results with the evaporator temperature boundary condition. As a result of the modification, the occurrence of an increase in condenser temperature at start-up was delayed due to the melting of the working fluid and increased thermal resistance. During shut-down, the wick-vapor thermal resistance led to a larger temperature difference between the evaporator and condenser wall temperatures in the low-temperature region. Overall, the simulated condenser wall temperature showed good agreement with the experiment results when compared with the given evaporator wall temperature. For validation, we simulated the SAFE-30 experiment using a heat transfer rate boundary condition to assess code agreement.

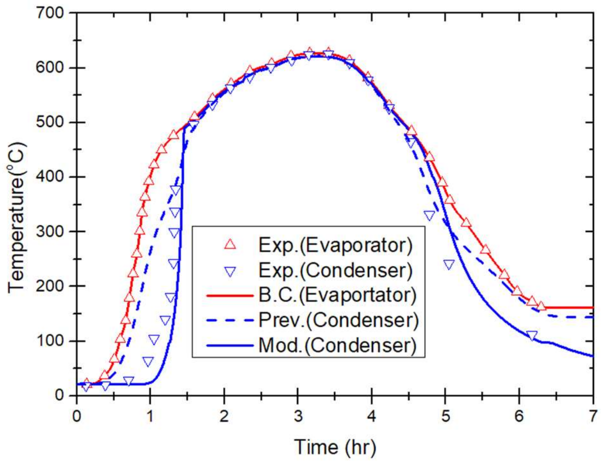

Fig. 2. Simulated wall temperature results with the evaporator wall temperature boundary condition.

2.3 Simulation condition

To simulate the SAFE-30 experiment, the heat pipe was modeled based on reference literature, as outlined in Table I. The condenser boundary conditions in the experiment were set as radiation boundary conditions, with a maximum heat removal of 660W at a condenser wall temperature of 900K, as determined by the experiment.

For the evaporator boundary condition, two conditions were imposed. Firstly, ignoring the radiation heat loss of the heat pipe evaporator, the heat removal transient of the condenser with a maximum of 660W was given. Secondly, considering the heat loss at the heat pipe evaporator, the power of the heater in the experiment with a maximum of 925W was imposed.

Table II: Simulation Evaporator Boundary conditions

Evaporator B.C.	B.C.1.	B.C.2.
Phenomena	Heat input	Heat input + Radiative heat loss
Max. power	660W	925W
Max. radiative heat removal rate from the Evaporator	0W	265W
Max. radiative heat removal rate from the Condenser	660W	660W

2.4 Simulation results

Figure 3 shows the simulation results with boundary condition 1. For the condenser wall temperature, the simulation closely matched the experimental results. However, the evaporator wall temperatures exhibit different profiles in specific regions. Compared to the experimental results, during the start-up and shut-down processes, the simulation shows an overshoot in the evaporator wall temperature results. This is because the condenser wick-vapor interface temperature, which is proportional to the vapor heat transfer rate, makes proper vapor heat transfer difficult at low condenser temperatures. As a result, heat accumulates during the start-up process and the evaporator temperature decreases slowly during the shut-down process, particularly after 5 hours.

Figure 4 displays the vapor heat transfer rate and heat pipe limit results. As expected, before 1 hour and after 5 hours, heat is transferred solely through conduction, with no vapor heat transfer occurring. During the overshoot region of the start-up process, around 1 hour, the vapor heat transfer rate exceeds the viscous limit and then decreases. This indicates that improvements are needed in the viscous limit region.

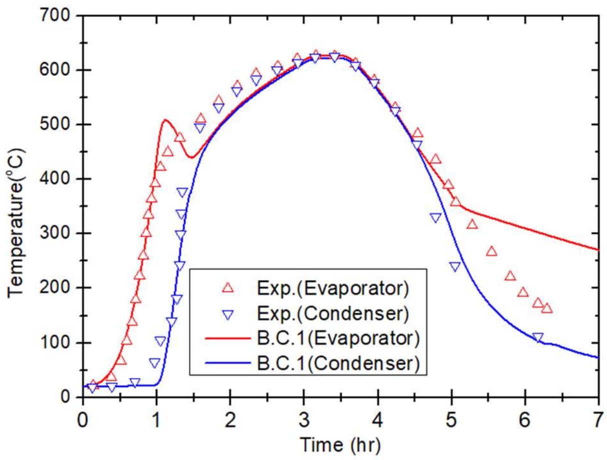

Fig. 3. Simulated wall temperature results with B.C.1

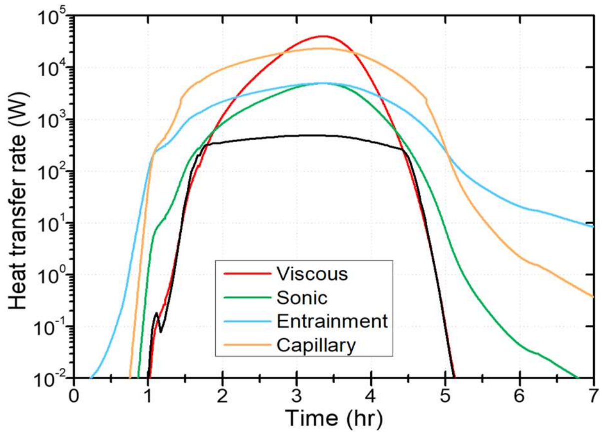

Fig. 4. Simulated vapor heat transfer rate and limit results with B.C.1

Figure 5 displays the simulation results with boundary condition 2, considering radiative heat transfer from the evaporator. After 5 hours, we observe that the evaporator temperature decreases properly due to radiative heat transfer, closely matching the experimental results.

However, during the start-up process, the wall temperature increases faster compared to the results of Boundary Condition 1. This is because, during the start-up process, the temperature of the heat pipe is relatively low, and the effect of the power increase becomes the dominant factor influencing the temperature profile. With more accurate modeling of the cartridge heater and the structure's heat capacity terms, boundary condition 2 yields more accurate results. Nevertheless, in both conditions, the simulation results exhibit an overshoot in temperature in the start-up region.

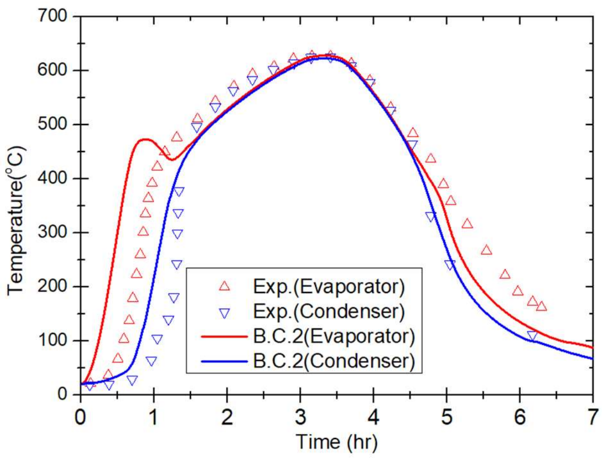

Fig. 5. Simulated wall temperature results with B.C.2

3. Conclusions

In this paper, we validated the experimental results of the SAFE-30 experiment to evaluate an augmented heat pipe code with added start-up/shut-down models. The simulation results confirmed that the inclusion of start-up/shut-down models yielded better temperature behavior predictions during the start-up/shut-down phase compared to conventional analyses. However, it was observed that the model tended to overpredict the evaporator temperature when reaching its limit during start-up, indicating the need for further refinement.

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