Preliminary Development of Alkali Metal Heat Pipe Code for Microreactor Transient Analysis

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1. Introduction

Recently, various researches on heat pipe cooled microreactors such as Megapower [1], Aurora [2], and eVinci [3] have been studied. The heat pipe cooled microreactor has a core that is comprised of fuel rods and heat pipes embedded in a solid structure which is called a monolith. The heat pipe is a passive heat transfer device driven by capillary force and is used to transfer the heat from the core to an energy conversion system. By replacing pumps and valves with heat pipes, compact design and mobility can be achieved [4].

However, the heat pipe cooled microreactors have several safety issues on core design. The thermal stress of the monolith due to the temperature gradient leads to structural failure and the thermal expansion of the steel monolith induces the reactivity feedback [5]. Therefore, a multi-physics analysis including thermal-structural-neutronics analysis is required to ensure the integrity of the reactor core.

In the previous study, a multi-physics analysis system was established with coupling thermal-structural analysis code and neutronics code [6]. The heat pipe was analyzed with ANL/HTP code which is a 1-D steady-state heat pipe analysis code developed by Argonne National Laboratory(ANL) [7]. However, the ANL/HTP cannot reflect axial heat conduction and non-uniform heat flux. Moreover, ANL/HTP can applicable to transient analysis only with the quasi-steady-state assumptions. Hence, to analyze the reactor core more realistic, 2-D and transient analysis of the heat pipe should be considered.

In this research, a preliminary alkali metal heat pipe code was developed based on Saad's 2-D transient water-copper heat pipe analysis code [8], and the code validation was performed.

2. Reproduction of water heat pipe code

2.1 Numerical Model

Saad proposed a model to simulate the 2-D transient operation of a heat pipe considering non-uniform boundary conditions, non-condensable gases, and surrounding media. The transient model consisted of a simple thermal resistance network. The governing equations were simplified to a set of first-order ordinary differential equations that can be solved fast using a simple network model. Saad described that this simplified model had a good agreement with Cao and Faghri's 2-D numerical model [9] with only 5 % of the computational time compared to the Cao and Faghri's model.

In this study, a water heat pipe code was reproduced based on Saad's research. Figure 1 shows a thermal resistance network model. The network model has a number of meshes in the radial and axial directions in the wick and wall region. But a single mesh is used for the vapor core region.

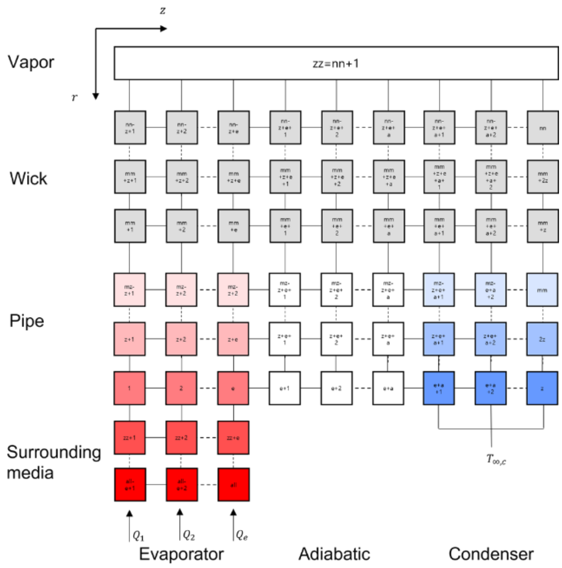

Figure 1. The thermal resistance network model

The heat source is located on the outer surface of surrounding media and the bulk temperature and heat transfer coefficient were used as the boundary conditions. Eq. (1) is the governing equation of the transient thermal resistance network model.

$$\frac{dT_i}{dt} = \frac{2}{\rho_i c_{p,i} V_i}\left[\frac{(T_{i,a} + T_{i,b} - 2T_i)}{R_{z,i}} + \frac{(T_{i,c} + T_{i,c} - 2T_i)}{R_{r,i}}\right] \quad (1)$$

where ρ_i: density, $c_{p,i}$: heat capacity, V_i: volume.

Eqs. (2)-(5) are thermal resistance used in this simulation. Eqs. (2) and (3) are the radial and axial thermal resistances, respectively, for surrounding media, wick, and wall. Eq. (4) is the thermal resistance for vapor. It was obtained from the Clausius-Clapeyron equation which is the relation between the saturation pressure of the working fluid and the temperature change [10]. Thus, it was calculated through Eqs. (6)-(8). The specific volume of fluid was neglected in Eq. (7) because it is much smaller than vapor. The thermal resistance of the interface between the wick and vapor where the evaporation and the condensation occur was neglected because it has a very low value, relatively. Eq. (5) is the thermal resistance for the condenser.

$$R_r = \frac{\ln(r_{i,o}/r_{i,i})}{2\pi L_i k_i} \tag{2}$$

$$R_z = \frac{L_i}{\pi(r_{i,o}^2 - r_{i,i}^2)k_i} \tag{3}$$

$$R_v = \frac{T_v(P_{v,e} - P_{v,c})}{\rho_v h_{fg} Q} \tag{4}$$

$$R_c = \frac{1}{2\pi r_{i,o} L_i h_c} \tag{5}$$

where $r_{i,o}$: inner radius, $r_{o,o}$: outer radius, L_i: length, k_i: thermal conductivity, T_v : temperature of vapor, P_v : pressure of vapor, ρ_v : density, h_{fg} : latent heat of vaporization, Q : transferred heat, h_c : heat transfer coefficient.

$$\frac{dP_s}{dT} = \frac{1}{T}\frac{h_g - h_f}{v_g - v_f} \tag{6}$$

$$\Delta T = T_v \frac{v_g - v_f}{h_g - h_f}\Delta P = T_v \frac{v_g}{h_g - h_v}\Delta P \tag{7}$$

$$\Delta T = \left(\frac{T_v}{\rho_g h_{fg} Q}\Delta P\right) Q = R_v Q \tag{8}$$

where P_s : saturation pressure, T : saturation temperature, h_g : enthalpy of saturated vapor, h_f : enthalpy of saturated liquid, v_g : specific volume of saturated vapor, v_f : specific volume of saturated vapor, T_v: temperature of vapor, ρ_g: density, h_{fg}: latent heat of vaporization, Q: transferred heat.

The reproduced network model was a set of first-order linear ordinary differential equations. The equation was solved using the ode15s function given by MATLAB. The ode15s function is based on a variable step method and a numerical differentiation formula.

2.2 Verification and Validation

The verification and validation of the reproduced model were performed by comparing with Saad's predictions and experimental data. The experiment was conducted for the water heat pipe with a screen wick. The heat pipe is heated by the rope heater and condensed by the water cooling jacket. The geometry of the heat pipe is provided in Table 1.

Simulations were performed for two cases. The first case is that the heat pipe was heated to 100 W for 2000 seconds to simulate the effect of the axial heat transfer. The other case is that the heat pipe was heated to 100 W from 0 to 3000 seconds and the heat was removed after 3000 seconds to simulate transient performance.

Figure 2 shows the heat pipe surface temperature of the reproduced model, Saad's prediction, and experimental results for the first case. It shows the significant effect of the axial heat transfer in the heat. Figure 3 shows the heat pipe evaporator, condenser surface temperature, and vapor temperature of the reproduced model, Saad's prediction, and experimental data. It shows good agreement with predictions and experimental results.

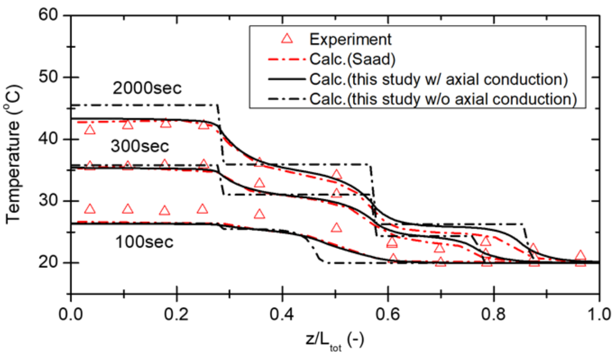

Figure 2. The result of surface temperature for 100sec, 300sec, and 2000sec

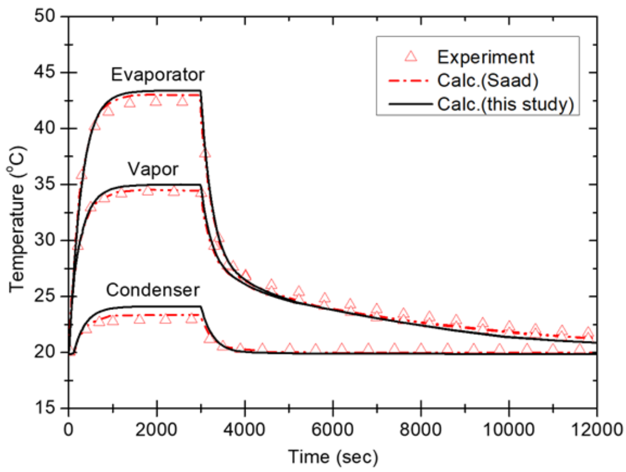

Figure 3. The result of temperature transient in evaporator, vapor, and condenser

Table 1. Geometry information of the heat pipe

Parameter	Value
Heat pipe length (m)	0.3556
Evaporator length (m)	0.1016
Adiabatic length (m)	0.1016
Condenser length (m)	0.1524
Heat pipe outer diameter (m)	0.01905
Heat pipe inner diameter (m)	0.01575
Wick type	Screen
Mesh number (m^{-1})	3937
Wire diameter (μm)	109.22
Wick thickness (μm)	655.32

3. Extension to alkali metal heat pipe code

3.1 Additional improvement

Next, the sodium properties were added to simulate an alkali metal heat pipe. It was obtained from LUHPIS code which is a heat pipe analysis code developed by KAERI [11]. The LUHPIS code is based on the lumped parameter model and quick thermal equilibrium assumption in the vapor. The code of this study is based on the 2-D mesh and transient calculation including the vapor. It can calculate the non-uniform power such as cosine shape power because of 2-D mesh. In addition, various types of wicks including grooved, sintered, and artery which is used to relieve pressure drop of liquid flow could be considered. For each wick model, the effective thermal conductivity, porosity, and permeability were added to predict temperature and operation limits.

3.2 Operation limits

The model of operation limits including capillary, viscous, sonic, entrainment, and boiling limit was added to simulate heat pipe performance [12]. Capillary limit occurs when the maximum capillary pressure was smaller than the total pressure drop in the heat pipe. The relation of the maximum capillary pressure was expressed as:

$$\Delta P_{c,max} \geq \Delta P_l(Q_{cap}) + \Delta P_v(Q_{cap}) \quad (9)$$

where $\Delta P_{c,max}$: maximum capillary pressure, ΔP_l : pressure drop of sodium liquid, ΔP_v: pressure drop of sodium vapor. The capillary limit was obtained for iterative calculations to satisfy Eq. (9).

Eqs. (10)-(13) are the model of operation limits including viscous, sonic, entrainment, boiling limit.

$$Q_{viscous} = \frac{d_v^2 A_v h_{fg}}{64\mu_v L_{eff}} \rho_v P_v \quad (10)$$

$$Q_{sonic} = A_v \rho_v h_{fg} \sqrt{\frac{\gamma R T_v}{2(\gamma + 1)}} \quad (11)$$

$$Q_{entrainment} = A_v h_{fg} \sqrt{\frac{\sigma \rho_v}{2r_h}} \quad (12)$$

$$Q_{boiling} = \frac{2\pi L_e k_{eff} T_v}{h_{fg} \rho_v \ln\left(\frac{r_o}{r_i}\right)} \left(\frac{2\sigma}{r_n} - \frac{2\sigma}{r_c}\right) \quad (13)$$

where d_v: diameter of vapor flow, A_v: area of vapor flow, h_{fg}: latent heat, μ_v: vapor viscosity, L_{eff}: effective length, ρ_v: vapor density, P_v: vapor pressure, γ: heat capacity ratio, R: gas constant, T_v: vapor temperature, σ: surface tension, r_h: hydraulic radius of wick porous, L_e: length of evaporator, k_{eff}: effective thermal conductivity of wick, T_v: vapor temperature, r_o: the outer radius of wick, r_i: inner radius of wick, r_n: radius of nucleation, r_c: radius of capillary. In this study, $r_n = 0.254\ \mu m$ was adopted.

4. Validation result and discussion

4.1 ANL experiment

The validation of the present study in a steady-state was conducted by comparing with ANL's HPTF experiment results [13]. The experiment was performed to analyze a sodium heat pipe performance for a space environment. The 0.7 m long sodium heat pipe consisted of Incoloy800. The wick consisted of 2.5 wraps of SS304 100 mesh screen and 2 arteries with a diameter of 3.18 mm. Since the exact length of the adiabatic section and condenser was not provided, an estimated length was used in the simulation. The detailed information on the heat pipe is provided in Table 2. HPTF was heated by a radio-frequency induction heater and condensed by a gas-water calorimeter. The heat pipe was heated from 6.51 kW to 8.39 kW.

Figure 4 shows the surface temperature calculation result of the present study compared with the result of ANL/HTP and experiment. It seems a good agreement with ANL/HTP results within 5 K and experiment results. Figure 5 shows the operation limits of the present study compared with the results of ANL/HTP. The discrepancy in the viscous limit is due to different sodium properties such as a 20 % difference in vapor viscosity, and the sonic limit is due to the difference between the model used in the present study and ANL/HTP. The ANL report [7] described the model used in ANL/HTP predicts a sonic limit about 15 % lower than the model used in the present study.

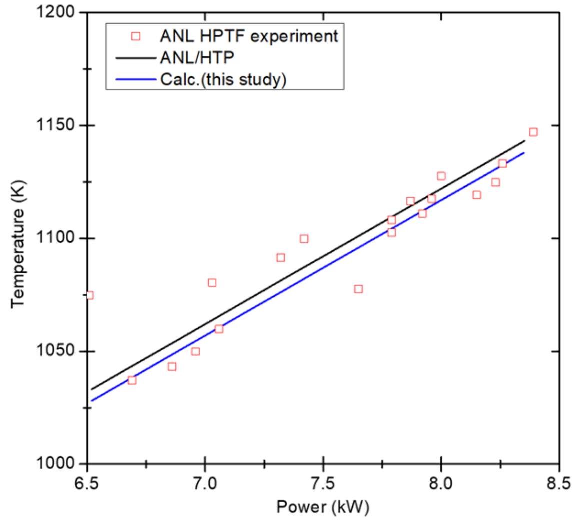

Figure 4. The result of evaporator surface temperature vs. power

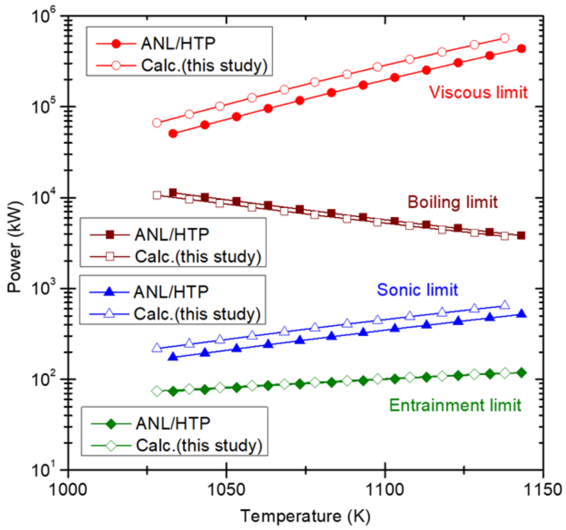

Figure 5. Comparison of ANL/HTP and calculated operation limits

Table 2. Geometry information of the heat pipe

Parameter	Value
Heat pipe length (m)	0.7
Evaporator length (m)	0.241
Adiabatic length (m)	0.281
Condenser length (m)	0.178
Heat pipe outer diameter (m)	0.0603
Heat pipe inner diameter (m)	0.0548
Wick type	Screen + Artery
Mesh number (m^{-1})	3937
Wire diameter (μm)	145
Wick thickness (μm)	870
Number of artery (#)	2
Artery diameter (mm)	3.18

4.2 LANL experiment

The validation of the present study about the transient response was conducted by comparing with the results of heat pipe modules for SAFE-30 reactor in Los Alamos National Laboratory designed for space fission system [14]. The length of the sodium heat pips is 1.2 m and the wick consisted of SS304L. The wick was fabricated of one support layer of 100 mesh screen, three capillary pumping layers of 400 mesh screen, and two liquid flow layers of 60 mesh screen. The detailed information on the heat pipe is provided in Table 3. In the experiment, the heat pipe was heated by an electrical cartridge heater and the heat source increased linearly by 80 W every 5 minutes for about 3 hours, maintained for about 30 minutes, and then gradually decreased to zero. The heat pipe was condensed by radiation surrounded by a water-cooled vacuum chamber. The maximum removed heat by radiation at the condenser was described as 660 W at the peak temperature of 900 K. In the simulation, this information was used to estimate the emissivity of radiation heat transfer. It was assumed that the heat source for the simulation increased linearly to 660 W for 3 hours, maintained for 30 minutes, and then decreased linearly.

Figure 6 shows the evaporator and condenser calculation result of the present study compared to experimental results. The peak temperature of the evaporator and transient response between 1 and 5 hours shows a good agreement. However, discrepancies in the start-up and shutdown operation are appeared due to the absence of a melting and solidification model in the vapor core. Figure 7 shows the heat transferred and operation limits. The boiling limit exists above the y axis range due to much higher than other limits. It seems that the heat transferred is below the operation limits during the simulation.

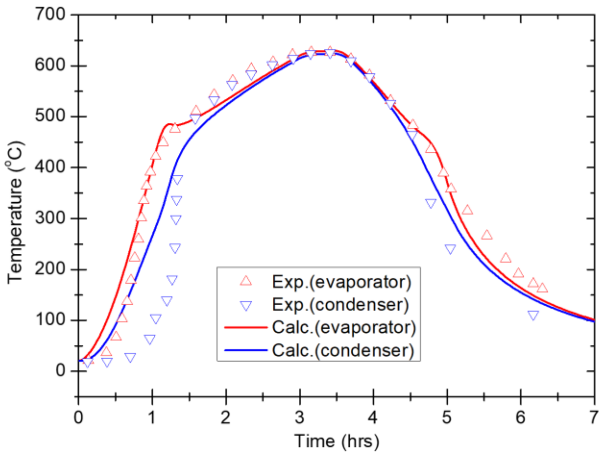

Figure 6. The result of temperature transient in evaporator and condenser

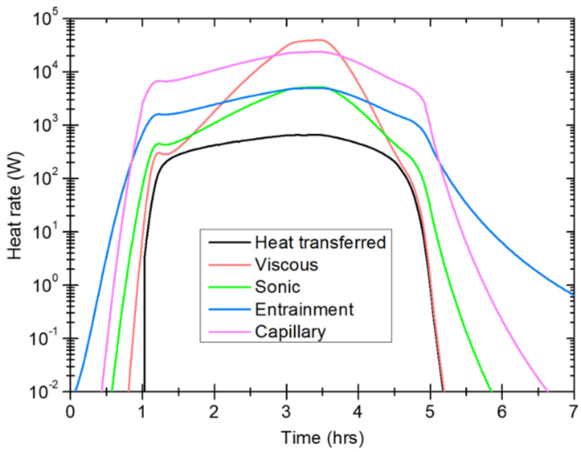

Figure 7. The result of heat transferred and operation limits

Table 3. Geometry information of the heat pipe

Parameter	Value
Heat pipe length (m)	1.2
Evaporator length (m)	0.43
Adiabatic length (m)	0
Condenser length (m)	0.77
Heat pipe outer diameter (m)	0.0254
Heat pipe inner diameter (m)	0.0221
Wick type	Screen + Artery
Wick outer diameter (m)	0.0207
Wick inner diameter (m)	0.0174
Effective pore radius (μm)	47

5. Conclusion

In this study, the water heat pipe code was reproduced based on Saad's work, and the code was extended to simulate the sodium heat pipe by adding the properties, various wick models, and model of operation limits. The validation calculations were conducted by comparing with experimental results in the steady-state and transient. The predicted transient behaviors of the heat pipes agreed well with the experimental data except for the start-up and the shutdown operation. The melting and solidification transition models should be implemented to simulate the start-up and shutdown transients.

6. Acknowledgments

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7. References

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