Numerical Simulation of Transient Behavior of Vapor-Liquid Distribution in a Loop Heat Pipe

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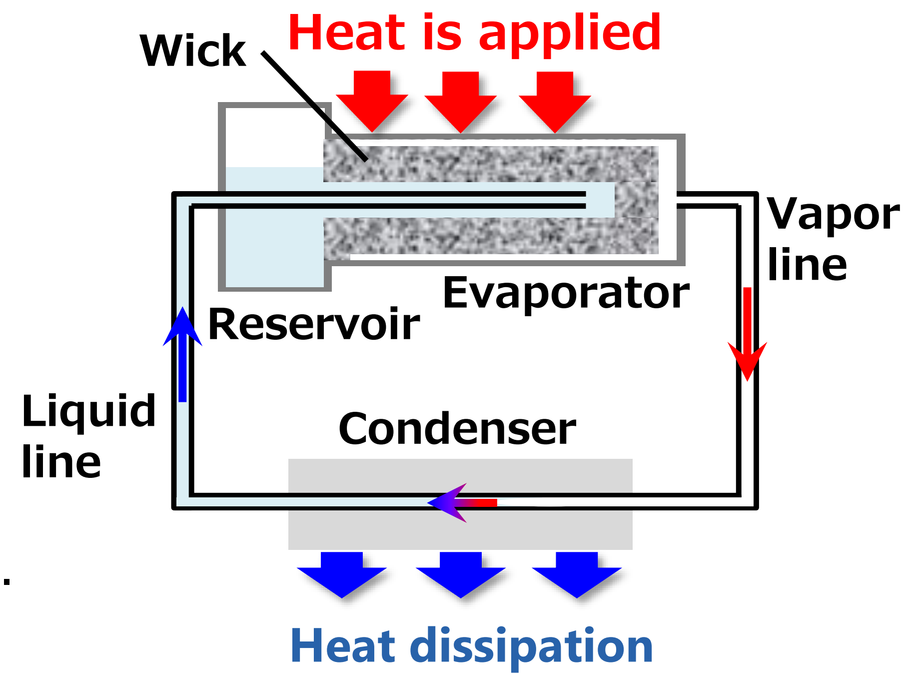
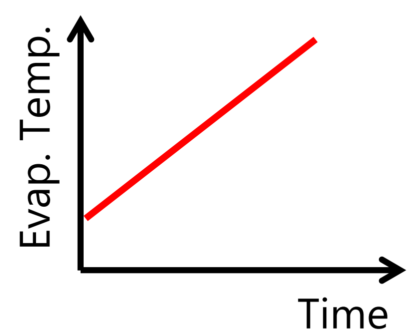
Loop heat pipe

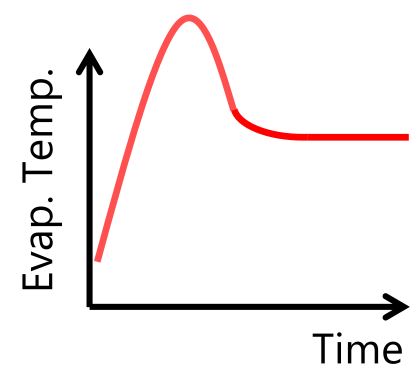
- Advantages
  - Heat transportation by the latent heat
    - Transporting a lot of heat
    - Long distance transport
  - Capillary force of the wick circulates the working fluid.
    - No electric power is required.
  - Shutdown
- Problem: <u>**Unstable Startup**</u>
  - Failure of startup
  - High temperature peak
  - Long time to convergence

Startup characteristics have to be understood.





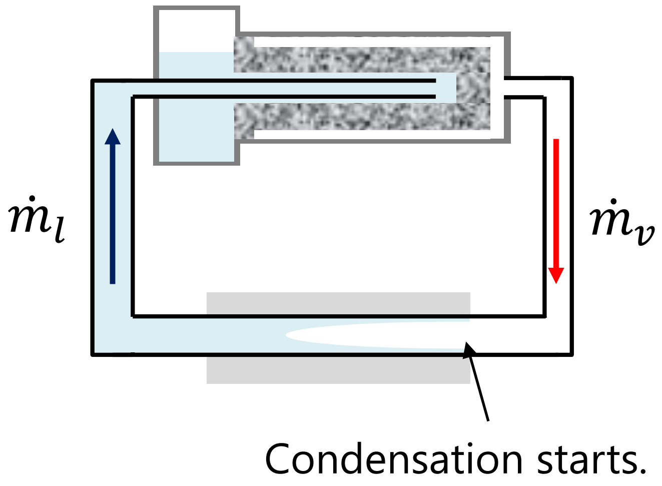
Failure of startup



High temp. peak

Previous study of numerical simulation

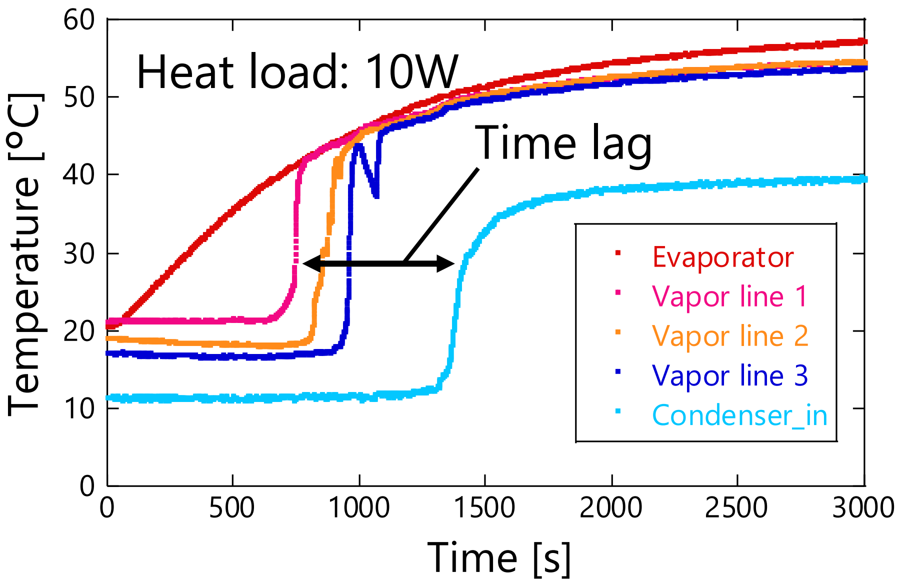
- Simplifying flow in transport lines
  - The mass flow rate in the vapor line and in the liquid line are respectively constant.
  - Condensation always starts at the condenser inlet.



As soon as evaporation occurs, the cond. inlet temp. would rise.

- Temperature distribution during startup cannot be accurately reproduced.

It is necessary to accurately reproduce the energy propagation in the transport lines.



Computational studies on condensation

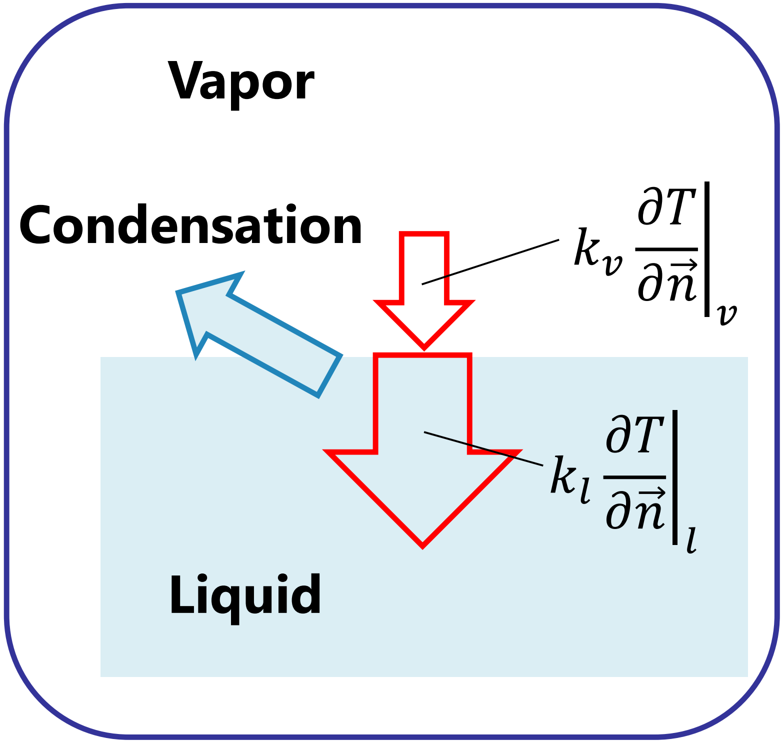
- Volume of fluid (VOF) method
  - Void fraction transport equation

$$\rho_v \frac{\partial \alpha_v}{\partial t} + \rho_v \frac{\partial (u\alpha_v)}{\partial x} = \underline{S_{\alpha_v}}$$

Mass source term

- Mass source term:
  Amount of phase-change

$$S_{\alpha_v} = \left(k_l \frac{\partial T}{\partial \vec{n}}\bigg|_l - k_v \frac{\partial T}{\partial \vec{n}}\bigg|_v \right) \frac{A_{int}}{h_{lv} \cdot V}$$



- Various condensation flow can be reproduced.
- Calculation cost is high.

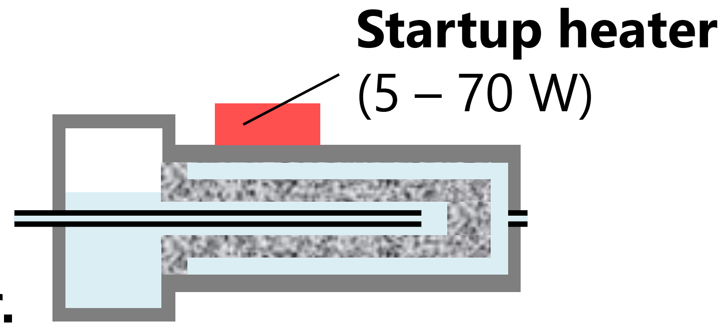
A_{int} : interface area
h_{lv} : latent heat
k : conductivity
T : temperature
u : velocity
α_v : void fraction
V : volume

One-dimensional modeling is required to investigate the startup characteristics.

Vapor-liquid distribution in transport lines

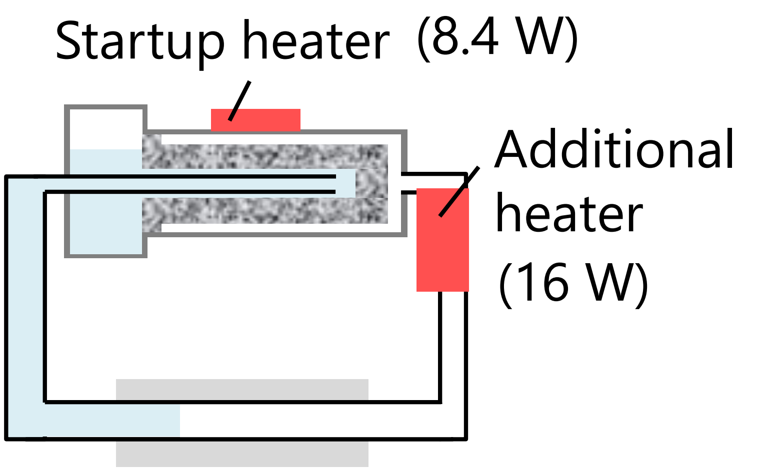
- General solution of startup failure
  - The startup heater is attached to the evaporator.

→ **Nucleation boiling is easy to occur.**



- Failure of startup heater
  - The additional startup heater is required on the vapor line to start the LHP's operation

→ **Vapor-liquid distribution in the transport lines would affect the startup characteristics.**



The model that can investigate the influence of the vapor-liquid distribution in the transport lines is necessary to understand startup characteristics.

Objective

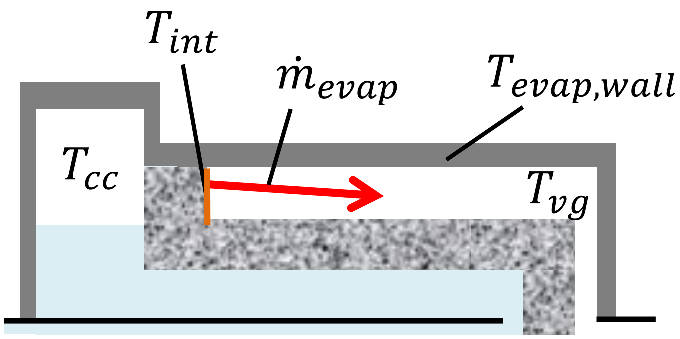
Developing the one-dimensional model of an LHP to investigate the startup characteristics.

- Reproducing the accurate energy propagation in the transport lines by using the Volume of fluid method.
- Modeling the condensation in one dimension.

Numerical model

Evaporator and reservoir model

- Evaporator
  - The evaporation occurs as soon as heat is applied.
- Reservoir
  - Fluid is always saturated.
  - Amount of liquid in reservoir is the remainder of liquid in the transport lines.



- Amount of evaporation
  - Tanasawa's simplified model

$$\dot{m}_{evap} = \frac{2\gamma}{2-\gamma}\sqrt{\frac{M}{2\pi R}}\left[\frac{\rho_v h_{lv}\left(T_{vg} - T_{int}\right)}{{T_{sat}}^{3/2}}\right]$$

- $\gamma = 0.01$ is used for the calculation.
- T_{int}: vapor-liquid interface temperature

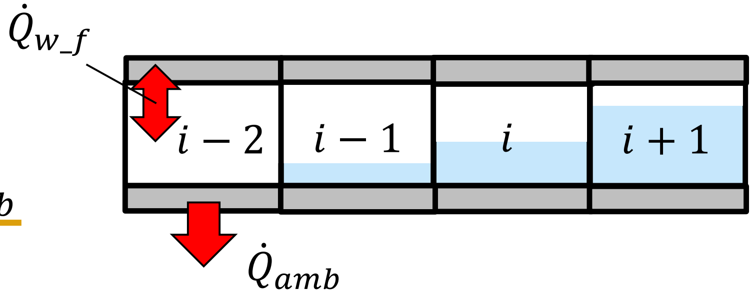
$$T_{int} = T_{sat}(P_{vg})$$

$\dot{m}_{evap}$	: amount of evaporation [kg/s]
γ	: accommodation coefficient
$T_{evap,wall}$	: evap. wall temp. [K]
T_{int}	: interface temp. [K]
h_{lv}	: latent heat [J/kg]
h_{evap}	: heat transfer coef. [W/(m^2*K)]
A_{wick}	: contact area [m^2]
M	: molecular weight [kg/mol]
R	: gas constant [J/K/mol]

Governing equation for transport lines

- Heat conduction equation

$$\rho_{wall} c_{p_{wall}} \frac{\partial T_{wall}}{\partial t} = k_{wall} \frac{\partial^2 T_{wall}}{\partial x^2} - \underline{\dot{Q}_{w\_f}} + \underline{\dot{Q}_{amb}}$$



- Momentum conservation equation

$$\frac{\partial(\rho_f u)}{\partial t} + \frac{\partial(\rho_f u u)}{\partial x} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\mu_f \frac{\partial u}{\partial x}\right) - \underline{\frac{\xi}{d_{in}} \frac{1}{2} \rho_f u_i^2}$$

Pressure drop

  - Mass conservation

$$\frac{\partial(\rho_f u)}{\partial x} = 0$$

- Energy conservation equation

$$\rho_f c_{p_f} \frac{\partial T_f}{\partial t} + \rho_f c_{p_f} \frac{\partial T_f}{\partial x} = \frac{\partial}{\partial x}\left(k_f \frac{\partial T_f}{\partial x}\right) + \dot{Q}_{w\_f} + \underline{S_v \cdot h_{lv}}$$

Heat generation by phase change

Nomenclature

c_p : specific heat [kg/m²/s]
d_{in} : diameter [m]
h_{lv} : latent heat [J/kg]
k : thermal conductivity [W/(m·K)]
p : pressure [Pa]
$\dot{Q}$: heat flow [W/m³]
T : temperature [K]
u : velosity [m/s]
μ : viscosity [Pa·s]
ξ : Darcy friction coefficient [-]
ρ : density [kg/m³]

Condensation model

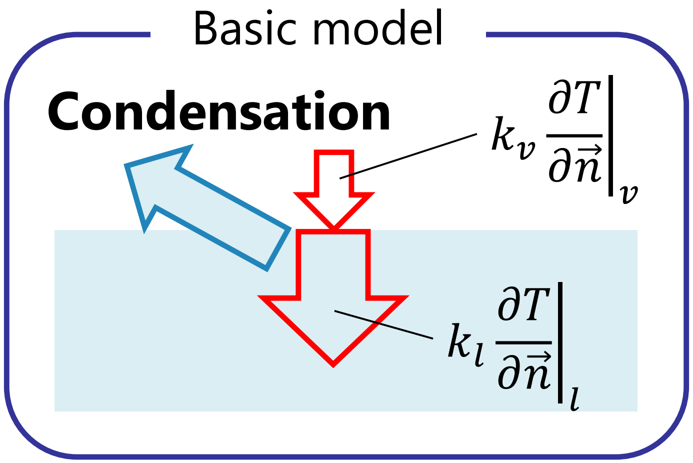
- Void fraction transport equation

$$\rho_v \frac{\partial \alpha_v}{\partial t} + \rho_v \frac{\partial (u\alpha_v)}{\partial x} = S_{\alpha_v}$$

A_{int} : interface area
h_{lv} : latent heat
k : conductivity
T : temperature
u : velocity
α_v : void fraction
V : volume

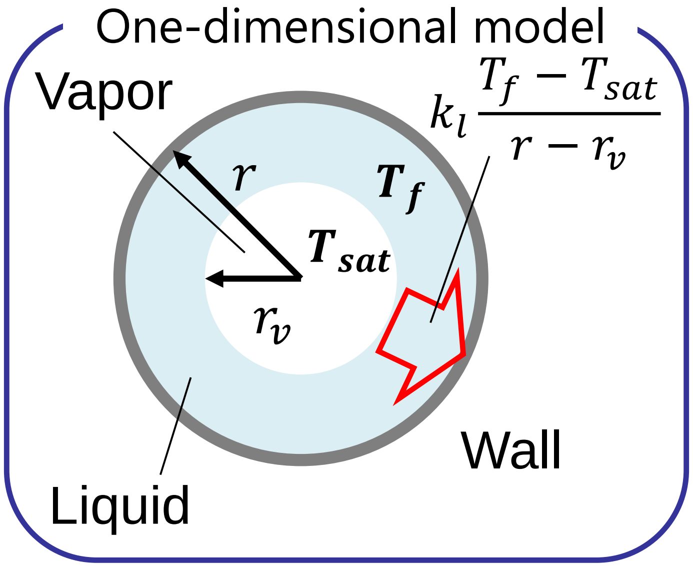
  - Amount of condensation

$$S_{\alpha_v} = \left(k_l \frac{\partial T}{\partial \vec{n}}\bigg|_l - k_v \frac{\partial T}{\partial \vec{n}}\bigg|_v \right) \frac{A_{int}}{h_{lv} \cdot V}$$

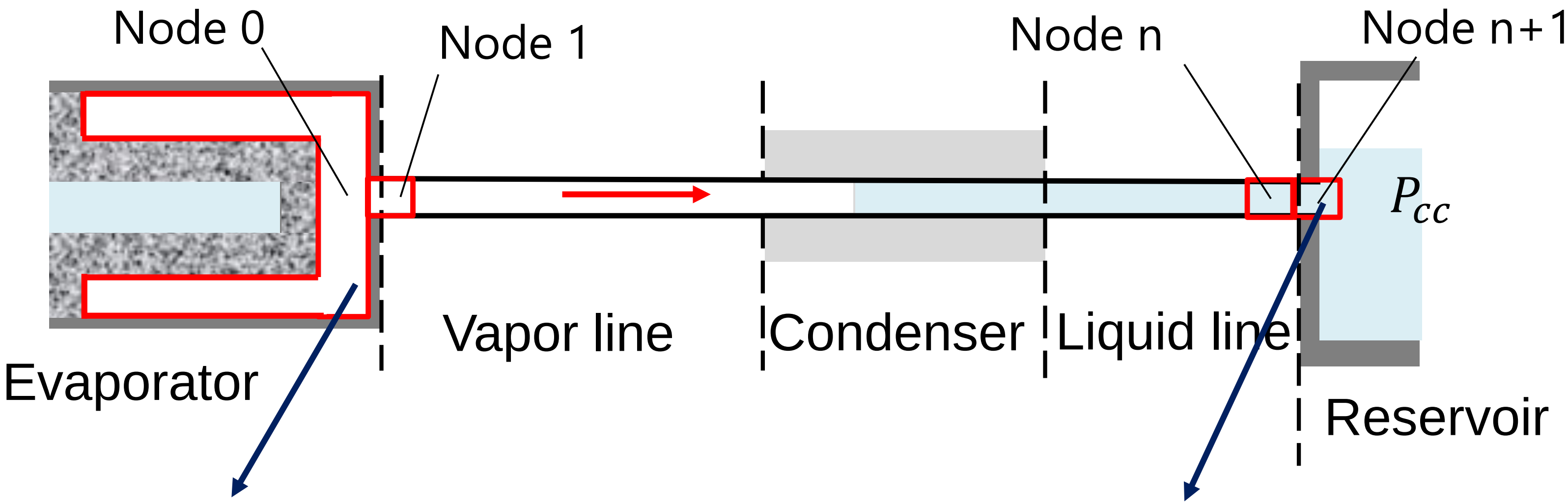


- One-dimensional model
  - Vapor: Saturation temperature based on pressure (T_{sat})
  - Liquid: Temperature from the energy equation (T_f)

$$S_{\alpha_v} = k_l \frac{T_f - T_{sat}}{r - r_v} \cdot \frac{A_{int}}{h_{lv} \cdot V}$$



Evaporator / transport lines boundary



$u_0 = u_{vg}$

- u_{vg} is calculated from $\dot{m}_{evap}$.

$P_0 = P_1$

$T_{wall,0} = T_{evap,wall}$

$T_{fluid,0} = T_{vg}$

$u_{n+1} = u_n$

$P_{n+1} = P_{cc}$

- P_{cc} is calculated as the saturation pressure.

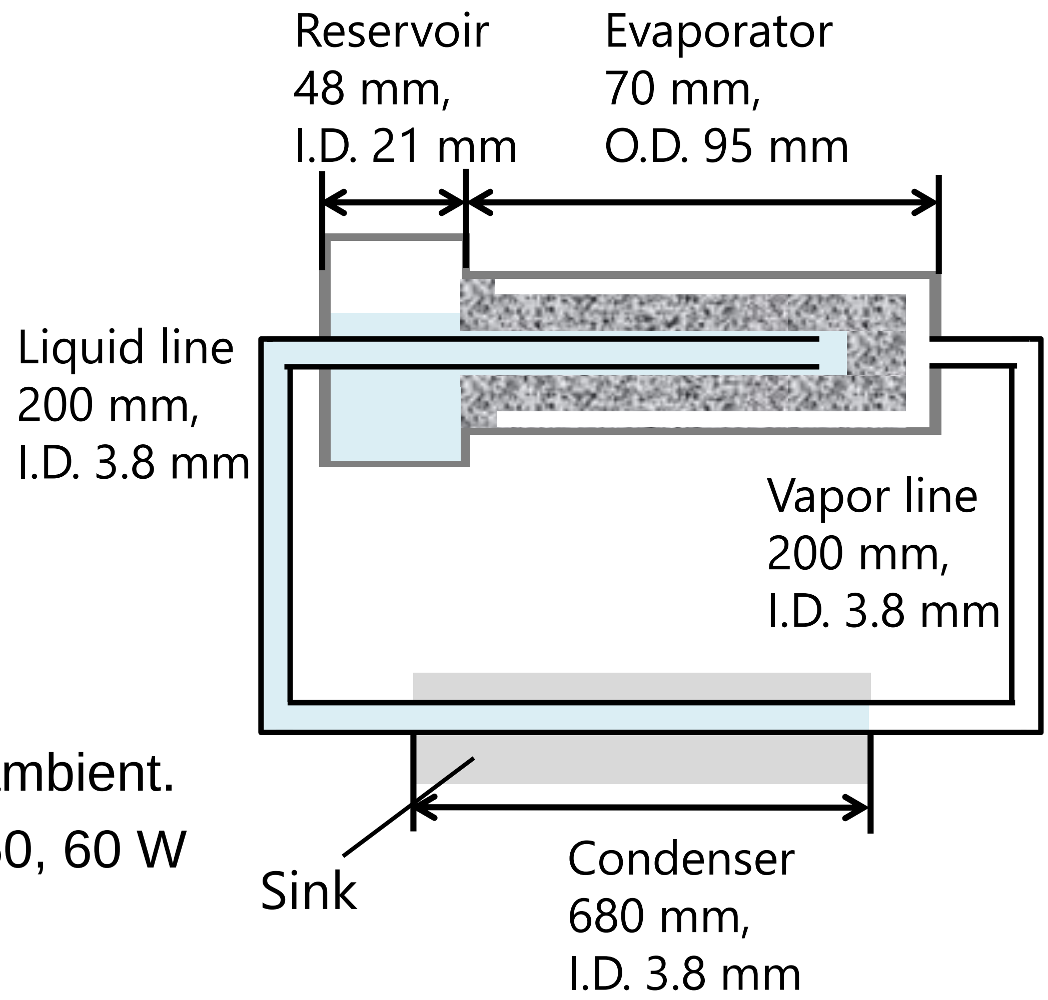
$T_{wall,n+1} = T_{cc}$

$T_{fluid,n+1} = T_{cc}$

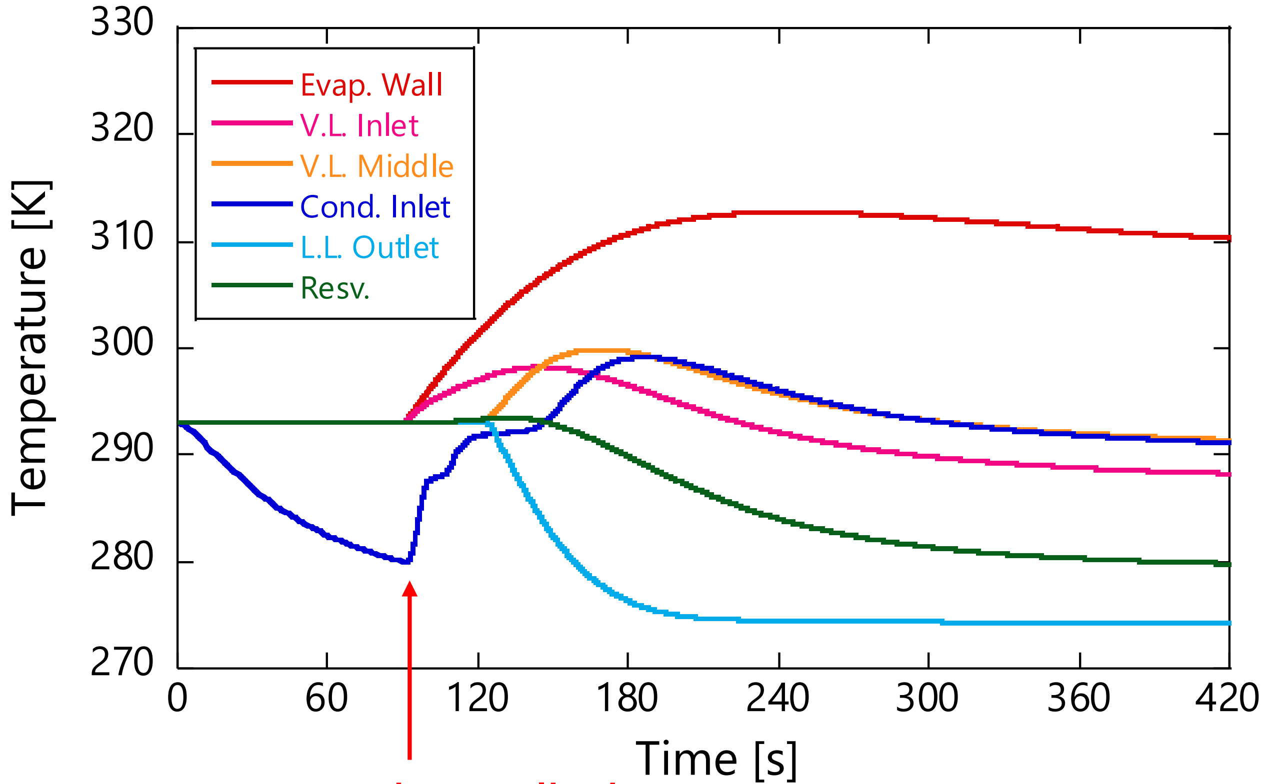
Calculation results

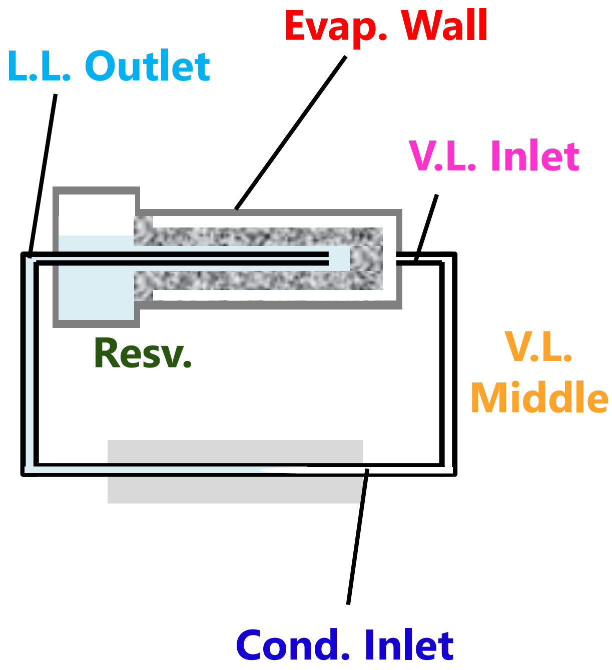
Calculation conditions

- Wick
  - PTFE wick
  - Pore diameter: 1 μm
  - Porosity: 0.5
- Working fluid
  - Acetone
  - Filling ratio: 50 vol.%
- Boundary condition
  - Sink temperature: 0 ºC
  - LHP is insulated from ambient.
  - Heat load: 10, 20, 40, 50, 60 W
- Initial condition
  - Initial temperature: 20 ºC



Fluid temperature ($\dot{Q}_{in} = 40$ W)

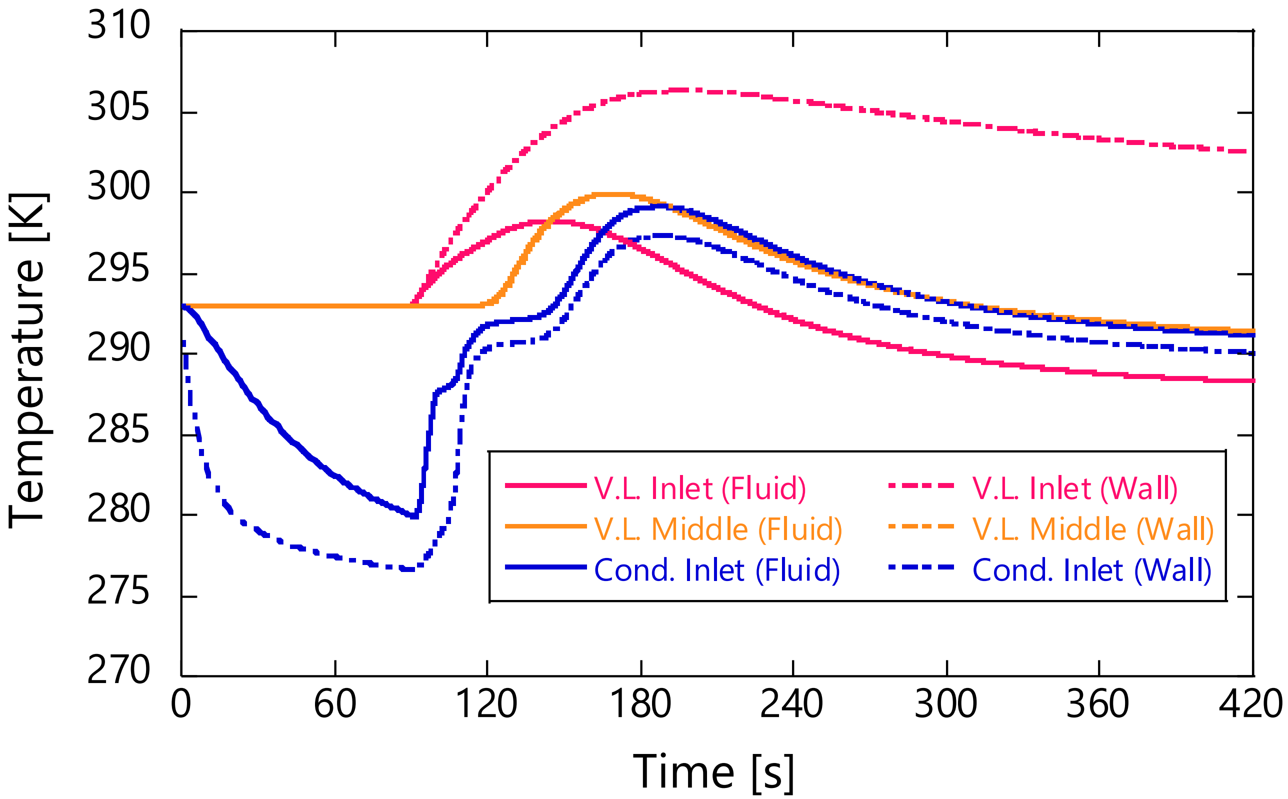




Heat is applied.

- There is a difference in the time when the temperature rises in the V.L.
- V.L. Inlet temperature is lower than Cond. Inlet temperature.

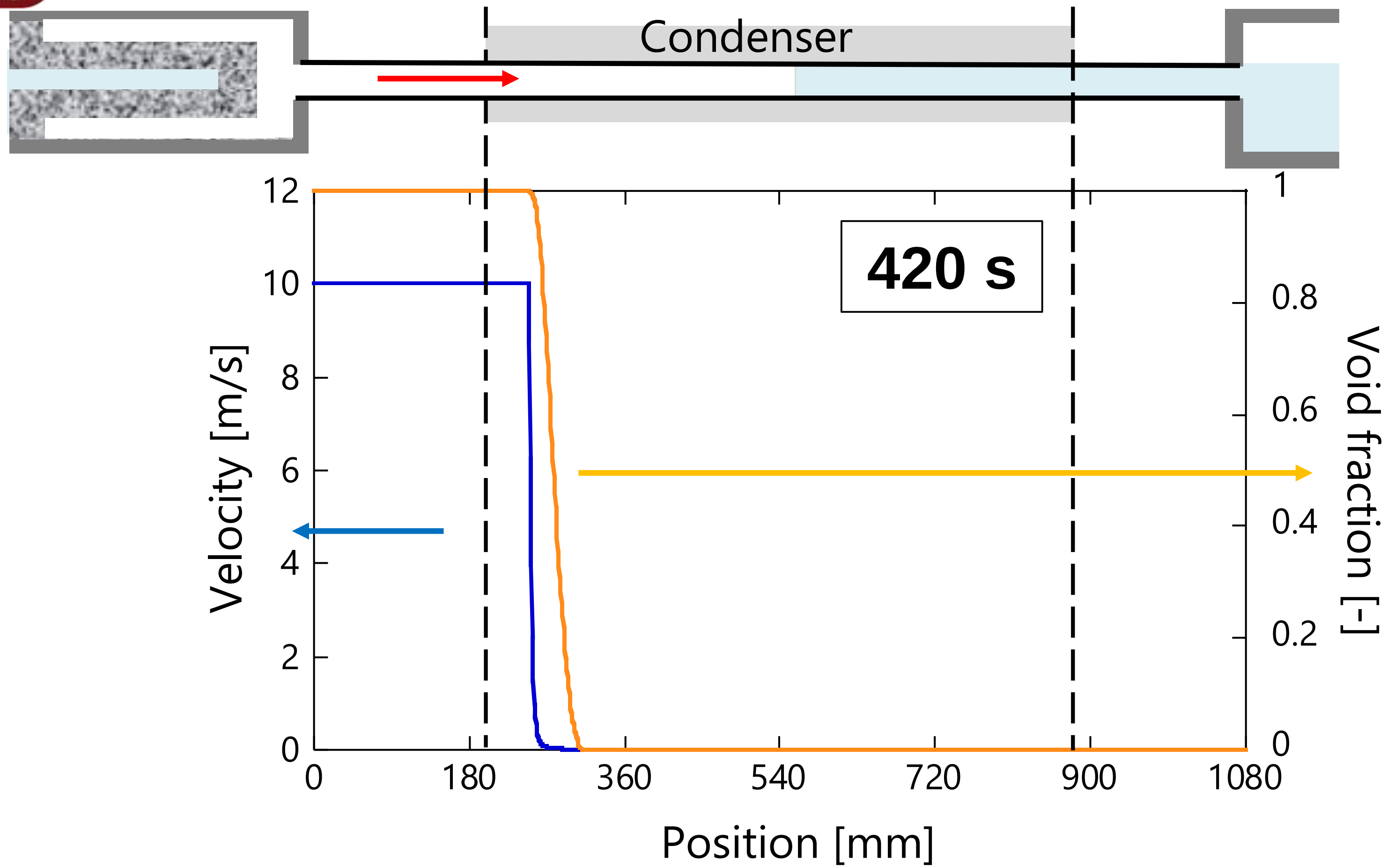
Time lag between fluid and wall



– There is a difference between the time when the wall temperature rises and the time when the fluid temperature rises at Cond. Inlet.
– Fluid temperature is the same as the wall temperature at V.L. Middle.

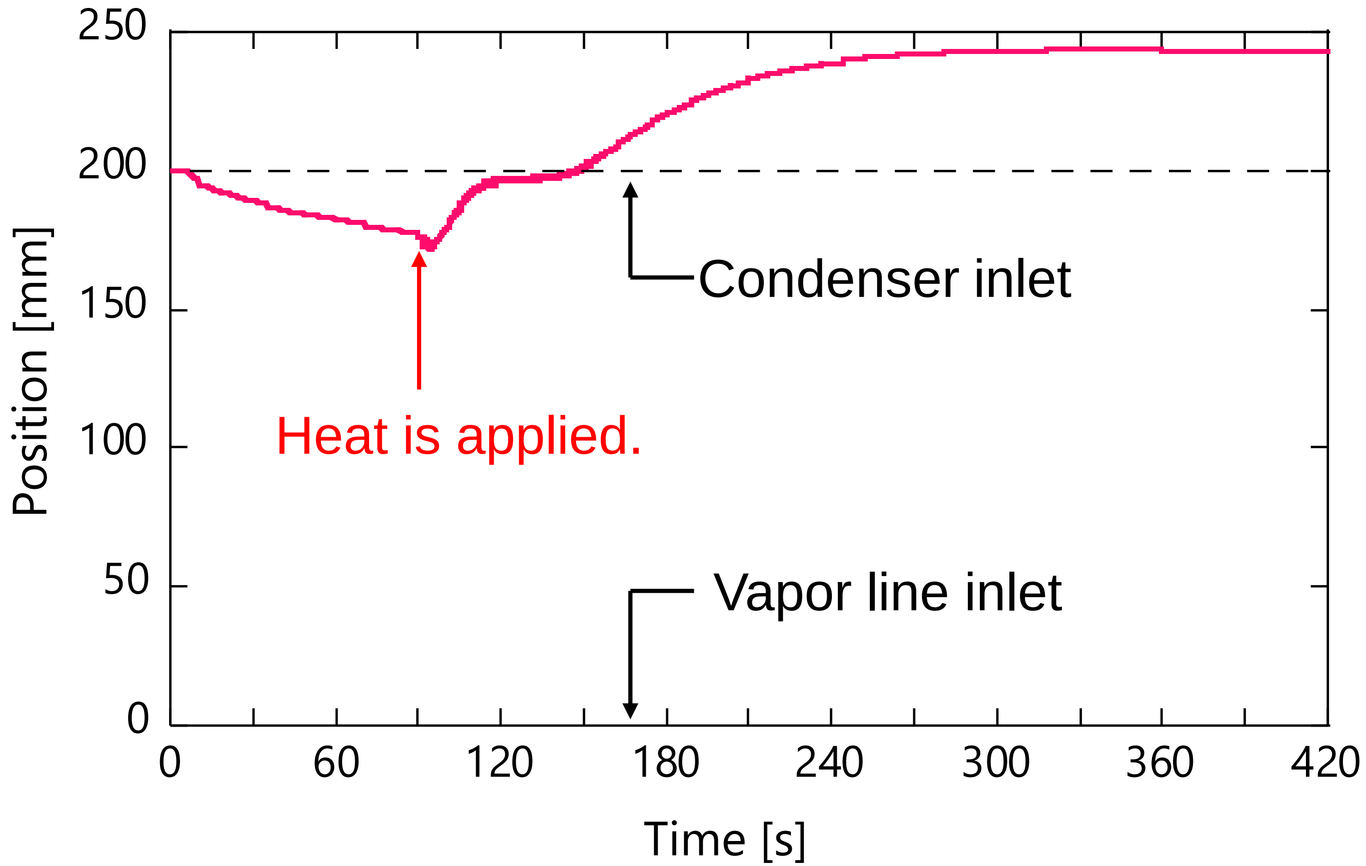
The cause of time lag is not heat capacity of the pipe wall.

Velocity and void fraction distribution



– Vapor penetrates the condenser.
– Vapor completely condenses in the condenser.
– Velocity of the vapor is almost constant.

The position where condensation starts

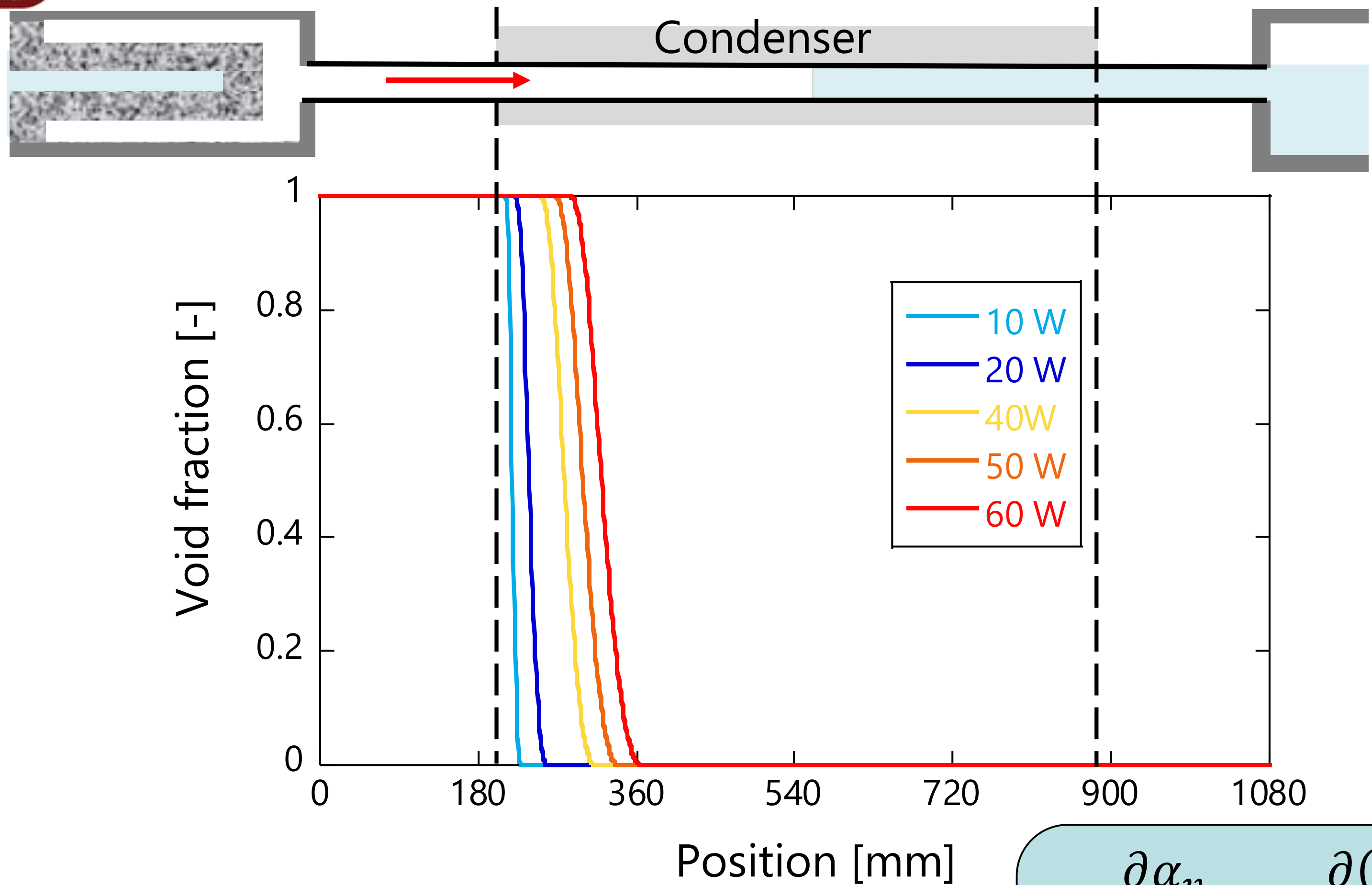


– Vapor is condensed in the condenser.

– Condensation does not start at the condenser inlet.

This model can investigate the position where condensation starts.

Void fraction distribution



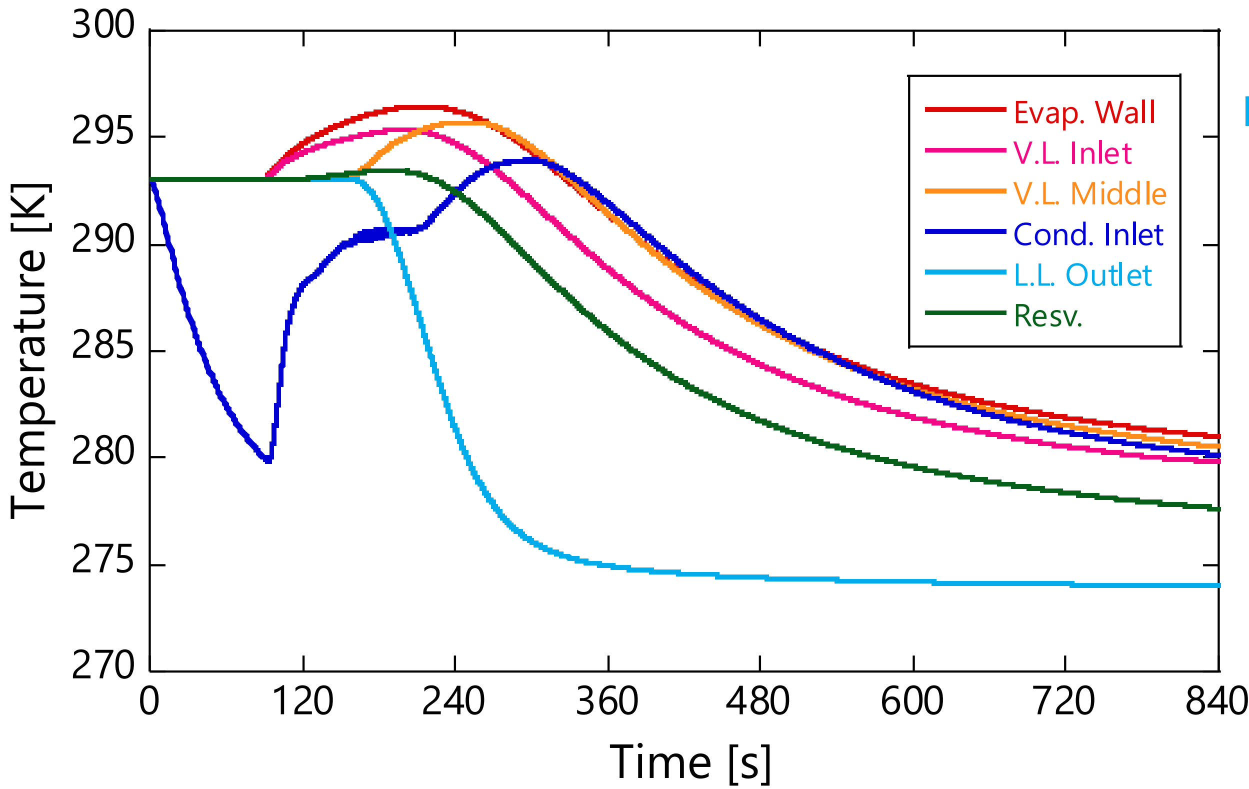
- The tilt of each heat load is almost same.
- Two-phase length is very short.

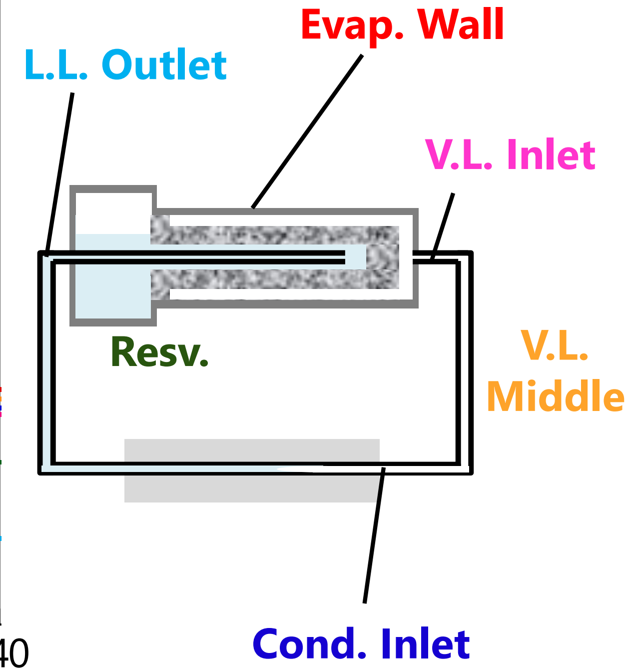
Mass source term should be revised.

$$\rho_v \frac{\partial \alpha_v}{\partial t} + \rho_v \frac{\partial (u \alpha_v)}{\partial x} = S_{\alpha_v}$$

$$S_{\alpha_v} = k_l \frac{T_f - T_{sat}}{r - r_v} \cdot \frac{A_{int}}{h_{lv} \cdot V}$$

Fluid temperature ($\dot{Q}_{in} = 10$ W)





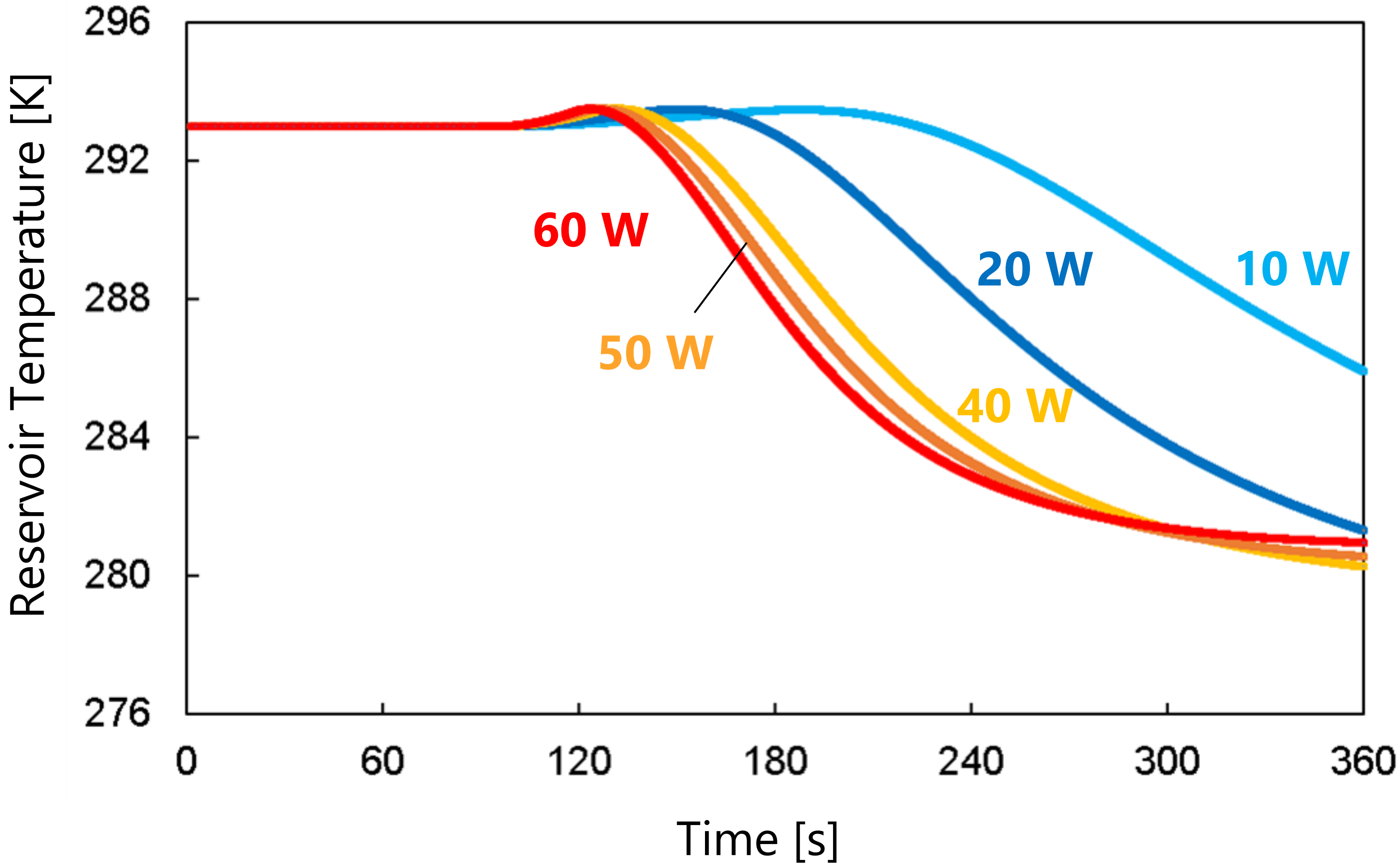
– Cond. inlet temperature becomes higher than Evap. wall temperature.

Cause: heat generation by phase change at Cond. inlet

$$\rho_f c_{p_f} \frac{\partial T_f}{\partial t} + \rho_f c_{p_f} \frac{\partial T_f}{\partial x} = \frac{\partial}{\partial x}\left(k_f \frac{\partial T_f}{\partial x}\right) + \dot{Q}_{w\_f} + \underline{S_v \cdot h_{lv}}$$

Condensation model needs modification.

Reservoir temperature



– Reservoir temperature decreases due to the returning liquid.
  - This tendency is not consistent with experiments.

Phase change in the reservoir should be modeled.

Conclusion

The one-dimensional model of an LHP was developed.

- Time lag can be reproduced.
- The change of the position where the condensation starts can be calculated.
- One-dimensional condensation model was proposed.

- Future works
  - Revising the condensation model
  - Considering the phase change in the reservoir
  - Validation