NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

Experiments and computations to address the safety case of heat pipe failures in Special Purpose Reactors

(NEUP Project 19-17416)

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MRP Microreactor Program
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Argonne NATIONAL LABORATORY

Introduction

- Special Purpose Reactor
- Operation of heat pipe
  - Viscous limit

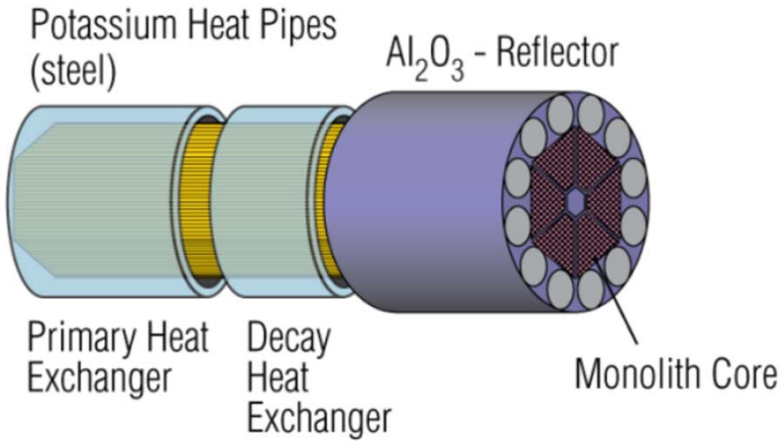
$$\dot{q}_v = \frac{d^2 h_{fg}}{64 \mu_v l_{eff}} \left(1 - \frac{P_1^2}{P_0^2}\right) \rho_0 P_0$$

  - Sonic limit

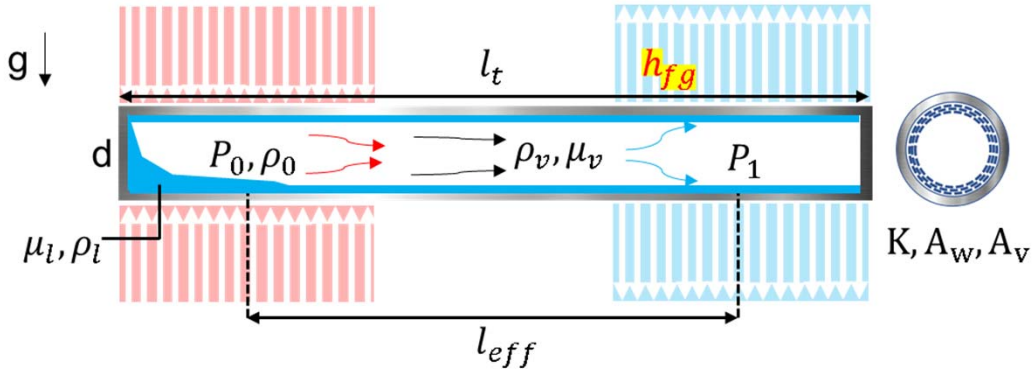
$$\dot{q}_s = 0.474 h_{fg} \sqrt{\rho_0 P_0}$$

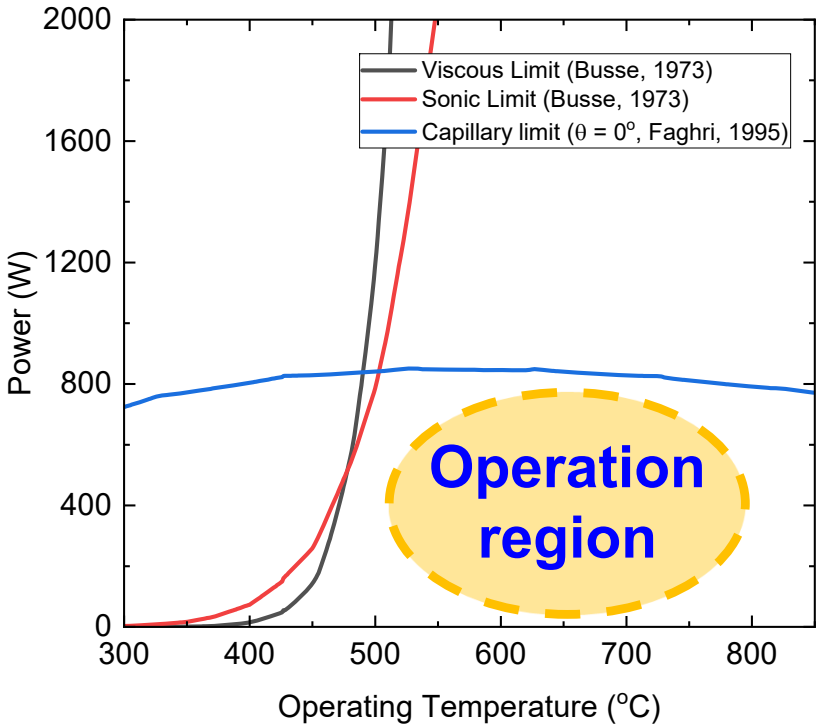
  - Capillary limit

$$\dot{q}_c = \frac{\sigma_l \rho_l h_{fg}}{\mu_l} \frac{K A_w}{l_{eff}} \left(\frac{2}{r_{eff}} - \frac{\rho_l g l_t \cos\theta}{\sigma_l}\right)$$



Special Purpose Reactor

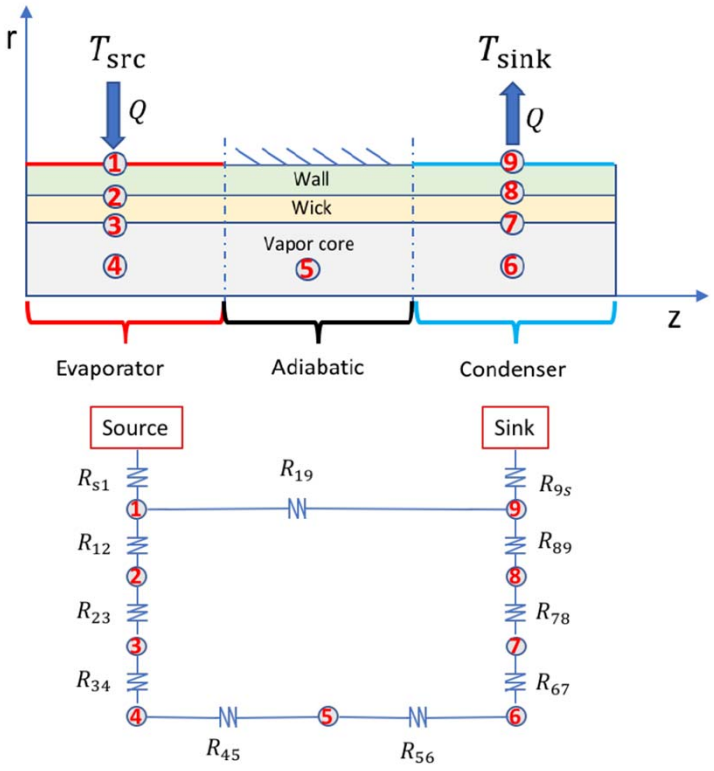




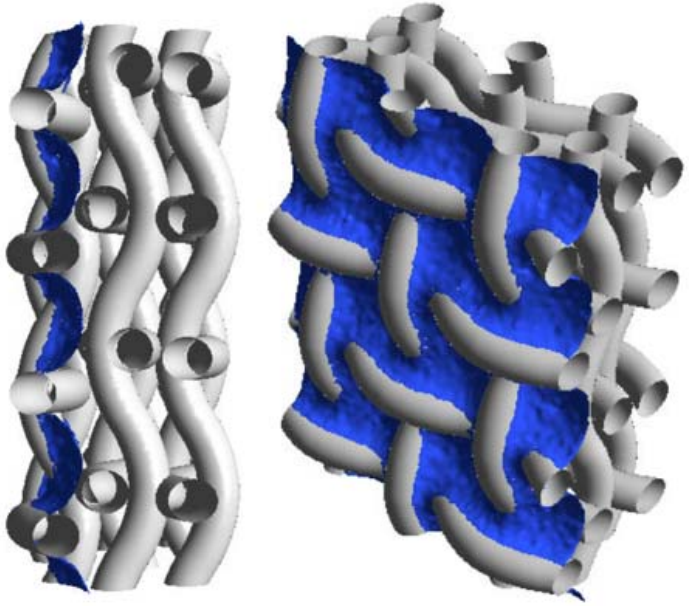
MRP Microreactor Program

Introduction

- Issues remaining for the licensing of microreactors
  - The heat pipe modeling is either over-simplified or too expensive
- Knowledge gaps
  - The two-phase flow phenomena in a heat pipe
  - The separate effects of a heat pipe
  - The integral study of heat pipes bundle



(Hu et al., 2019)

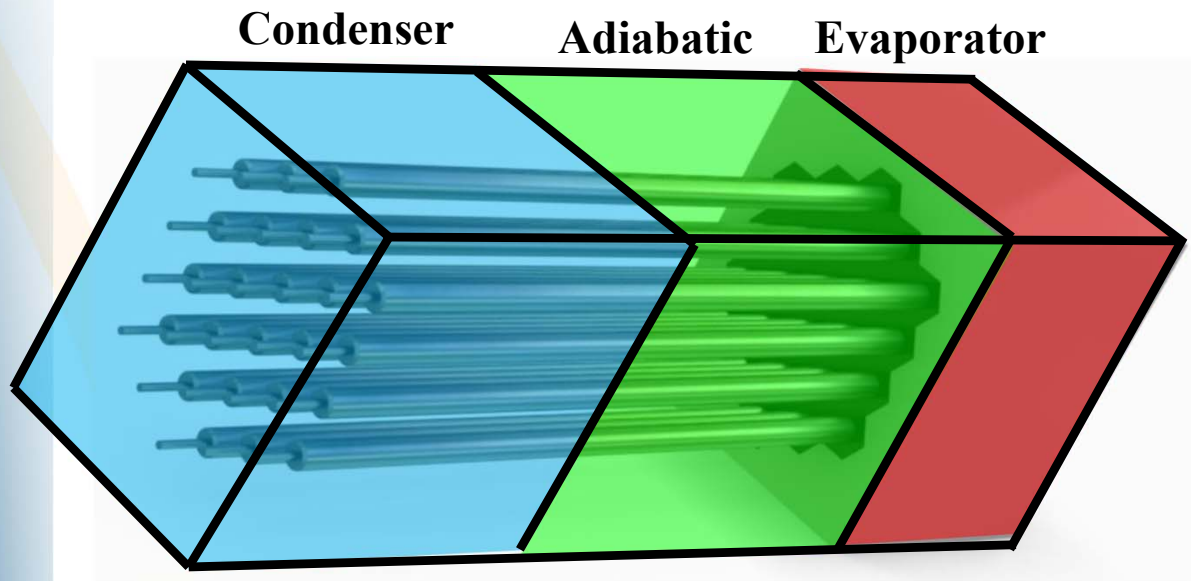


<Volume of Fluid (VOF) model>
(Dutra et al., 2022)

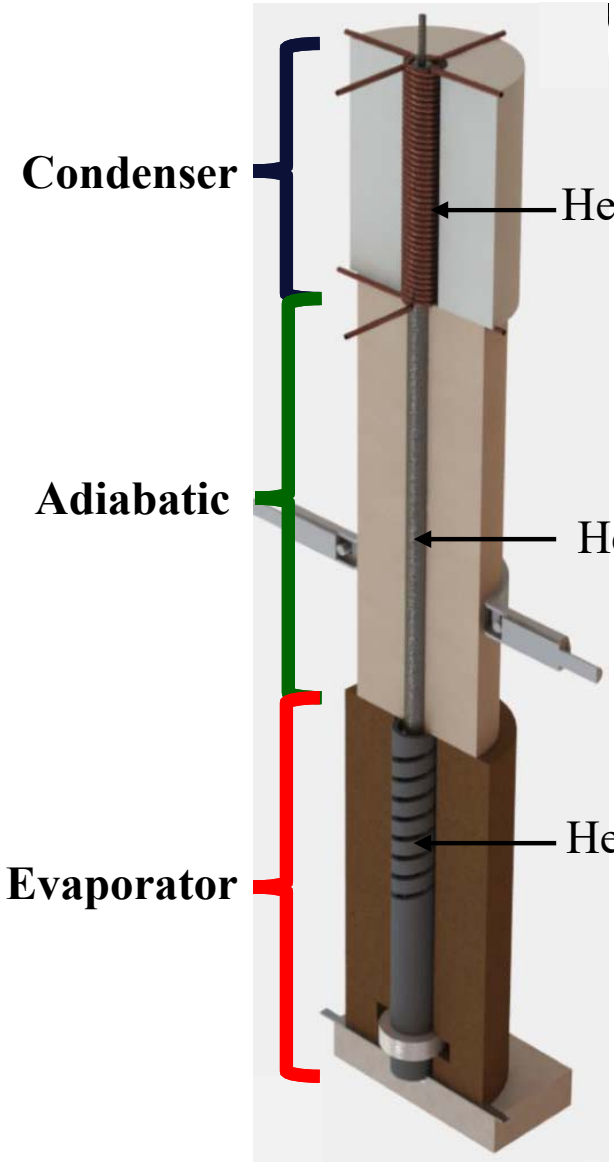
MRP Microreactor Program

Project goal

- Separate effect of sodium heat pipe
  - Visualization using X-ray radiography
  - Key parameter investigation
- Integral effect of heat pipes bundle
  - Operation under various conditions



<Test facility for integral effect of sodium heat pipe bundle>



<Test facility for separate effect of single sodium heat pipe>

MRP Microreactor Program

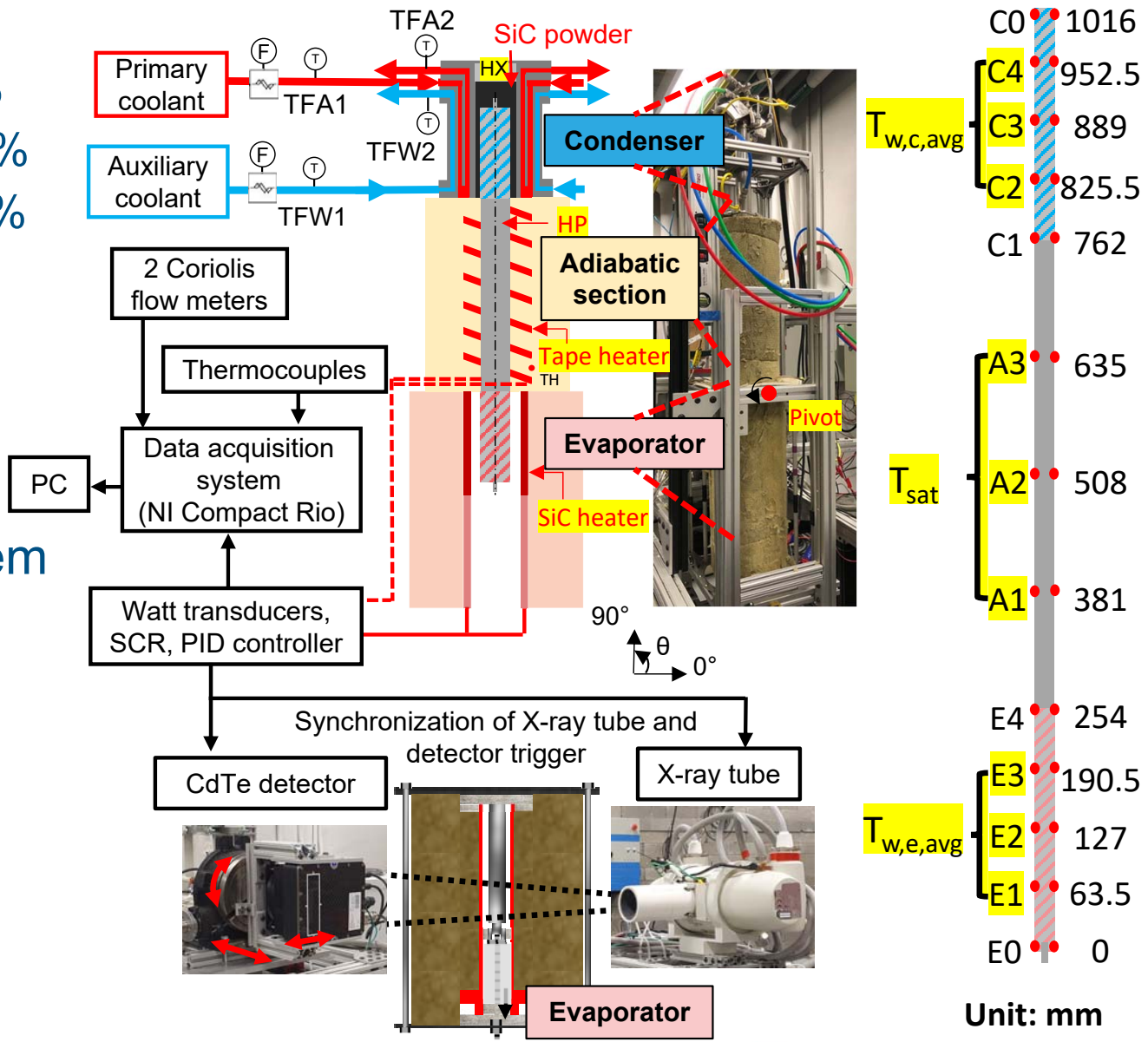
1. Single heat pipe tests

Flow phenomenon and separate effect investigation with MIchigan SOdium Heat pipe test facility (MISOH1)

MRP Microreactor Program

Experimental apparatus

- Sodium heat pipe
  - HP-a filling ratio = 67%
  - HP-b filling ratio = 102%
  - HP-c filling ratio = 172%
- MISOH1 test facility
  - Evaporator
  - Adiabatic
  - Condenser
- X-ray radiography system
  - X-ray generator
  - Thor detector
  - Triggering module



MRP Microreactor Program

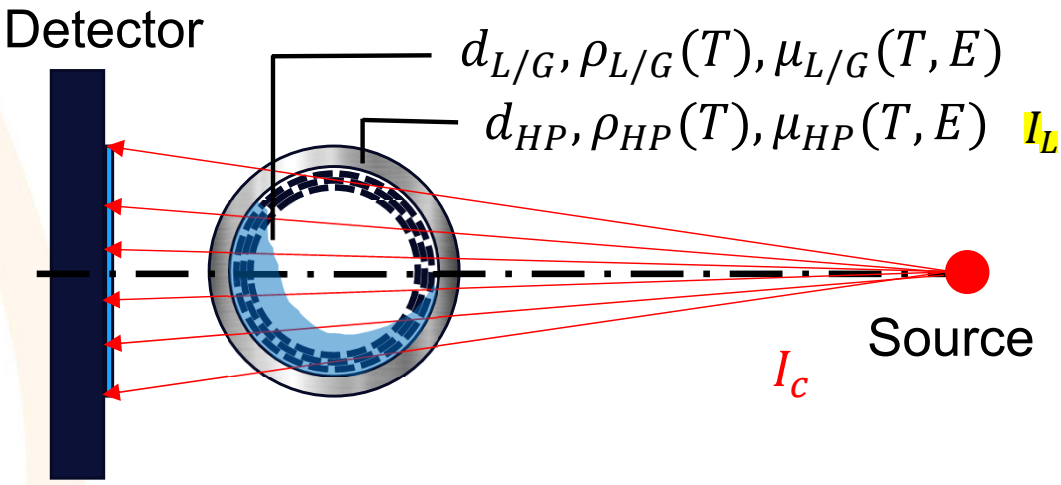
Experimental apparatus

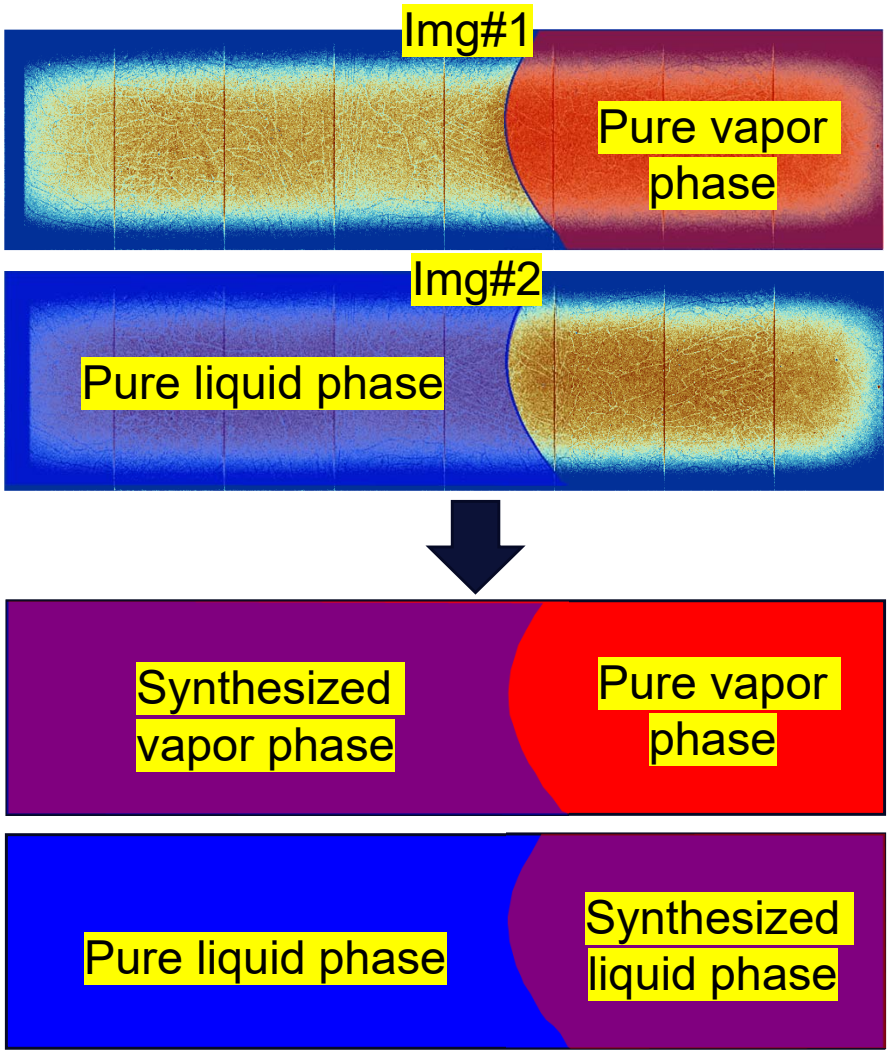
- Data processing (X-ray)
  - Pure liquid/vapor intensity ($I_{L/G}$):

$$I_{L/G}(T) = I_c e^{-\rho_{HP}(T)\mu_{HP}(E)d - \rho_{L/G}(T)\mu(E)d}$$

  - Normalized attenuation value (I_M):

$$I_M = \frac{\ln(I) - \ln(I_L)}{\ln(I_G) - \ln(I_L)}$$

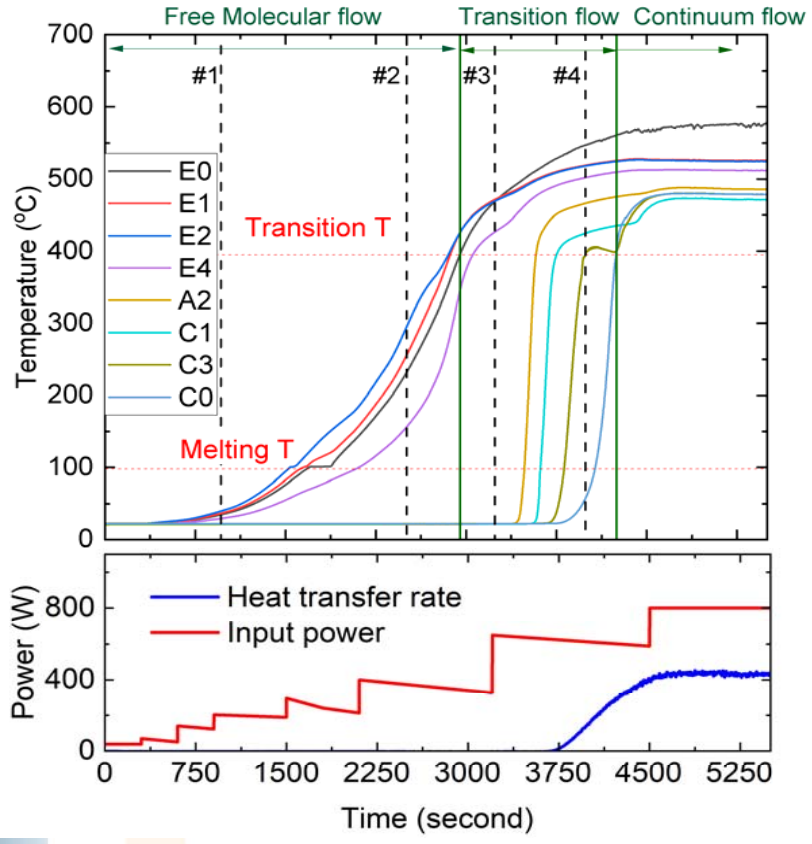


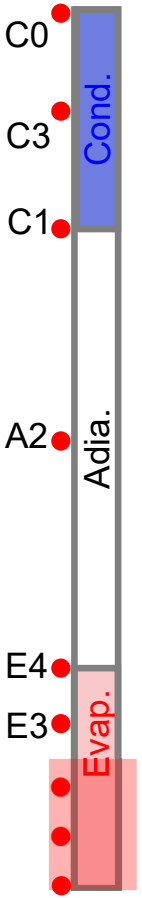


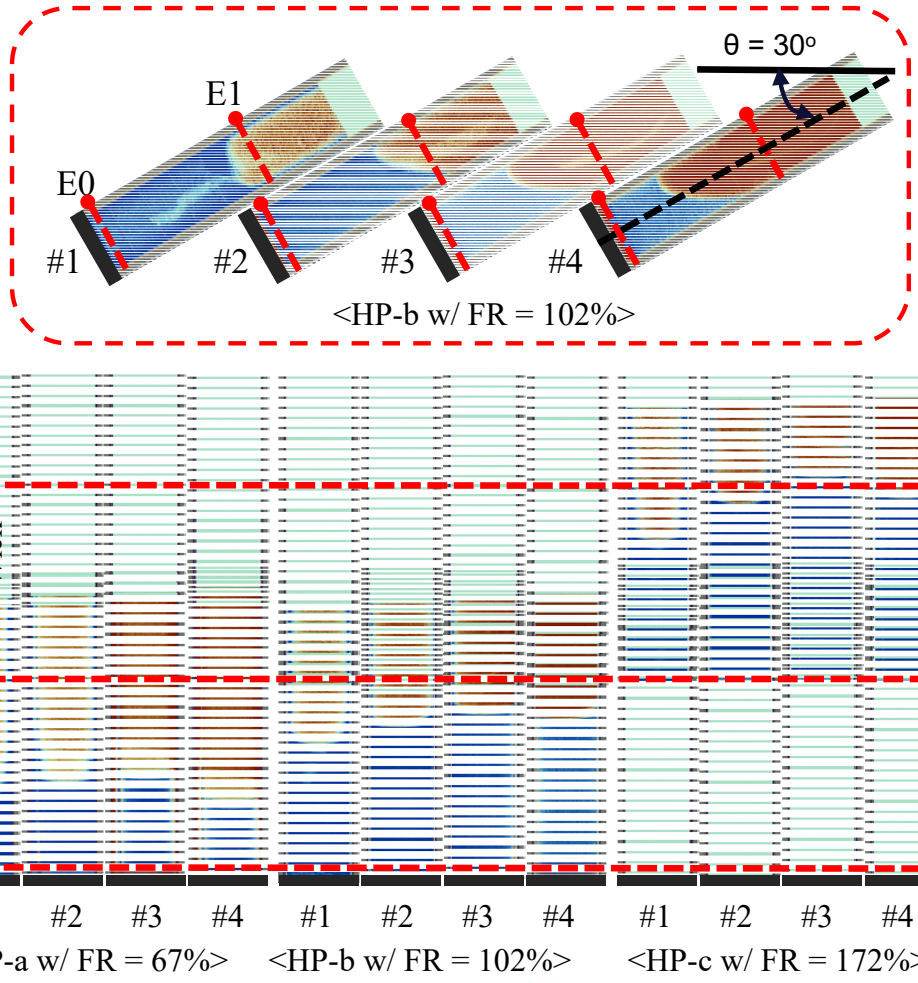
MRP Microreactor Program

Result 1: Heat pipe transient characteristics

- Heat pipe experiences various flow regimes during startup process
- The visualization of heat pipes with different filling ratios and inclination angles



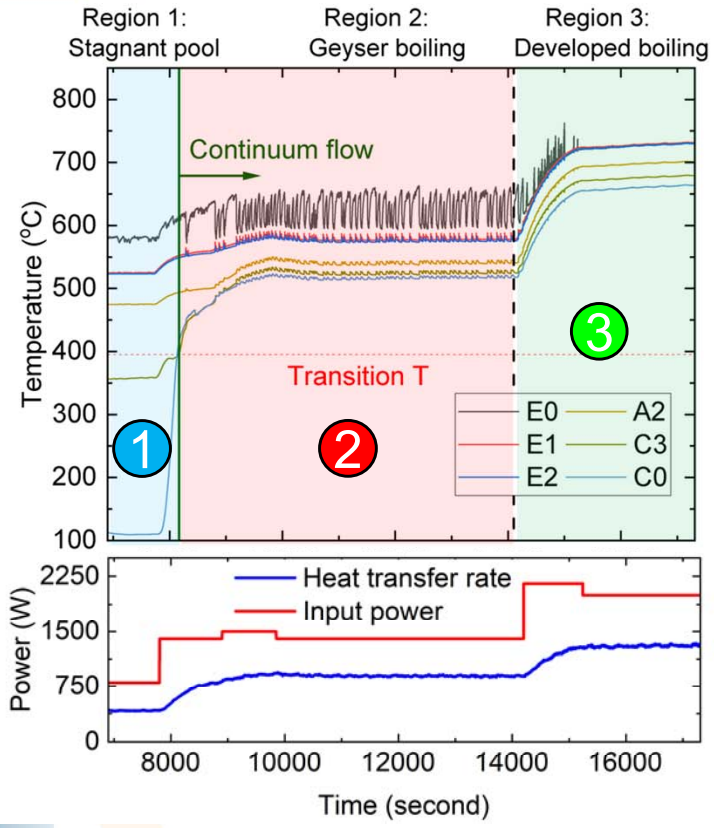


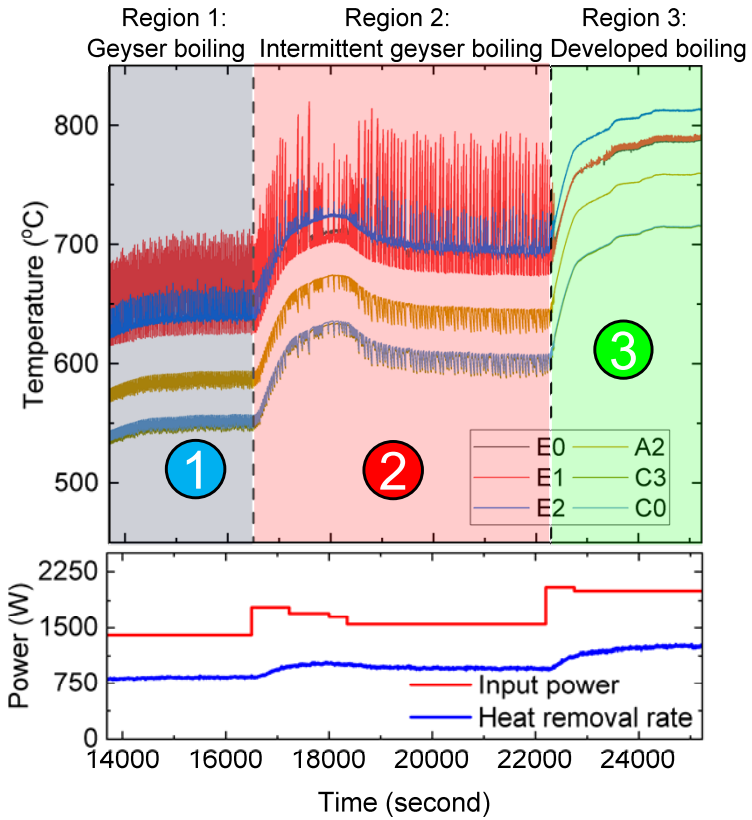


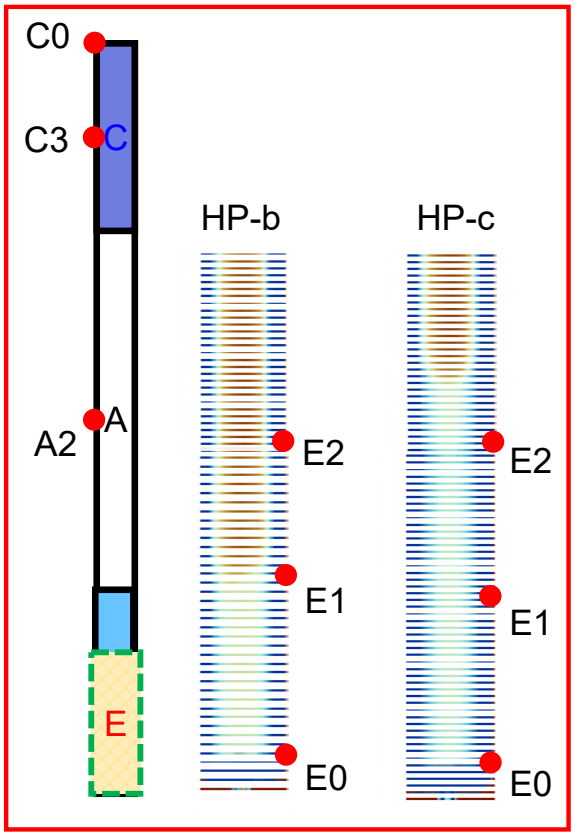
MRP Microreactor Program

Result 1: Heat pipe transient characteristics

- Heat pipes experience two-phase flow phenomenon varies with the operation conditions







HP-b (102% FR):
- Vertical orientation (90^o)
- Cooling air mass flow rate: 7 g/s

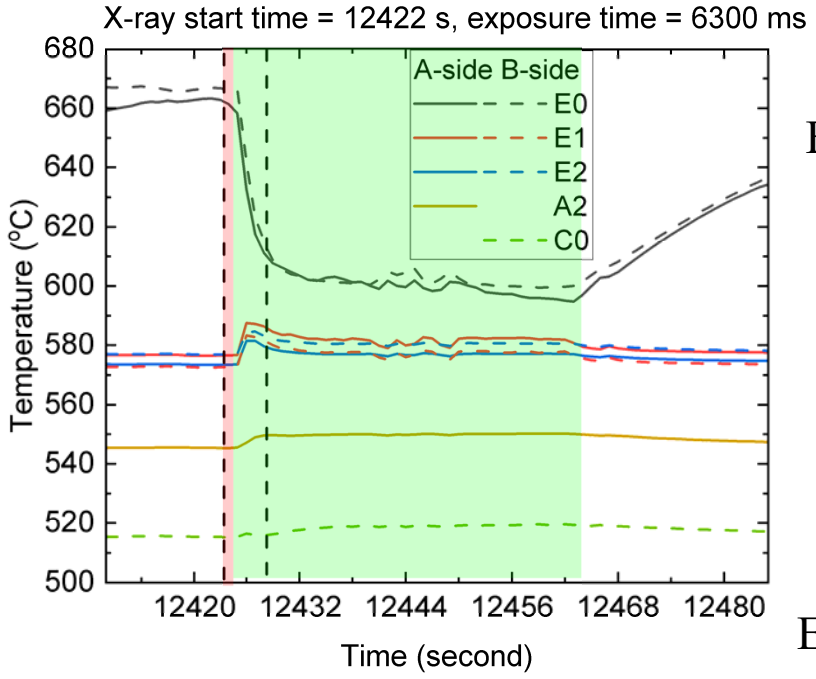
HP-c (172% FR):
- Vertical orientation (90^o)
- Cooling air mass flow rate: 4 g/s

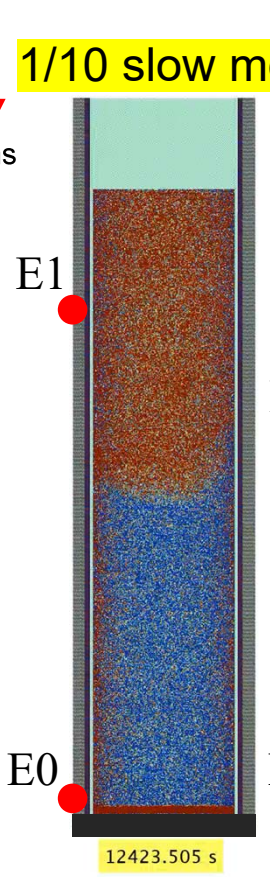
MRP Microreactor Program

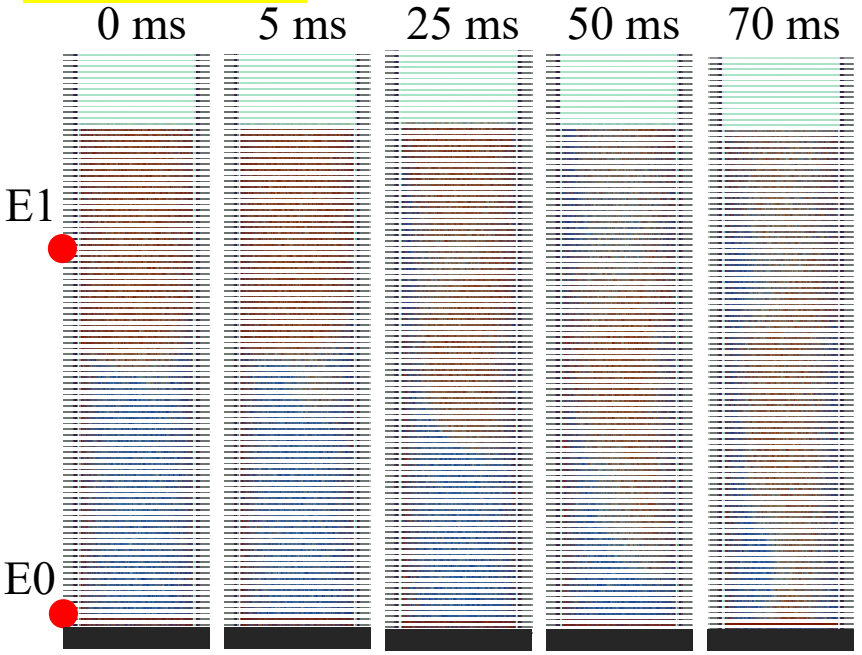
Result 2: Flow phenomenon

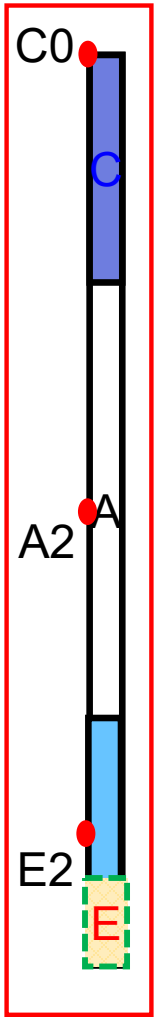
- Sequence of geyser boiling phenomenon video synchronized with temperature data

HP-b (102% FR):
- Vertical orientation (90^o)
- Primary channel: m_a= 7 g/s
- Auxiliary channel: m_w= 10 g/s







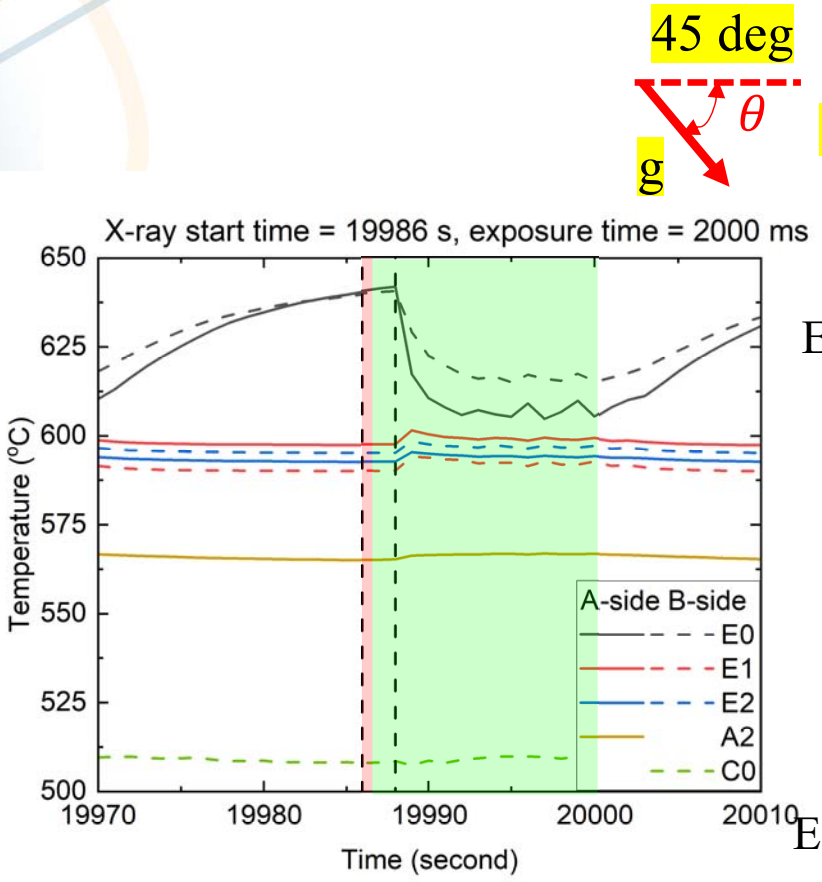


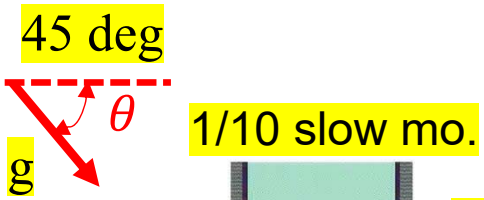
MRP Microreactor Program

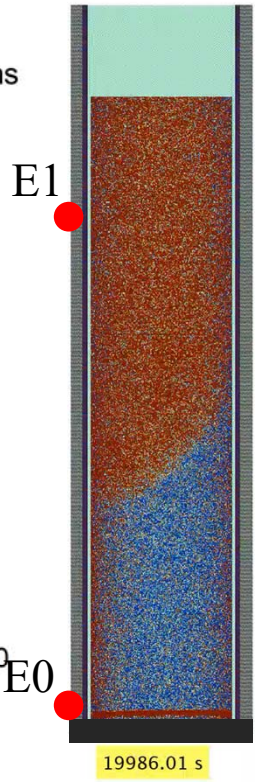
Result 2: Flow phenomenon

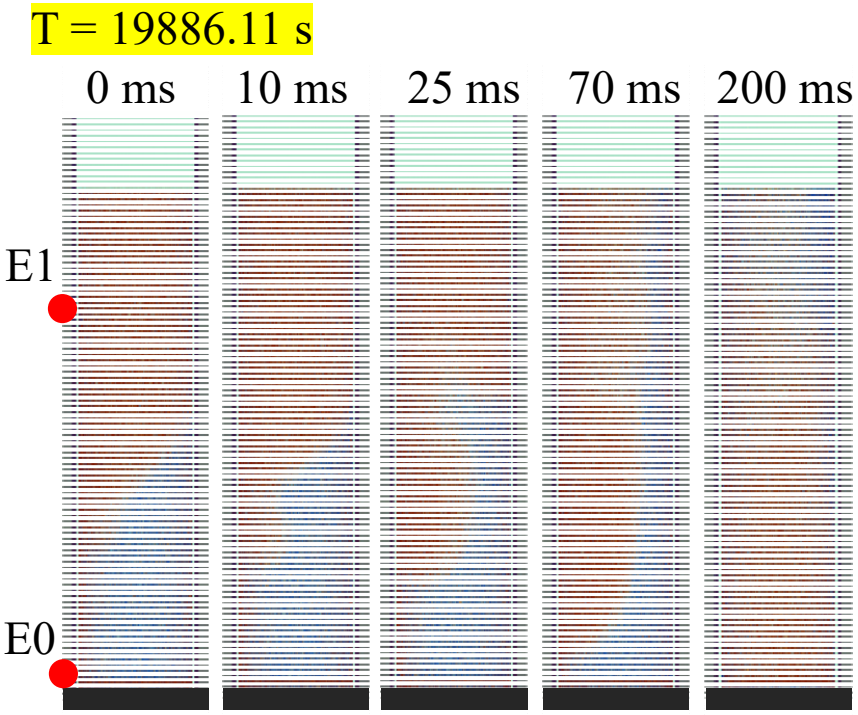
- Sequence of geyser boiling phenomenon video synchronized with temperature data

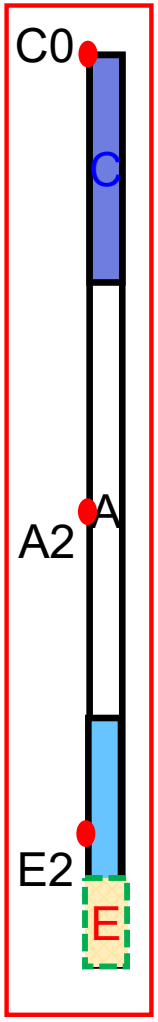
HP-b (102% FR):
- Inclined condition (45^o)
- Primary channel: m_a= 7 g/s
- Auxiliary channel: m_w= 10 g/s







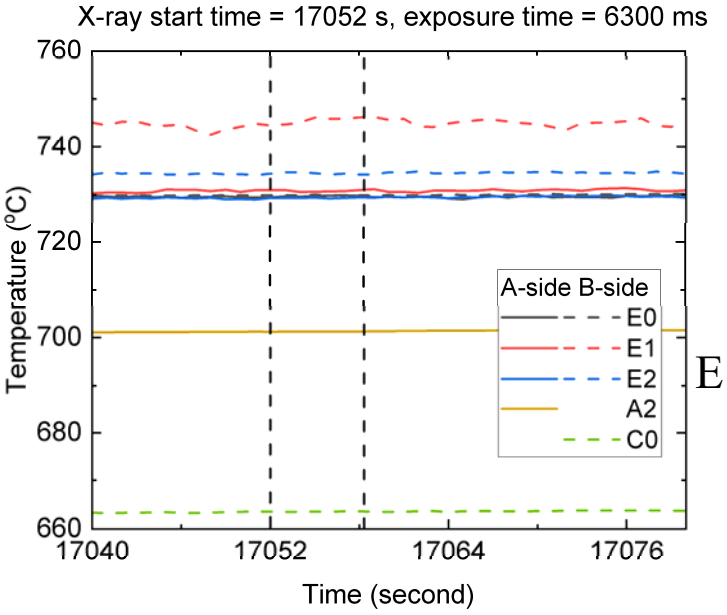


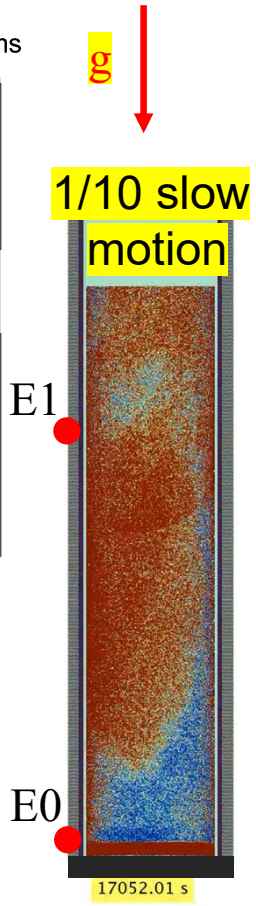


MRP Microreactor Program

Result 2: Flow phenomenon

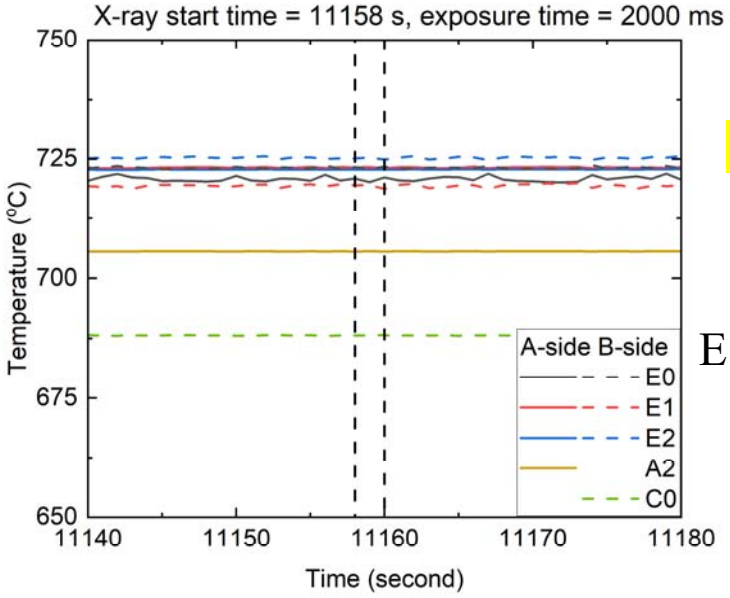
- Sequence of developed boiling phenomenon video synchronized with temperature data

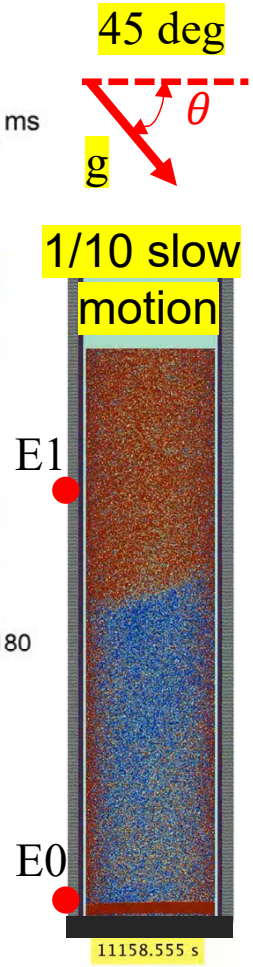




HP-b (102% FR):

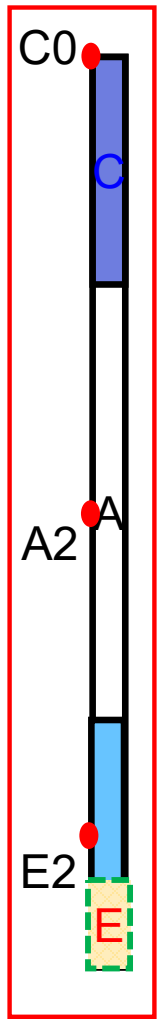
- Vertical orientation (90^o)
- Primary channel: m_a= 7 g/s
- Auxiliary channel: m_w= 10 g/s





HP-b (102% FR):

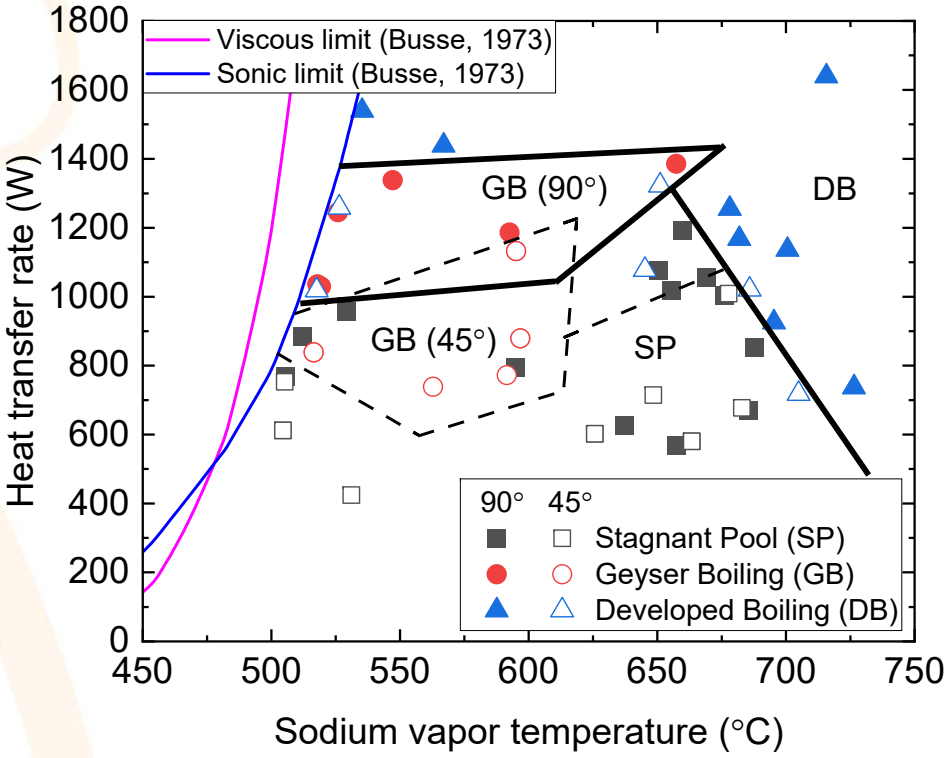
- Inclined condition (45^o)
- Primary channel: m_a= 1 g/s
- Auxiliary channel: m_w= 10 g/s



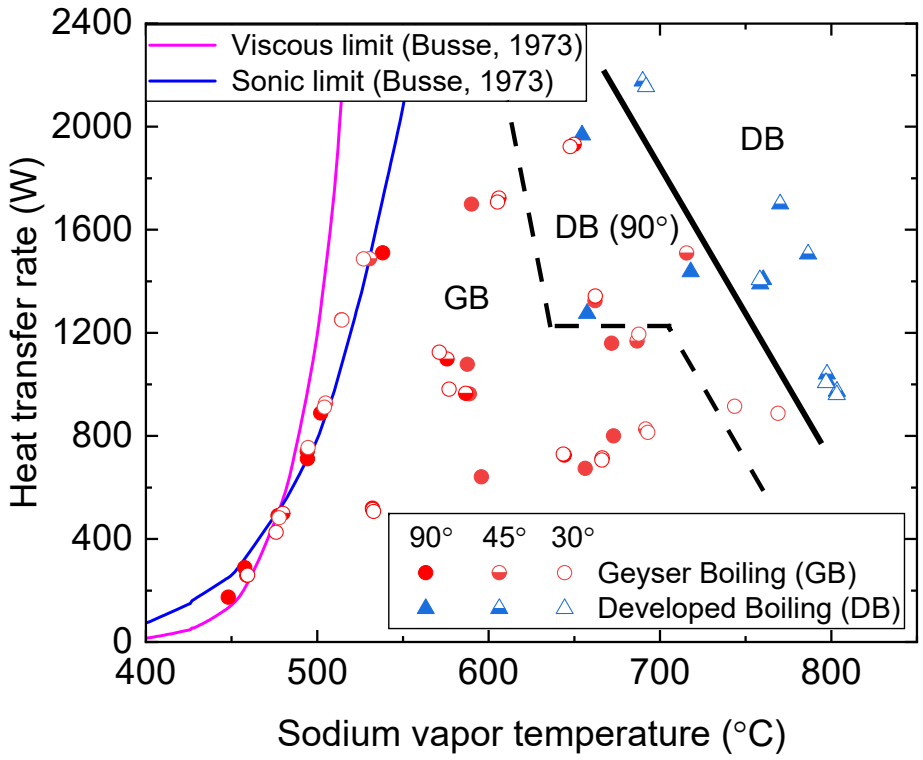
MRP Microreactor Program

Result 2: Flow phenomenon

- Boiling flow regime map
  - The initiation of boiling phenomena is closely related to the sodium filling ratio in the heat pipe and the orientation of heat pipe.



<HP-b w/ FR = 102%>

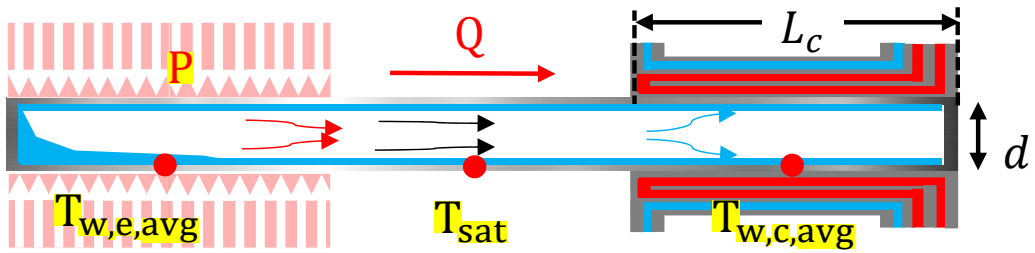


<HP-c w/ FR = 172%>

MRP Microreactor Program

Result 3: Effect of parameters

- Effect of parameters
  - Initial conditions
    - Inclination angles: 0, 15, 30, 45, 60, 75, and 90°
    - Three heat pipes with sodium filling ratio of 67%, 102%, and 172%
    - Initial sodium location
  - Boundary conditions
    - Input power: 500 W, 800 W, 1100 W,…(Threshold $T_{w,max} \leq$ 900°C)
    - Five condenser conditions
- Data reduction
  - Heat transfer rate of heat pipe: $Q = c_{p,P}\dot{m}_P(T_{fP2} - T_{fP1}) + c_{p,A}\dot{m}_A(T_{fA2} - T_{fA1})$
  - Heat transfer coefficient of heat exchanger: $h_{hx} = \frac{c_{p,P}\dot{m}_p(T_{fP2}-T_{fP1})}{[\pi d L_c (T_{w,c,avg}-T_{f,p.avg})]}$

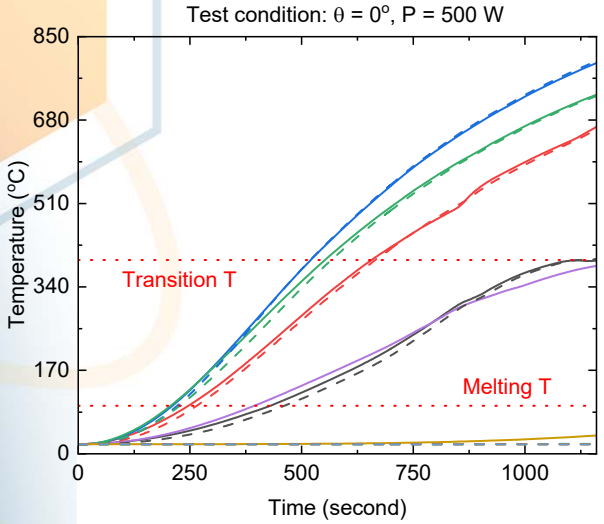


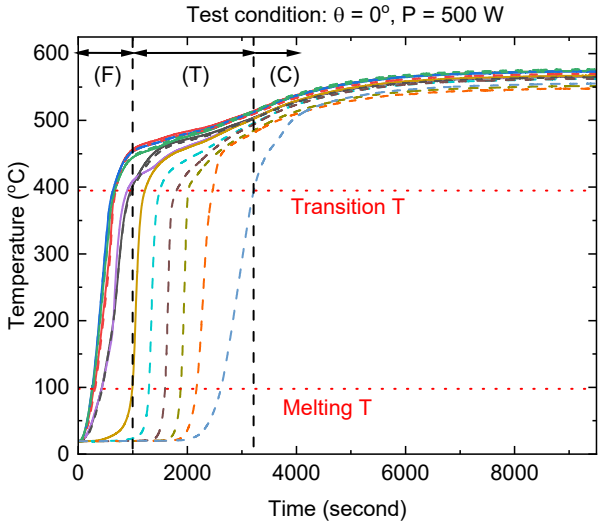
Primary coolant: $T_{fP1,2}$, $c_{p,P}$, $\dot{m}_p$
Auxiliary coolant: $T_{fA1,2}$, $c_{p,A}$, $\dot{m}_A$

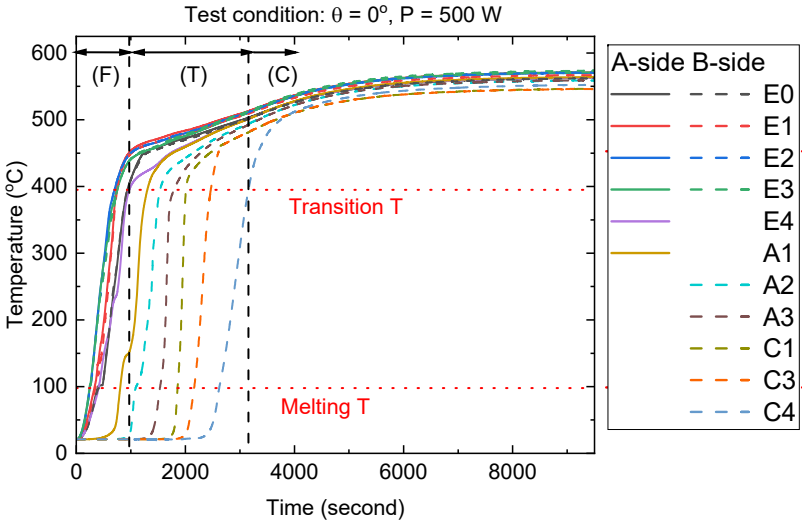
MRP Microreactor Program

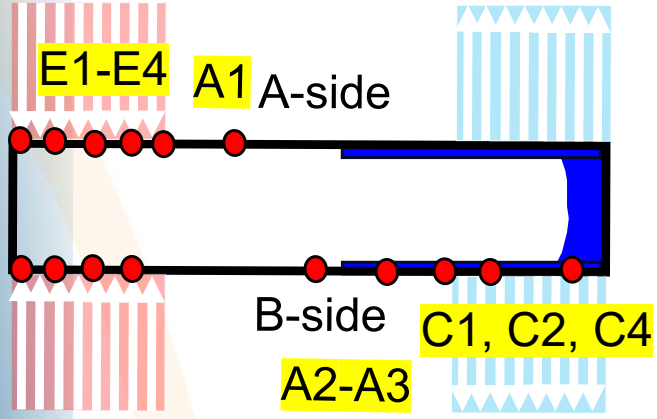
Result 3: Effect of parameters

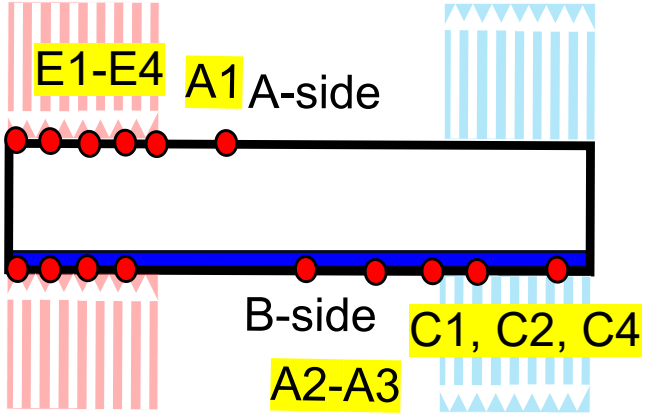
- Effect of initial sodium location on startup characteristics (HP-b)

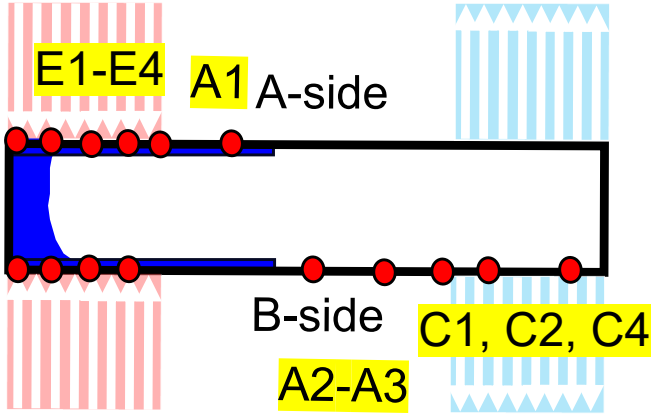








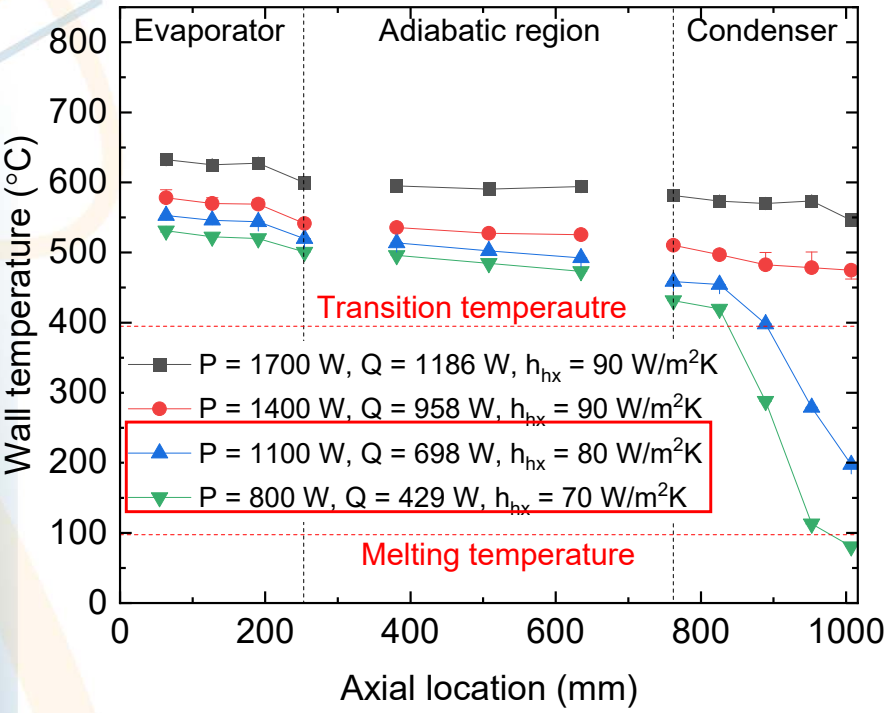




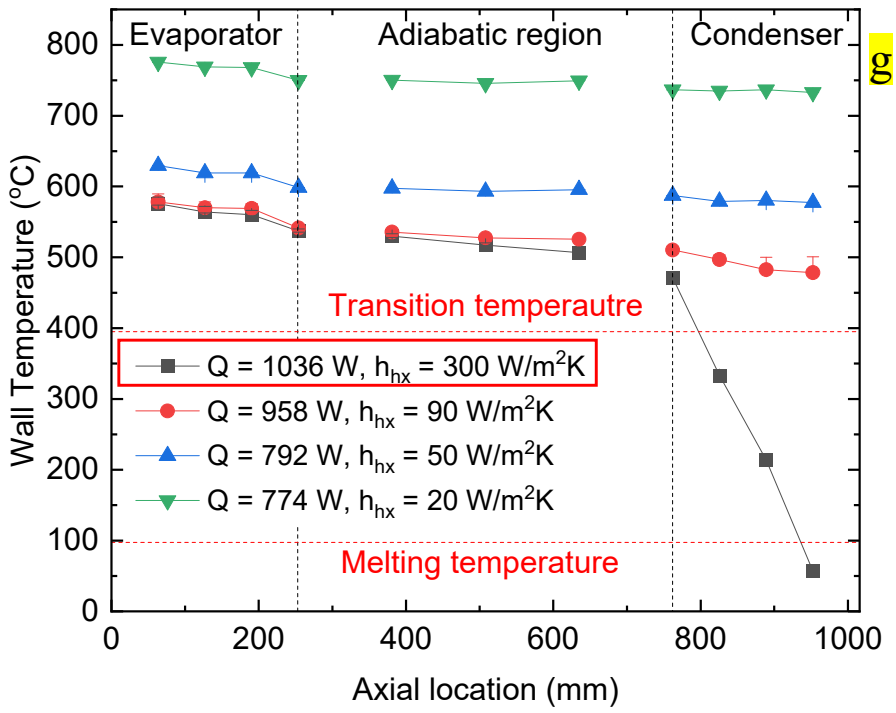
MRP Microreactor Program

Result 3: Effect of parameters

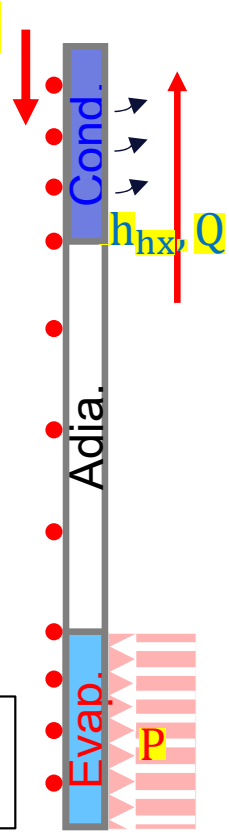
- Effect of boundary conditions (input power and cooling intensity)
  - The balance between the input power and the cooling intensity is important



HP-b (102% FR), Vertical orientation (θ = 90°)
Cooling conditions: m_a= 7 g/s, m_w= 10 g/s



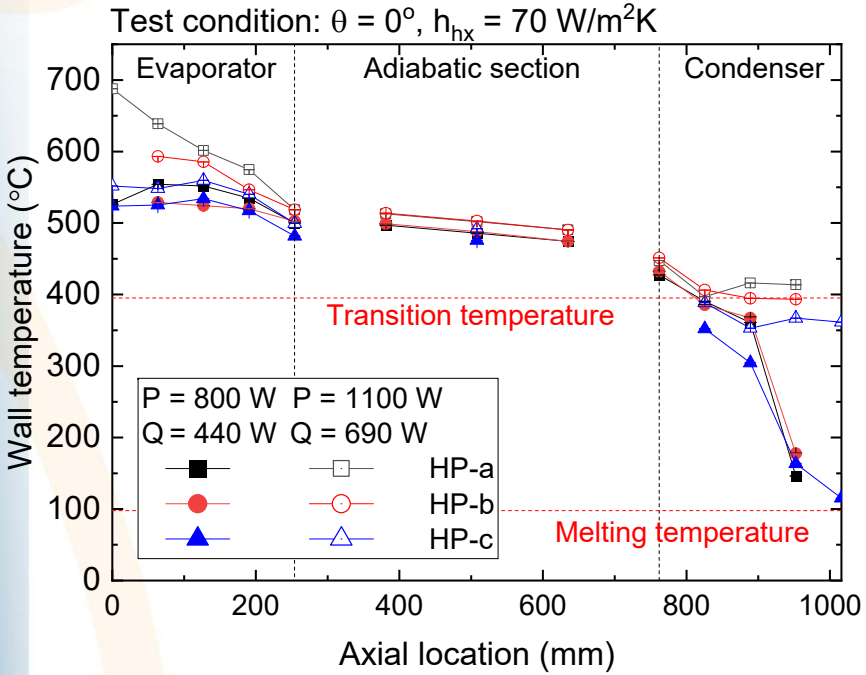
HP-b (102% FR), Vertical orientation (θ = 90°)
Input power: 1400 W, various cooling conditions

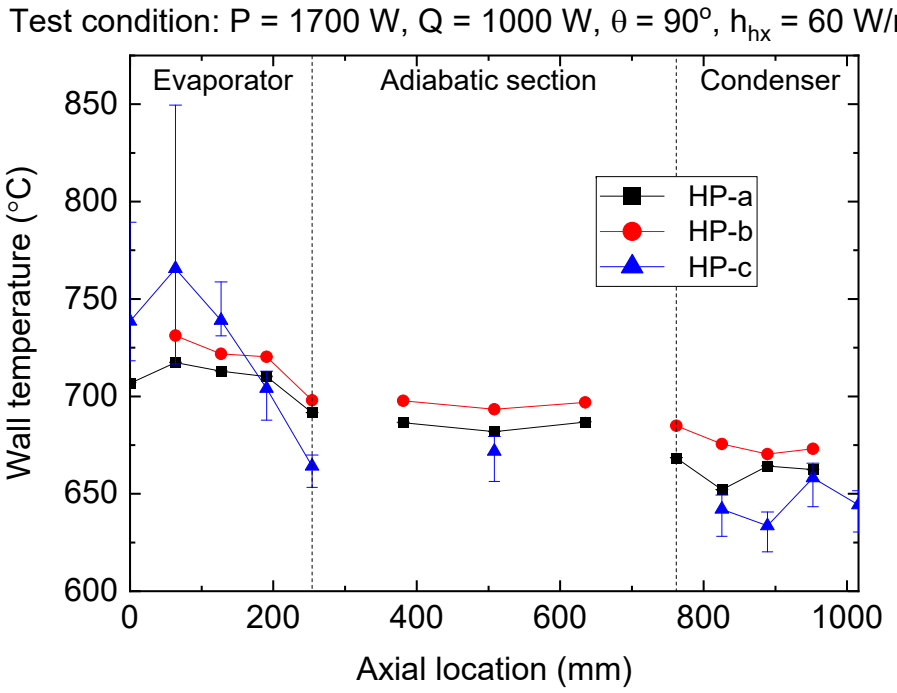


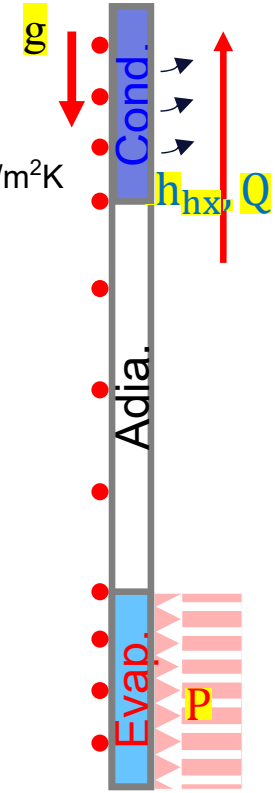
MRP Microreactor Program

Result 3: Effect of parameters

- Effect of initial conditions (sodium filling ratio and inclination angle)
  - Overheat for heat pipe with small sodium filling ratio under horizontal orientation (dryout condition)
  - Severe temperature oscillation for heat pipe with large sodium filling ratio under vertical orientation (geyser boiling)







MRP Microreactor Program

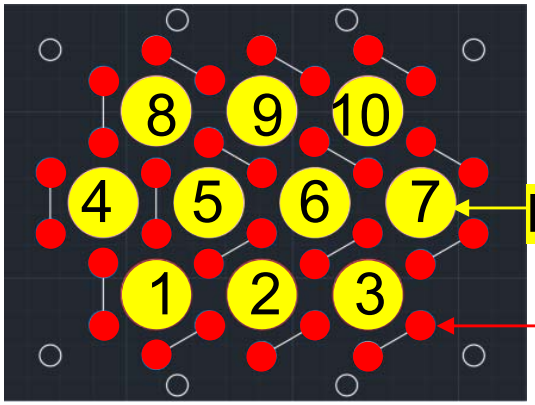
2. Sodium heat pipes bundle tests

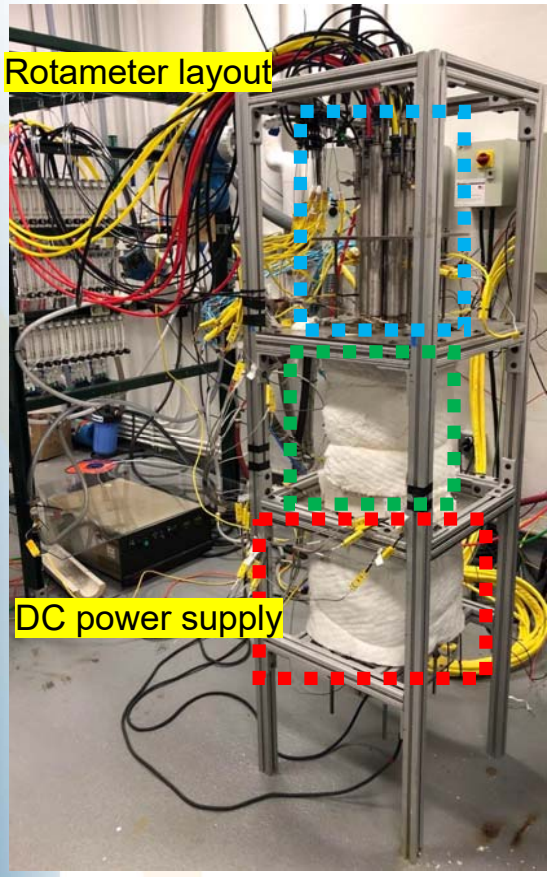
Integral effect study with MIchigan SOdium Heat pipe bundle test facility (MISOH2)

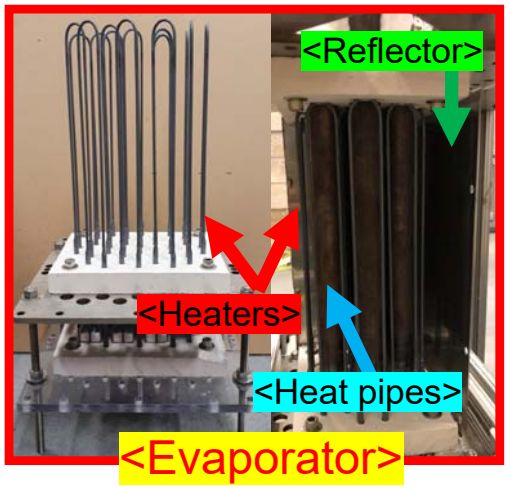
MRP Microreactor Program

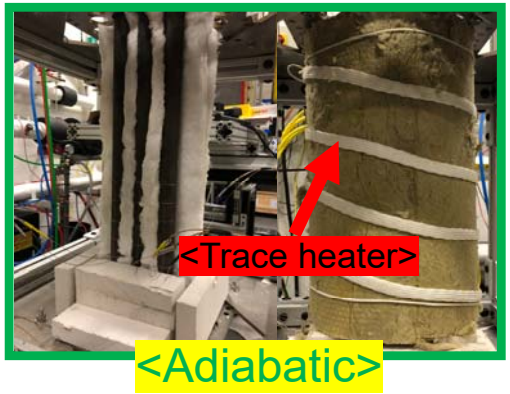
Experimental apparatus

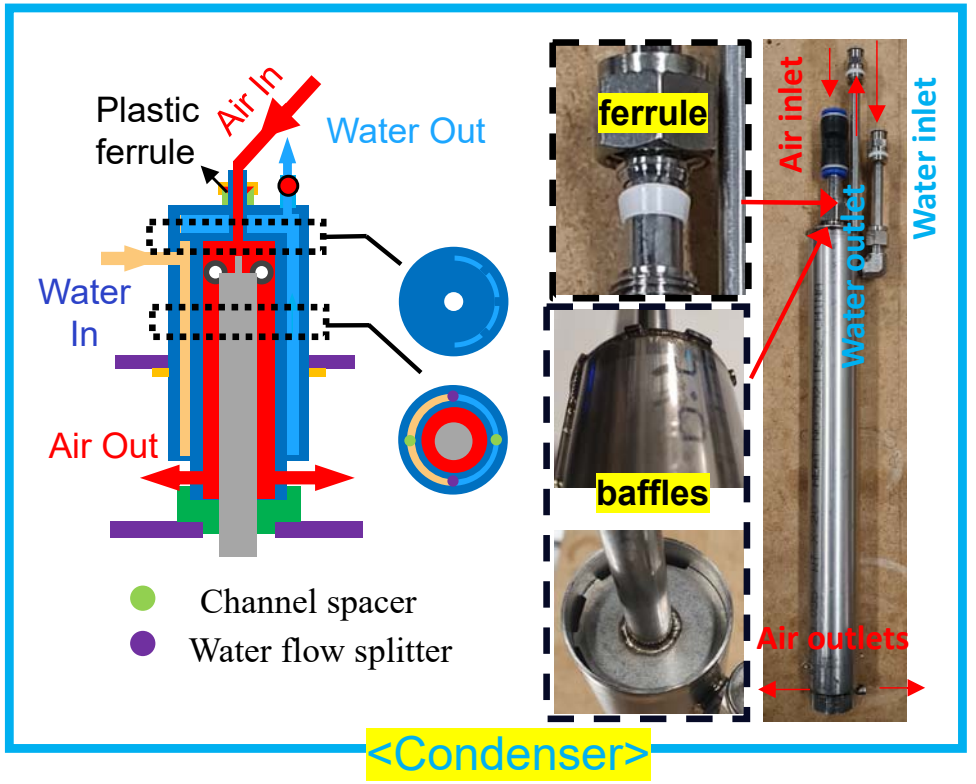
Spec. of the design
- Ten heat pipes array
- Triangular lattice
- P/D: 1.57
- 32 holes allocated for heating element(s)











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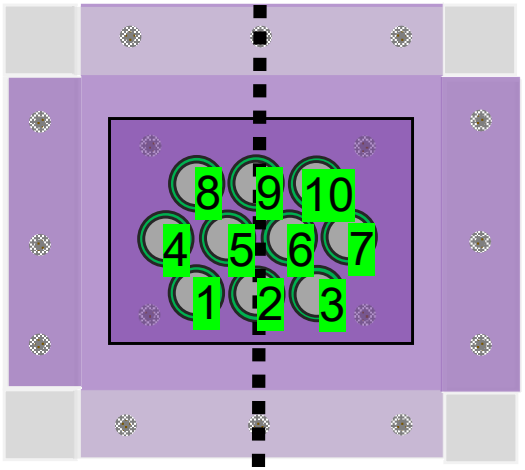
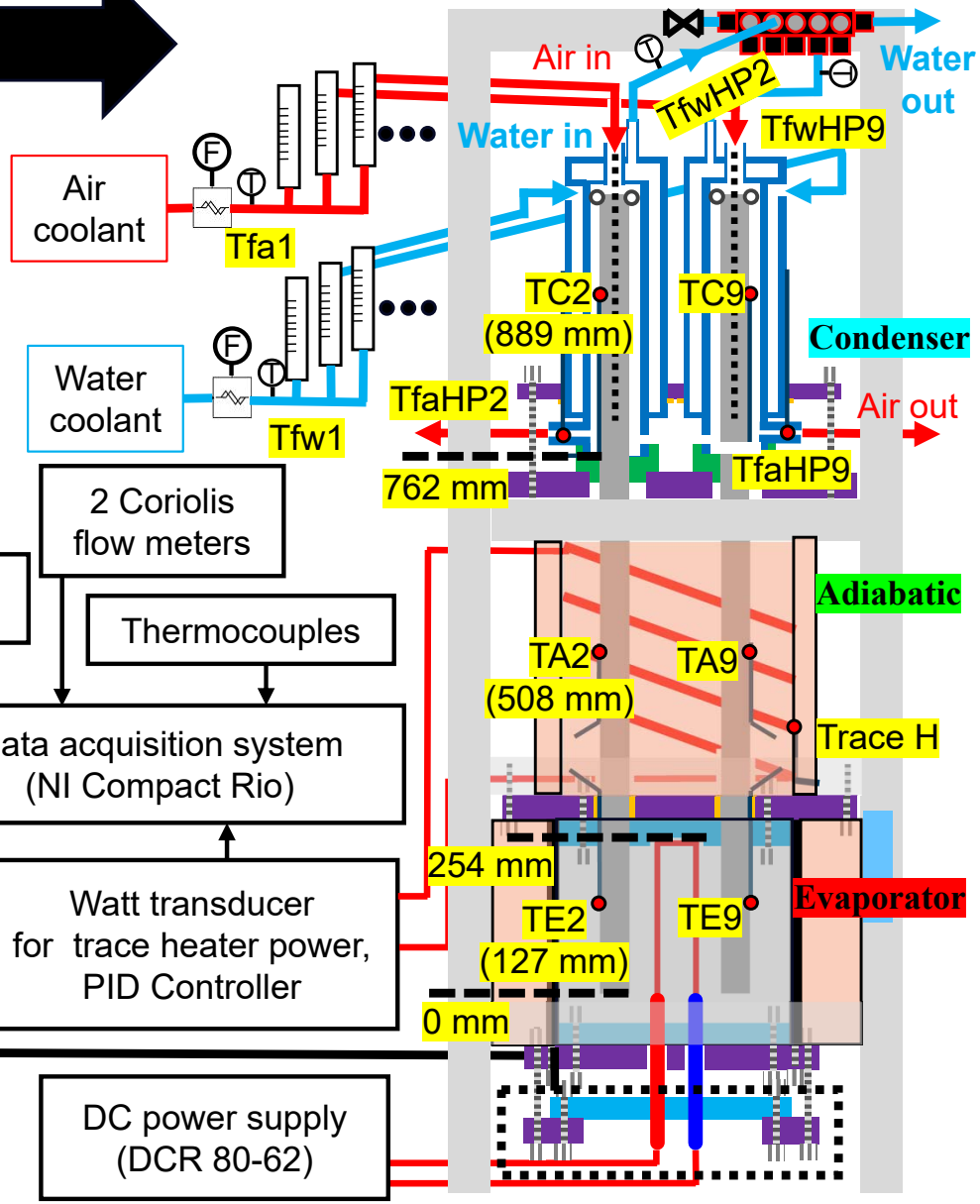
Experimental apparatus

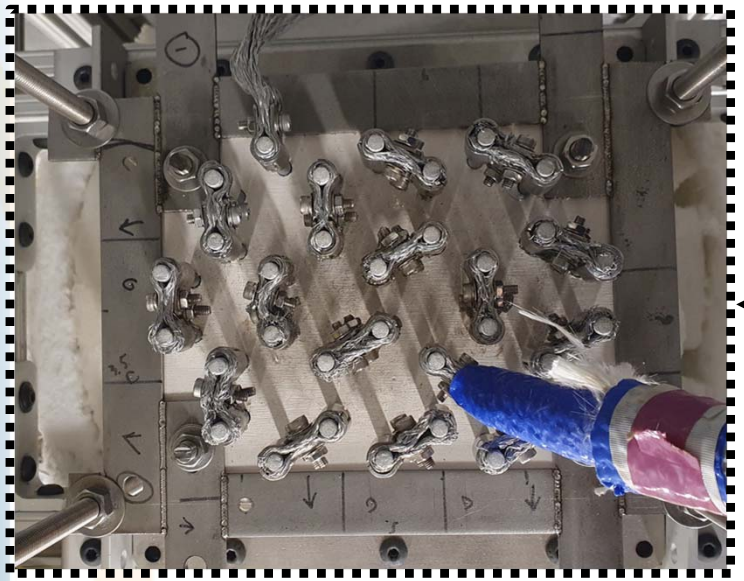
<Top cross-sectional view>



<Side cross-sectional view>



P (16 heaters) R



<Bridge connection for heaters>

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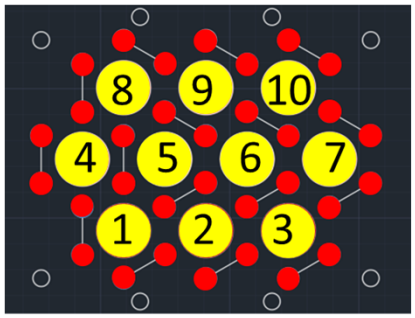
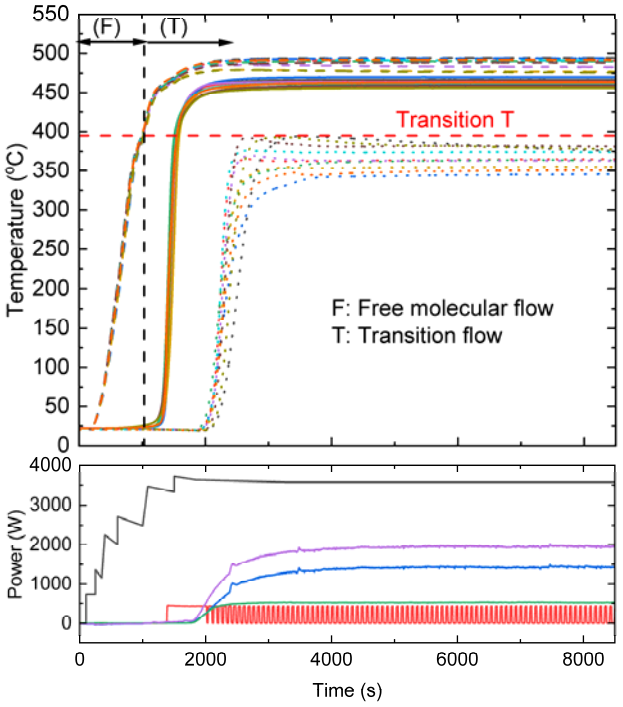
Preliminary Results

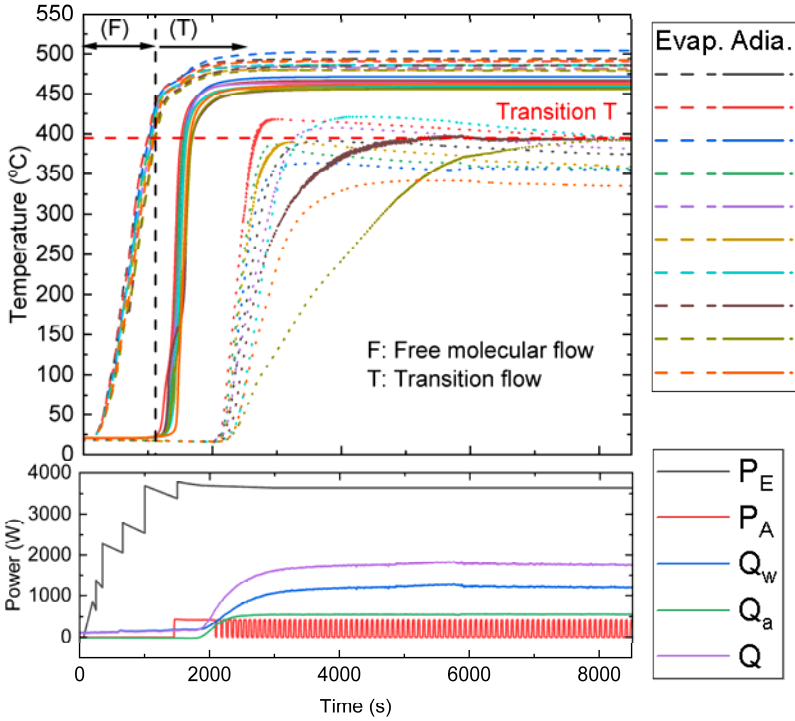
- Transient operation: startup process under uniform heating and cooling conditions



<HPs layout>



<Vertical orientation>



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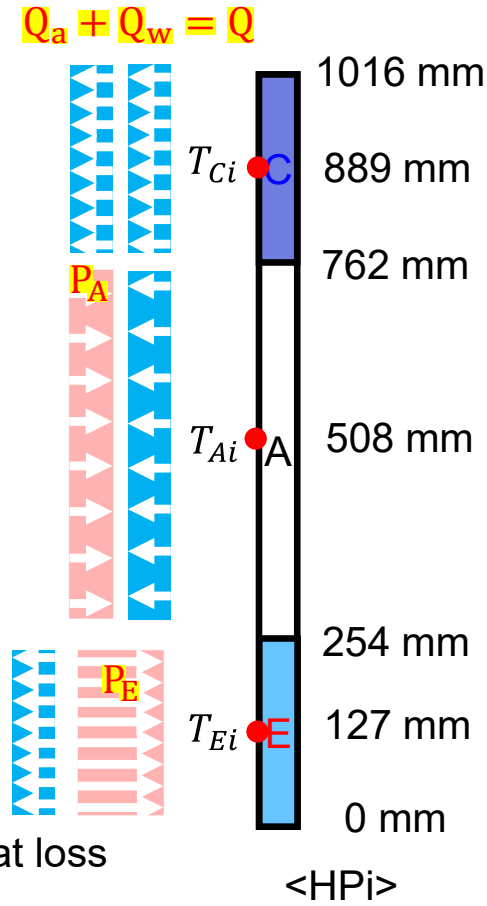

- HPs (FRs ranging from 90% - 110%)
- Condenser condition: $m_{a,i}$ = 0.5 g/s , $m_{w,i}$ = 5 g/s

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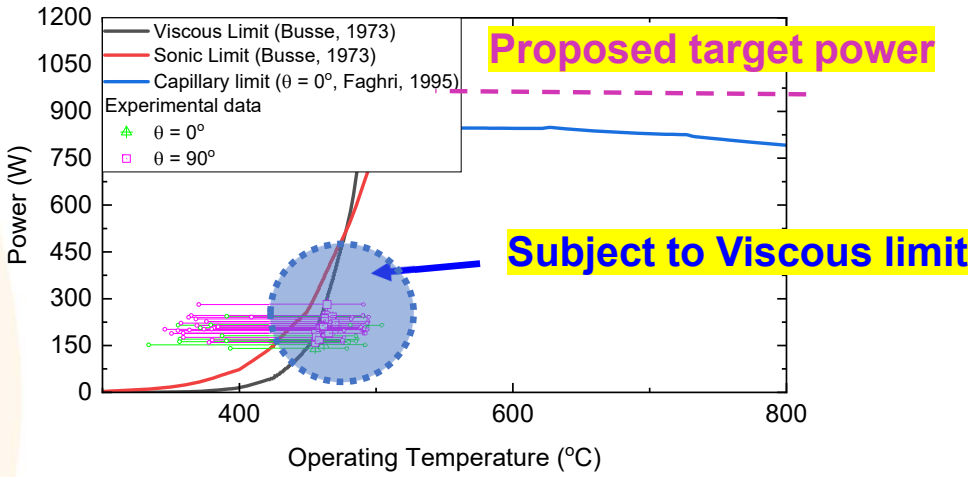
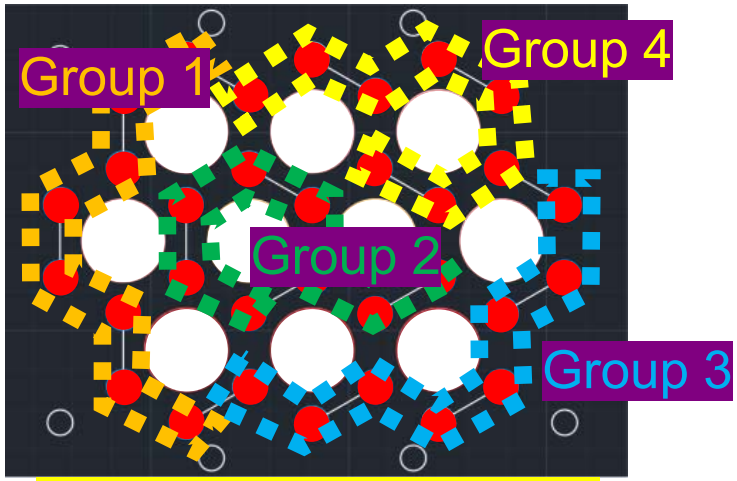
Conclusion and Future Works

- Conclusion
  - Separate effect of single sodium heat pipe
    - Boiling region of heat pipes with different sodium filling ratio under different inclination angles was identified.
    - Heat pipe with high sodium filling ratio experienced significant temperature oscillation under large inclination angles.
    - Heat pipe with low sodium filling ratio experiences dryout conditions under horizontal orientation.
  - Integral effect of heat pipes bundle
    - Ten heat pipes hexagonal lattice array with individual variable heat exchangers were designed and constructed (MISOH2 test facility)
- Future works
  - Power extension for MISOH2 test facility





<Multigroup heater arrays>

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