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

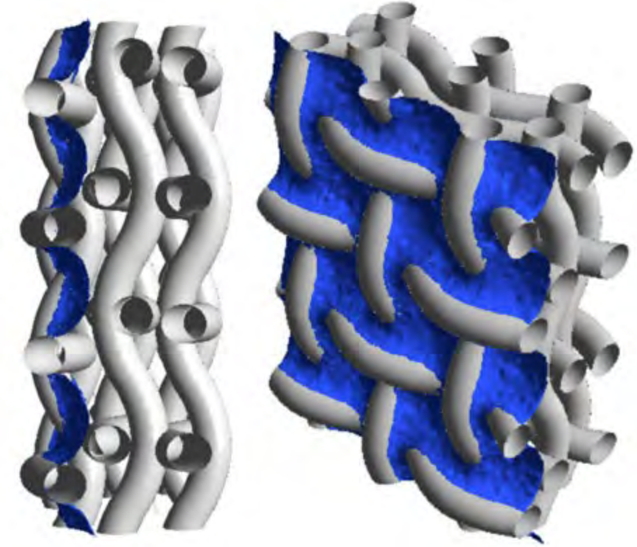
(NEUP Project 19-17416)

Date: March 6th, 2024

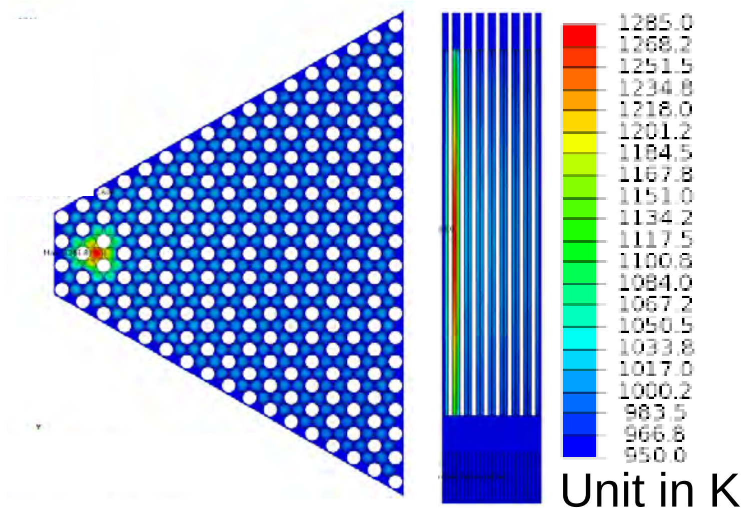
Authors: Victor Petrov, Annalisa Manera, Pei-Hsun Huang, Taehwan Ahn

Project overview

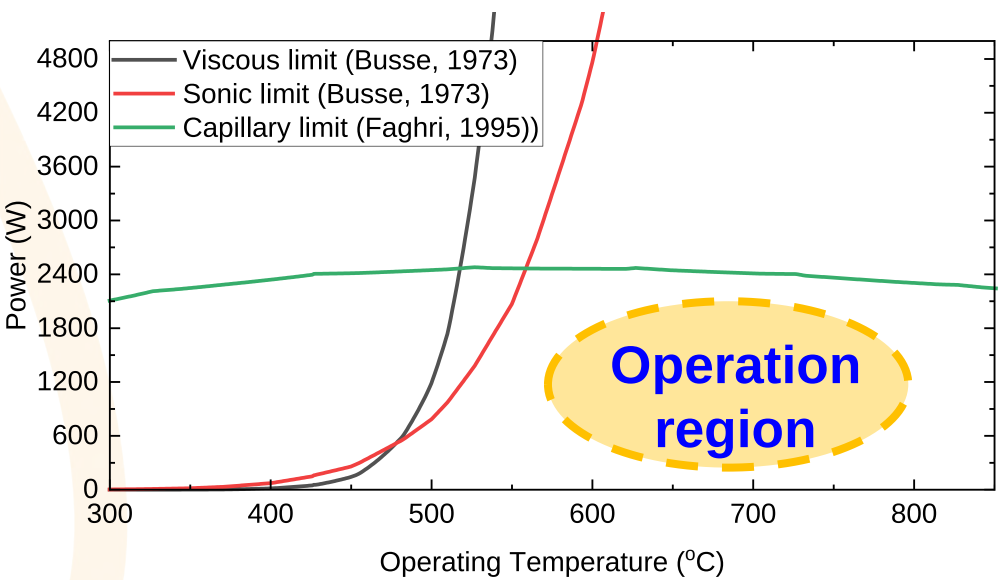
- Development of special purpose reactor
  - Heat pipe operation principle
  - Heat pipe modeling
- Knowledge gaps
  - The two-phase flow phenomena in heat pipes
  - Effect of parameters on heat pipe performance
  - Integral study on microreactors



(Dutra et al., 2022)



(Mcclure et al., 2015)

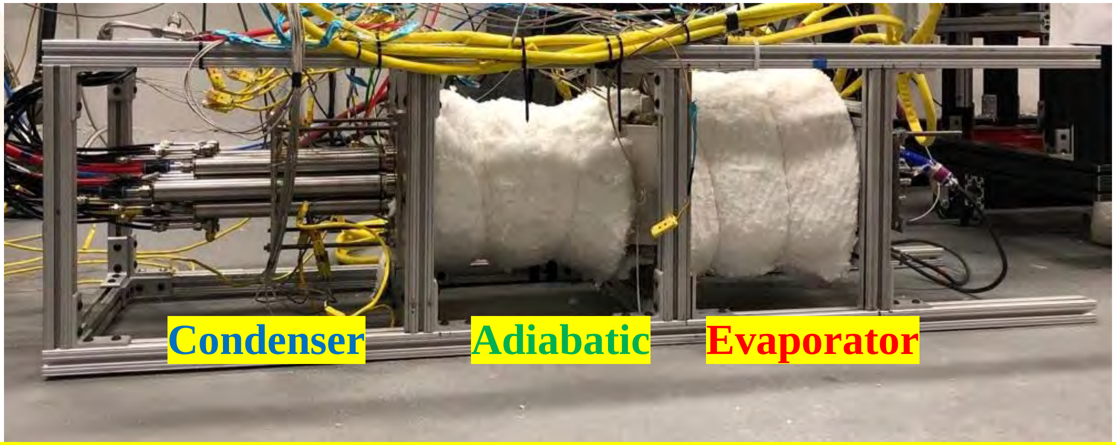


MRP Microreactor Program

Project goal

- Separate effect of single sodium heat pipe
    - o Parameter investigation
        - Heating condition - Input power
        - Cooling condition - Heat transfer coefficient of heat exchange
        - Inclination angles
        - Sodium content in heat pipe
    - o X-ray radiography measurement
- Integral effect of heat pipes bundle
    - o Startup process
    - o Normal operation
    - o Non-uniform boundary conditions
    - o Abnormal scenarios (1 or 2 heat pipe failure)

MIchigan SOdium Heat pipe test facility, MISOH1



MIchigan SOdium Heat pipes bundle test facility, MISOH2

MRP Microreactor Program

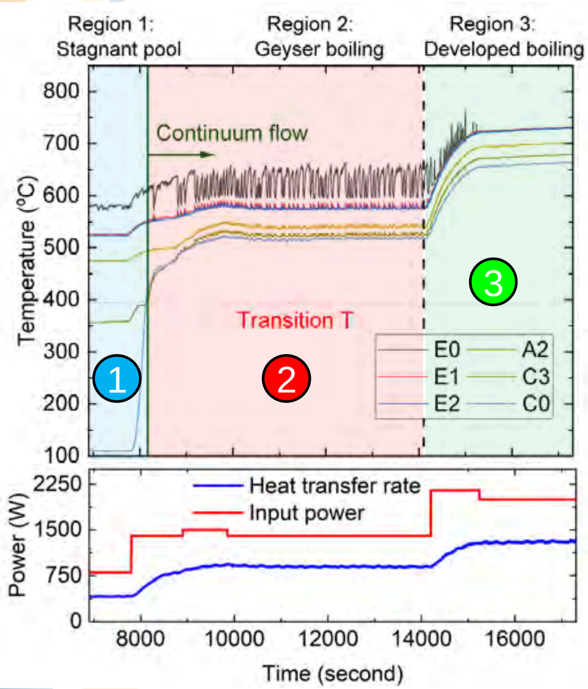
Separate effect of single sodium heat pipe:

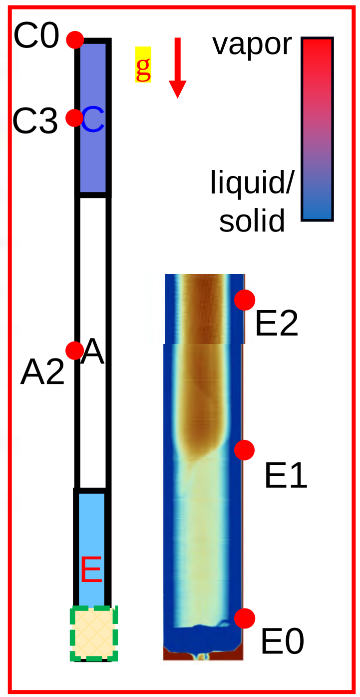
MIchigan SOdium Heat pipe test facility (MISOH1)

MRP Microreactor Program

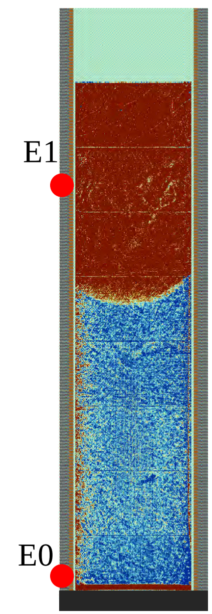
Separate effect of single sodium heat pipe – MISOH1 test facility

•Sodium flow characteristics
(temperature and x-ray image/video)

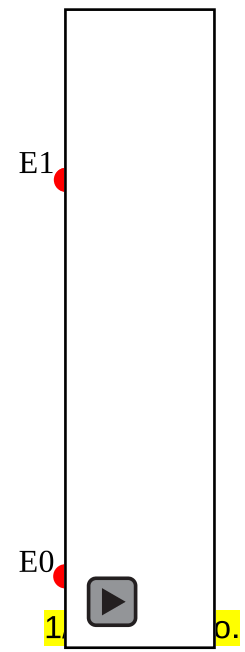




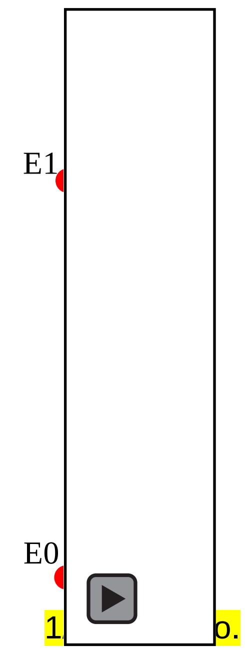
Region 1:
Stagnant pool



Region 2:
Geyser boiling



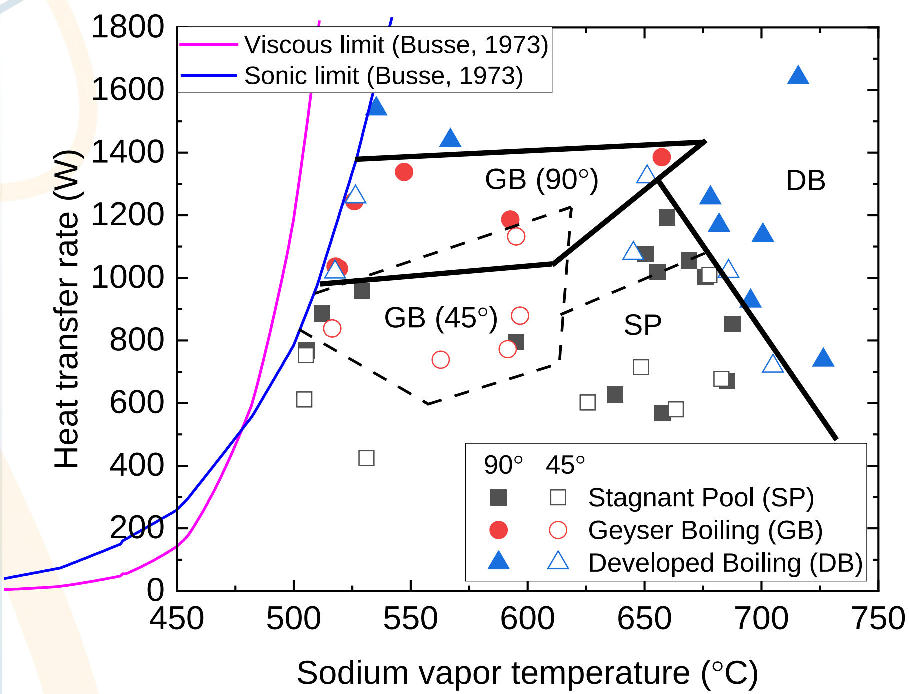
Region 3:
Developed boiling



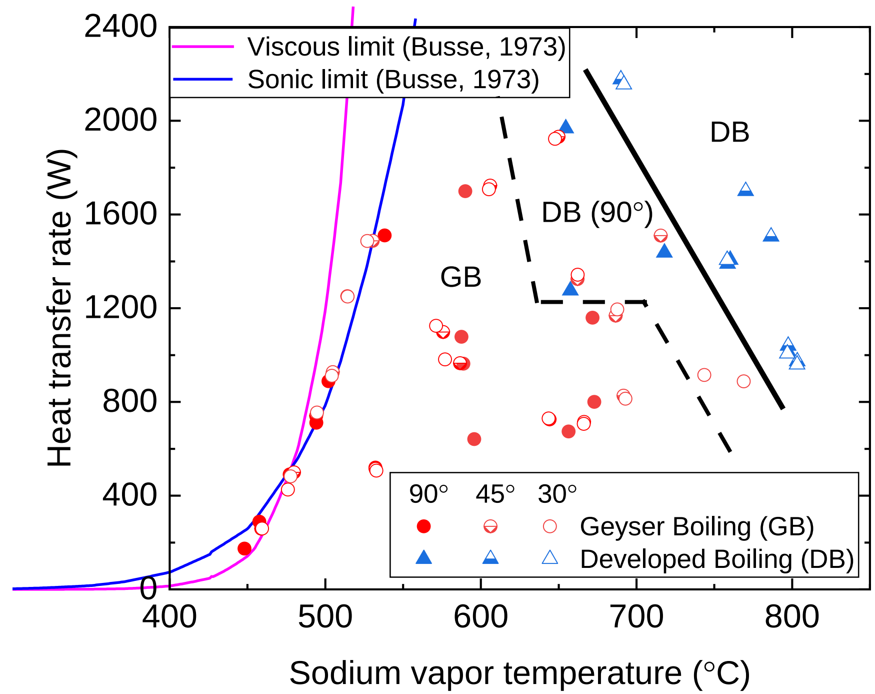
MRP Microreactor Program

Results: 2. Flow characteristics

- 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



Filling ratio = 102%



Filling ratio = 172%

MRP Microreactor Program

Integral study on microreactors

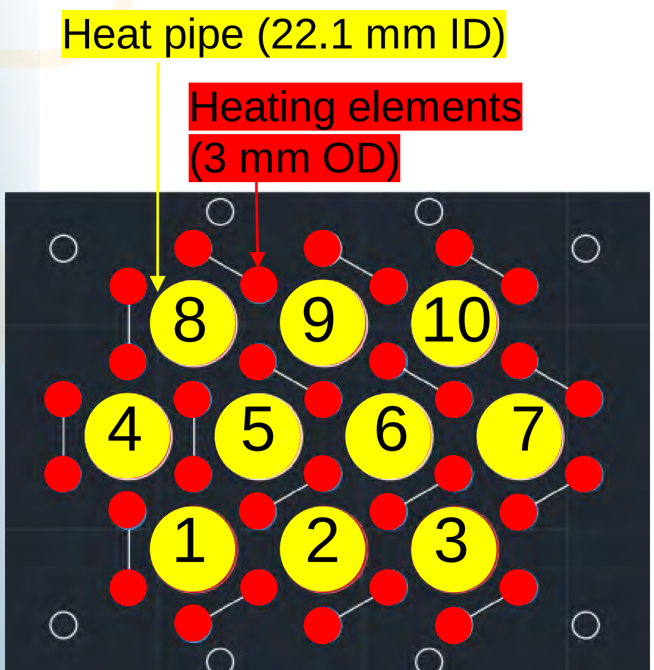
MIchigan SOdium Heat pipe bundle test facility (MISOH2)

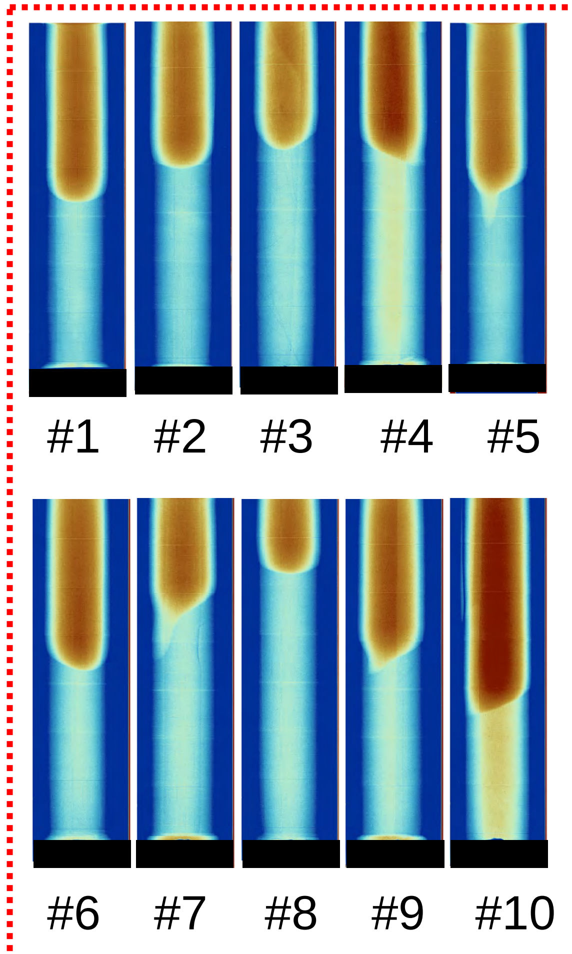
MRP Microreactor Program

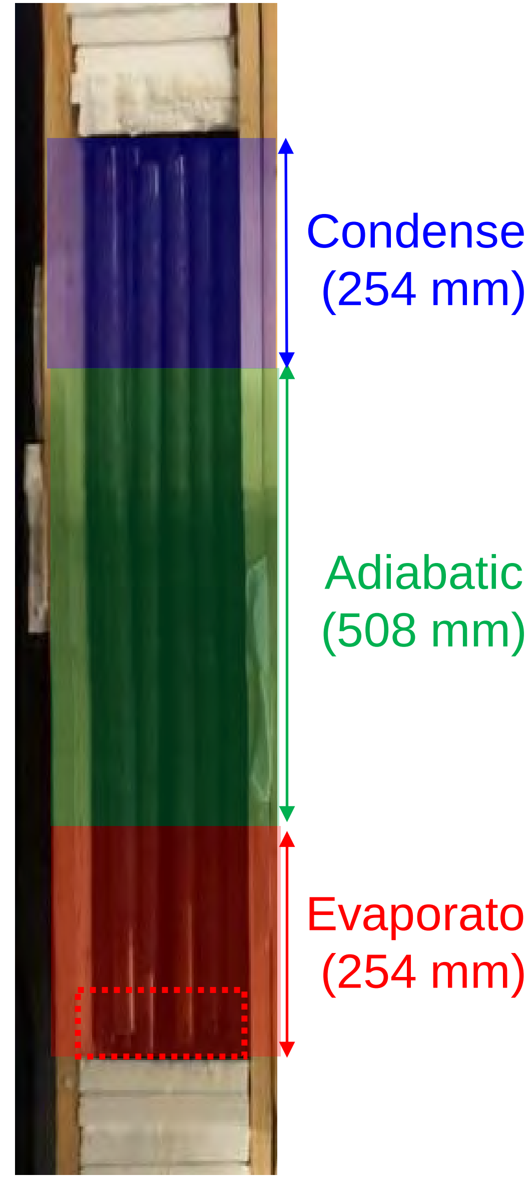
MISOH2 heating elements and heat pipes layout

Specification of the MISOH2 facility design
- o Ten heat pipes hexagonal array
- o 32 holes allocated for heating elements

•Sodium contents in selected heat pipe
- o 27 - 35 grams (80 – 110% filling ratios)

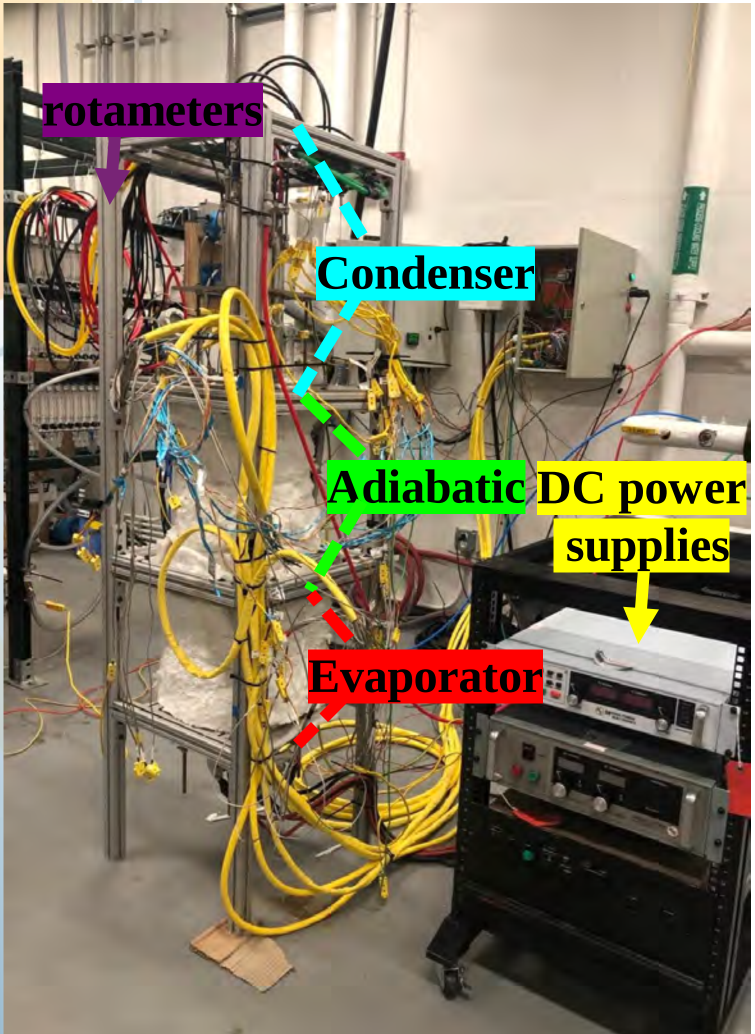


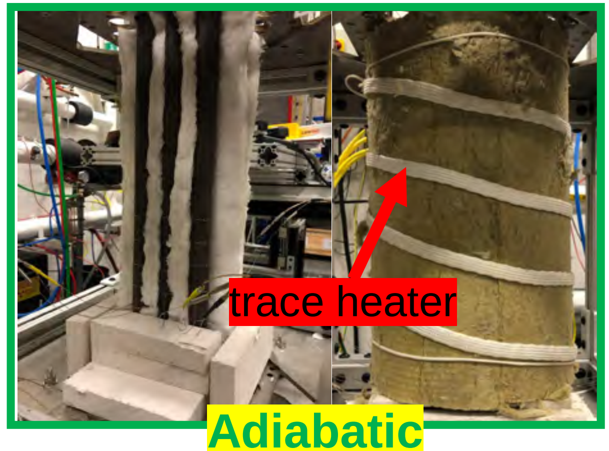


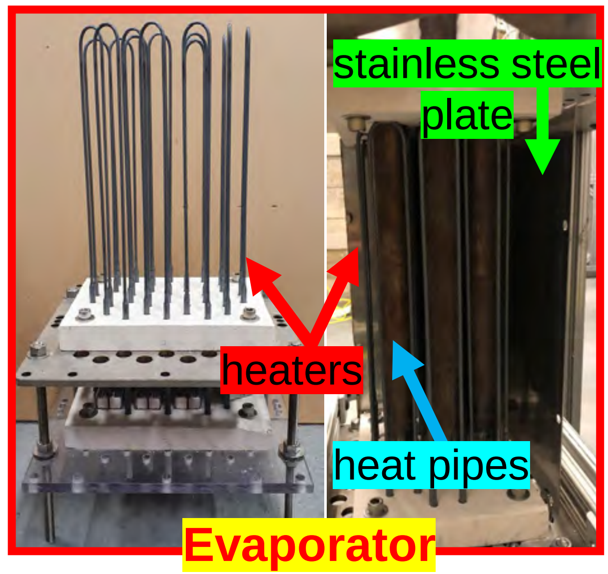


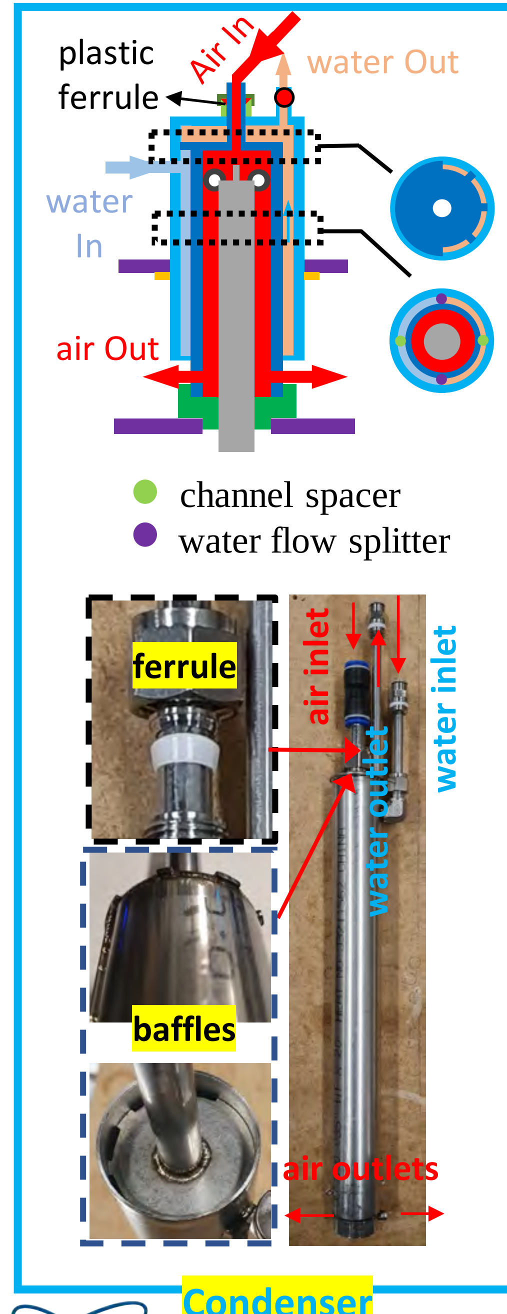
MRP Microreactor Program

Experimental apparatus





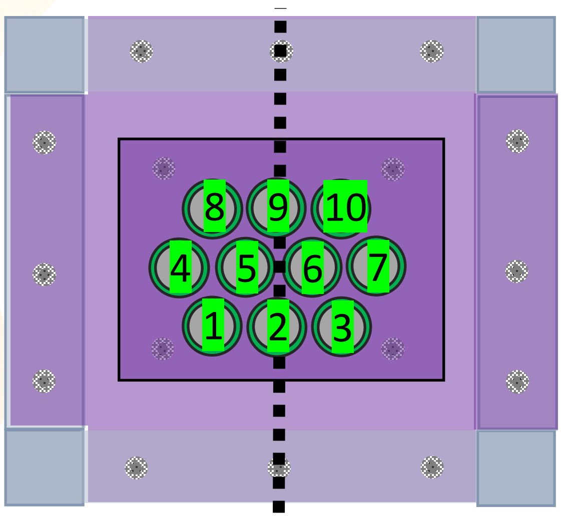




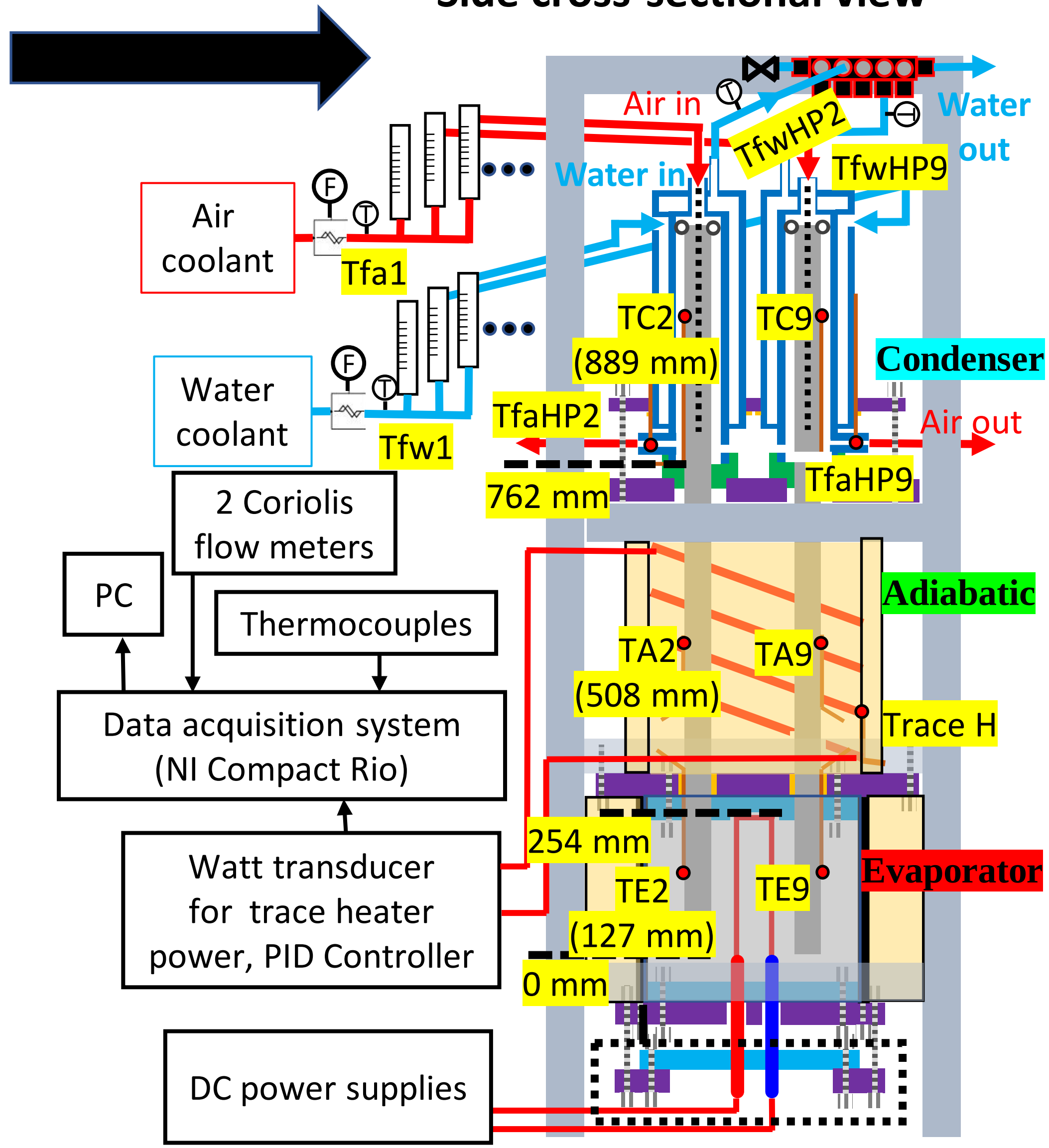
MRP Microreactor Program

Experimental apparatus

Top cross-sectional view



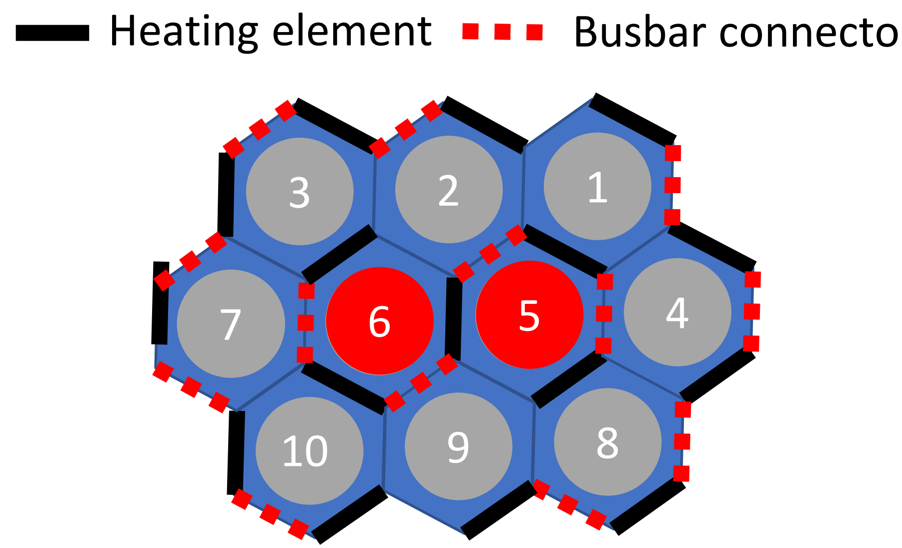
Side cross-sectional view



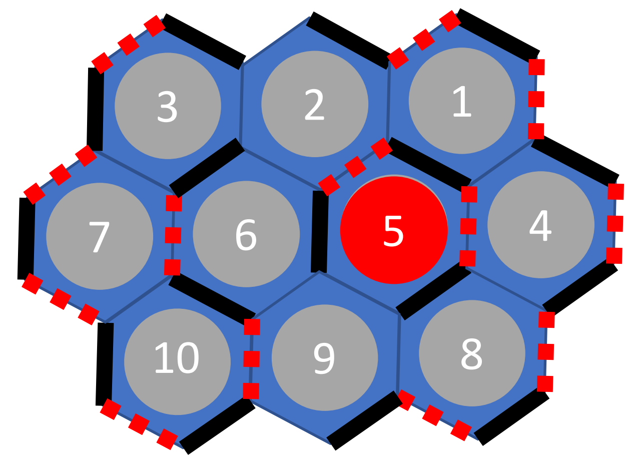
- Heat pipe
- 1.5”x1.5” Al extrusion
- 1” machined collar
- Calcium Silicate insulation
- Spacer plates
- Insulator

Case Study

- Normal operation
  - Change of input power
  - Change of cooling intensity
  - Change of inclination angle
- Non-uniform boundary conditions
  - Change of cooling intensity on individual heat pipe
  - Change of heat flux with different grouping of heating elements
- Abnormal operation
  - Replacing one heat pipe (HP05) with dummy stainless-steel tube
  - Replacing two heat pipes (HP05 and HP06) with dummy stainless-steel tubes



Normal operation (double heat pipe failure)



Normal operation with non-uniform heat flux (single heat pipe failure)

MRP Microreactor Program

Data reduction

- Heat transfer rate of heat pipe:

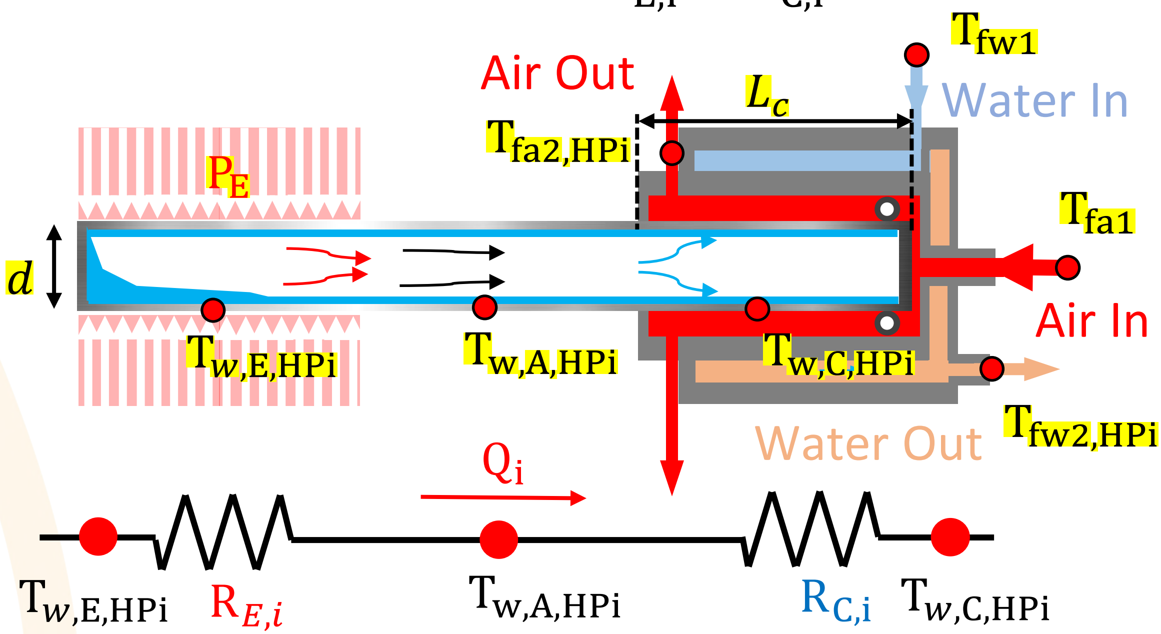
$$Q_{HPi} = c_{p,w}\dot{m}_{w,HPi}\left(T_{fw2,HPi} - T_{fw1}\right) + c_{p,a}\dot{m}_{a,HPi}\left(T_{fa2,HPi} - T_{fa1}\right)$$

- Heat transfer coefficient of heat exchanger:

$$h_{hx,HPi} = Q_{m,HPi}/[\pi d L_c\ (T_{w,C,avg,HPi} - T_{fm,avg,HPi})]$$

- Effective thermal resistance:

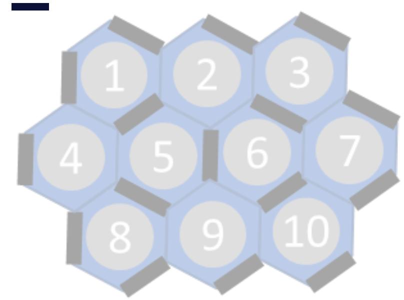
$$R = R_{E,i} + R_{C,i}$$



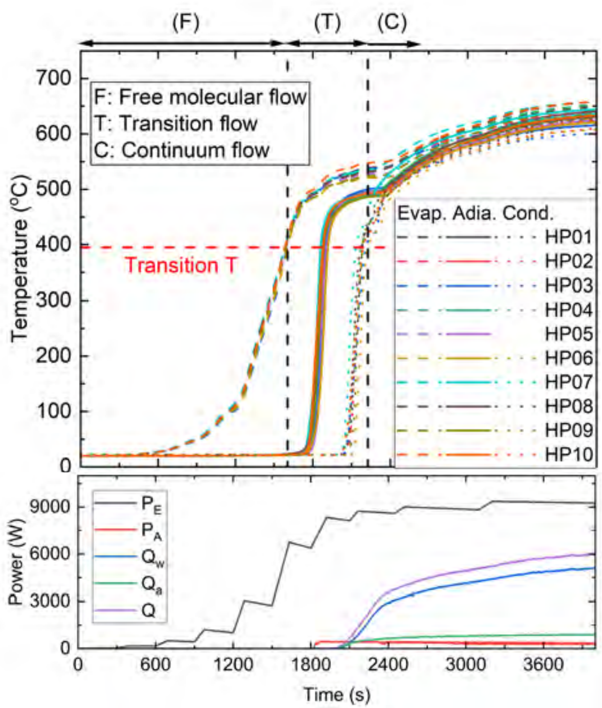
MRP Microreactor Program

Results 1: Uniform boundary conditions – startup process

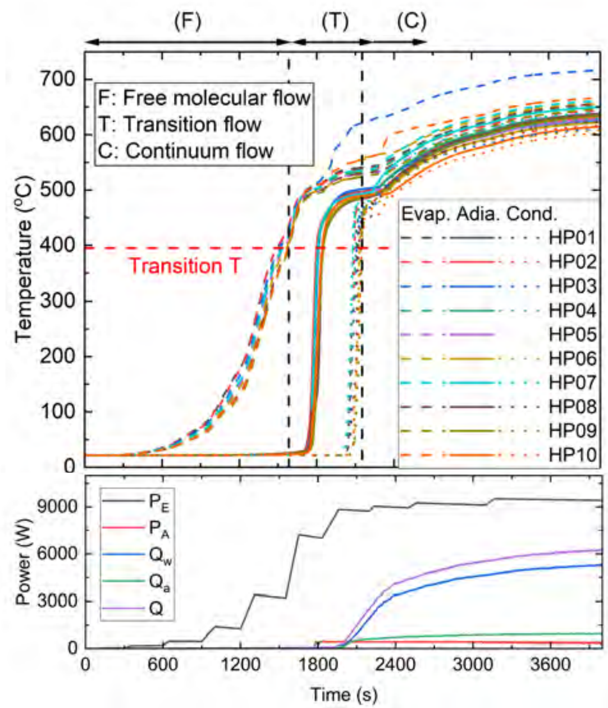
- Successful startup of heat pipes bundle at 9 kW of heating power (6 kW heat transfer rate).
- Time characteristics is similar between the two orientations.



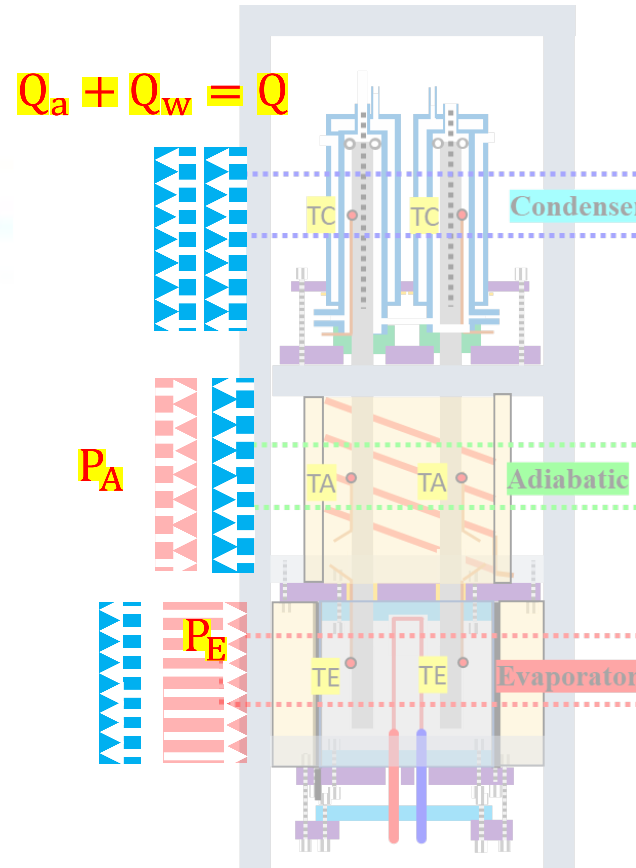
HP layout



Vertical orientation



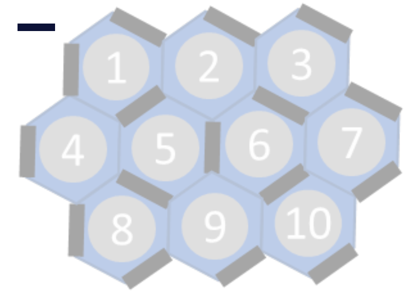
Horizontal orientation



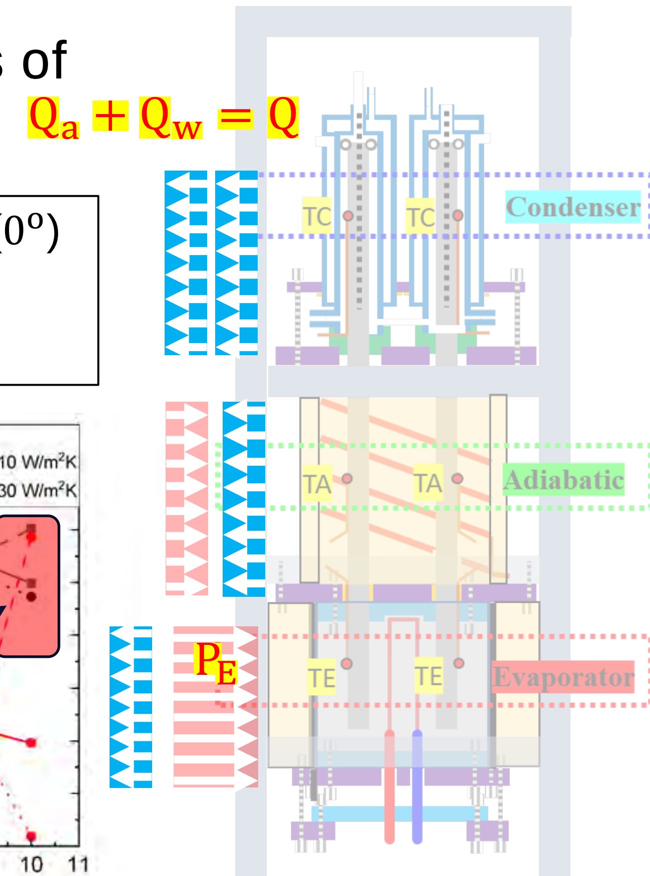
MRP Microreactor Program

Result 1: Uniform boundary conditions – steady-state operation

- The temperature is not uniform even with uniform boundary conditions, especially under horizontal orientation
- These cases serve as references for the scenarios of abnormal operation

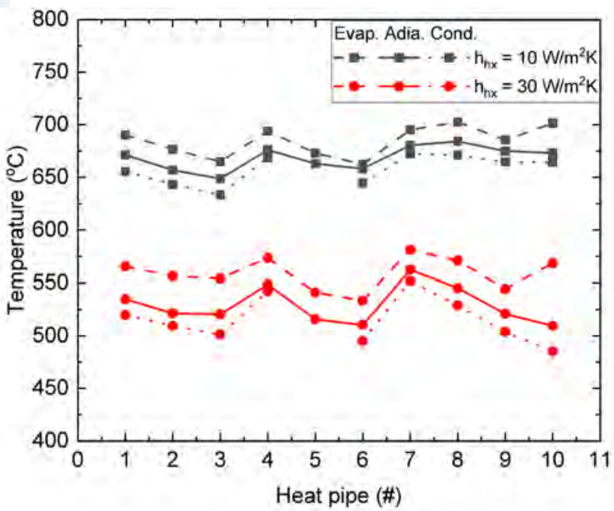


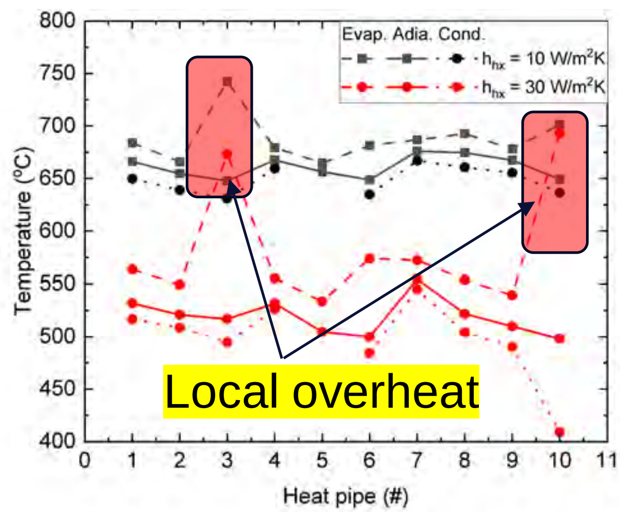
HP layout



- Vertical orientation (90°)
- P = 10 kW
- Q = 6.5 kW

- Horizontal orientation (0°)
- P = 10 kW
- Q = 6.5 kW



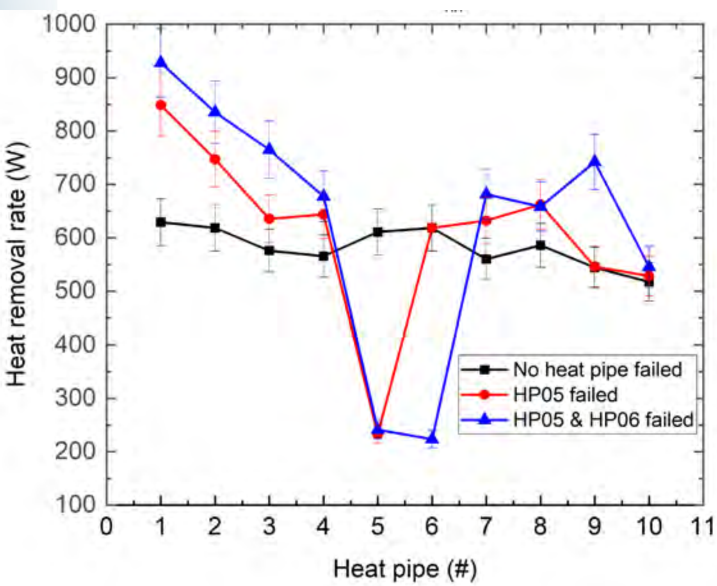


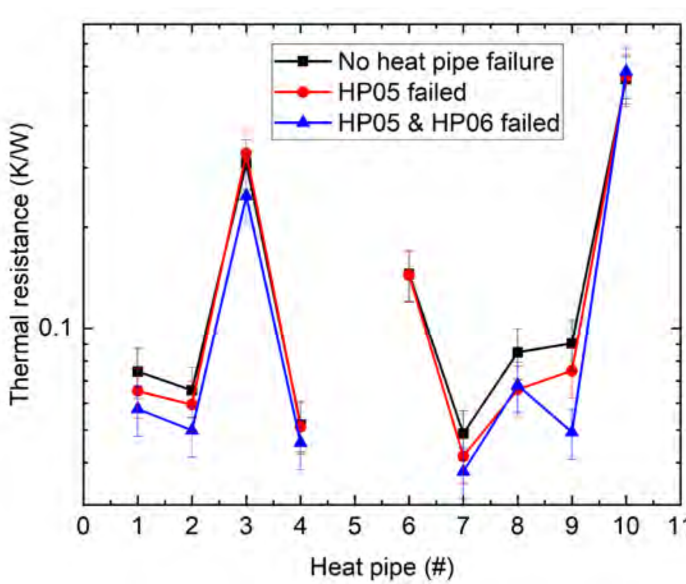
MRP Microreactor Program

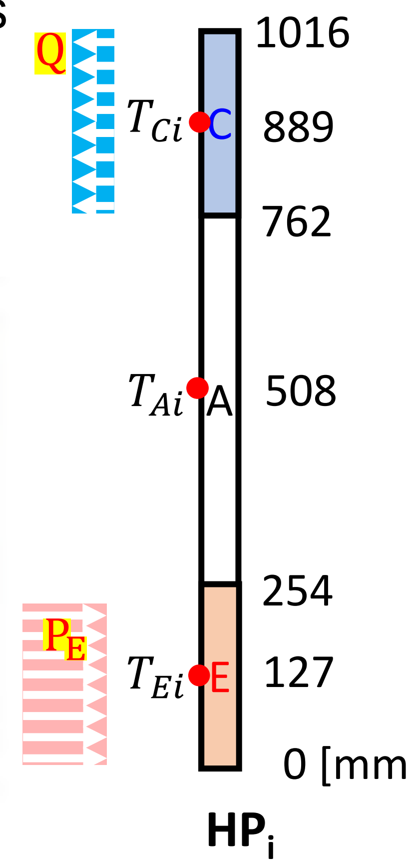
Result 3: Heat pipe failure events – steady-state operation

- Error bars applied based on error propagation
- Neighboring heat pipes compensate for the heat transfer under abnormal scenarios
- The performance of neighboring heat pipes was maintained without increasing effective thermal resistance

Test condition: $\theta = 0^o, P_E = 10\ kW\ (Q = 6.5\ kW),\ h_{hx,HPi} = 30\ W/m^2K$



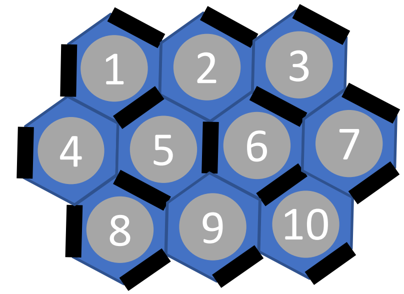




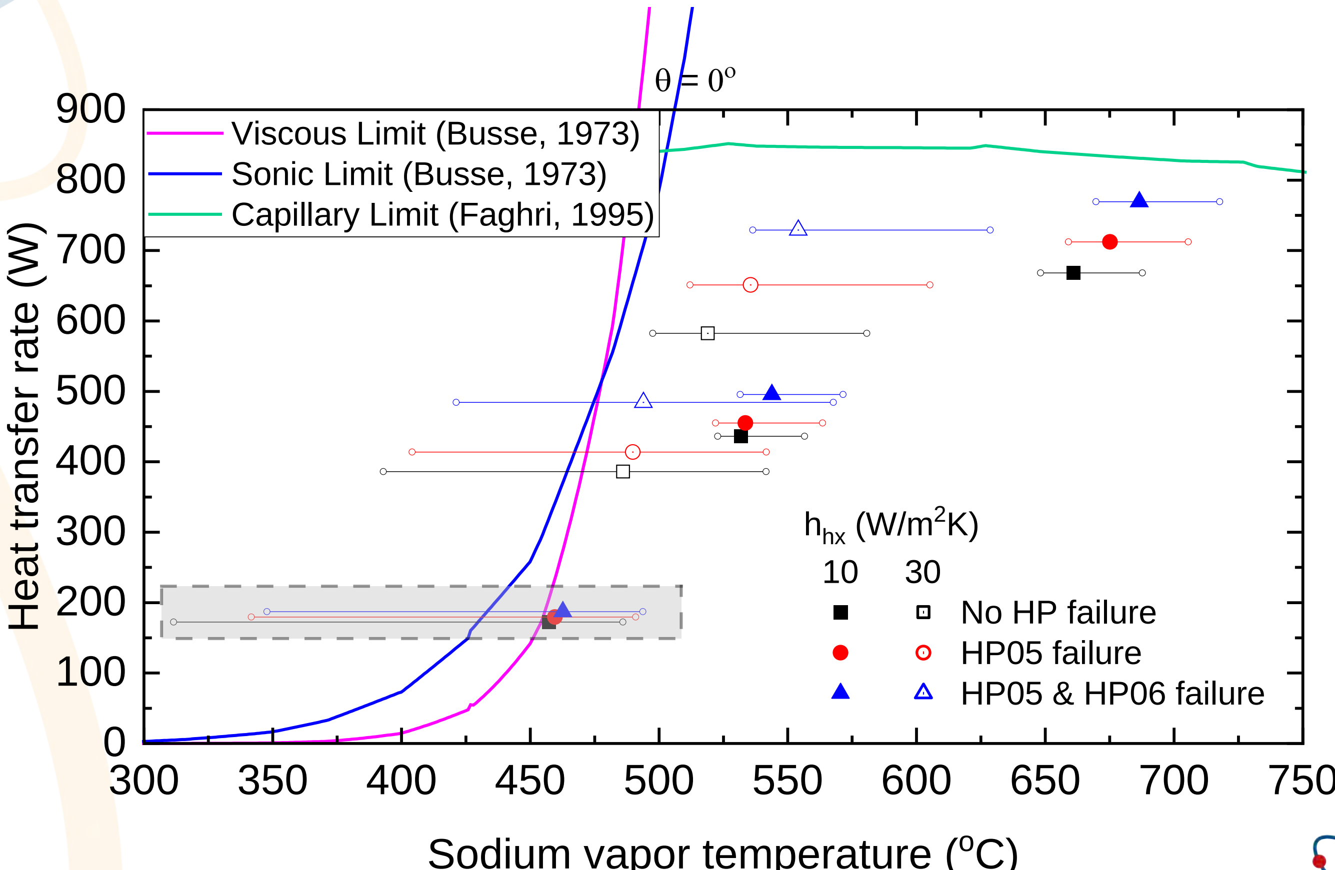
MRP Microreactor Program

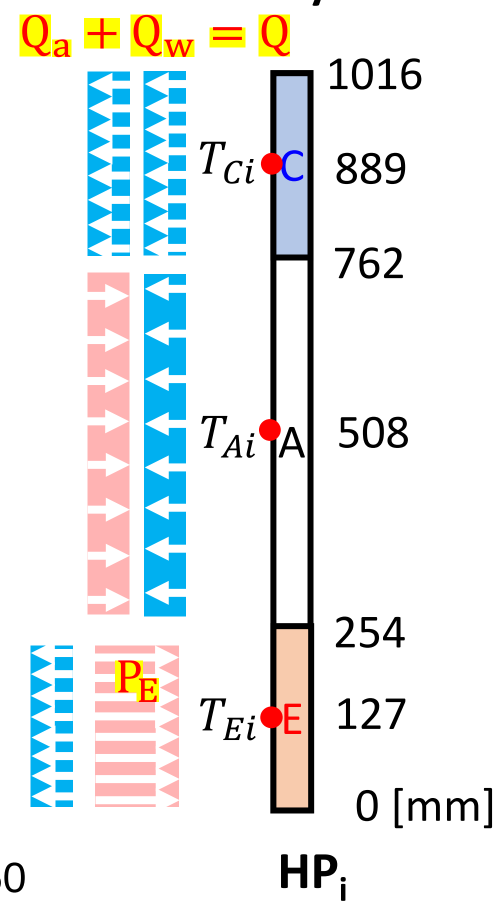
Result 4: Heat pipe operation map

- End-to-end temperature decreases with heat pipe failure events when operating near viscous limit
- Average heat pipe operation (excluding failed) sees an increase in vapor temperature and heat transfer rate with heat pipe failure events



HP layout





MRP Microreactor Program

Conclusion

Separate effect of single heat pipe

- Boiling phenomenon
- Heat pipe operation map

Integral effect of heat pipes bundle

- The startup time characteristics is similar regardless of inclination angle and the failure of heat pipe(s)
- Vertical orientation yields more uniform temperature distribution than horizontal orientation
- Show effect of non-uniform heating and cooling conditions on neighboring heat pipes
- Show effect of single heat pipe failure and double heat pipe failure
  - Neighboring heat pipes can compensate for the heat of transfer of failed heat pipes
  - The operation condition of neighboring heat pipes shifts while maintaining ideal performance

MRP Microreactor Program

Thank you
For your attention
Questions

peihsun@umich.edu

MRP Microreactor Program