MICHIGAN ENGINEERING
UNIVERSITY OF MICHIGAN

(NEUP Project 19-17416) Experiments and computations to address the safety case of heat pipe failures in Special Purpose Reactors

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DOE-NE Microreactor Program

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Two papers for ANS – ATH22: Data analysis for the experimental campaign of vertical orientated HP#1 (FR = 50%) and HP#13 (FR = 25%)

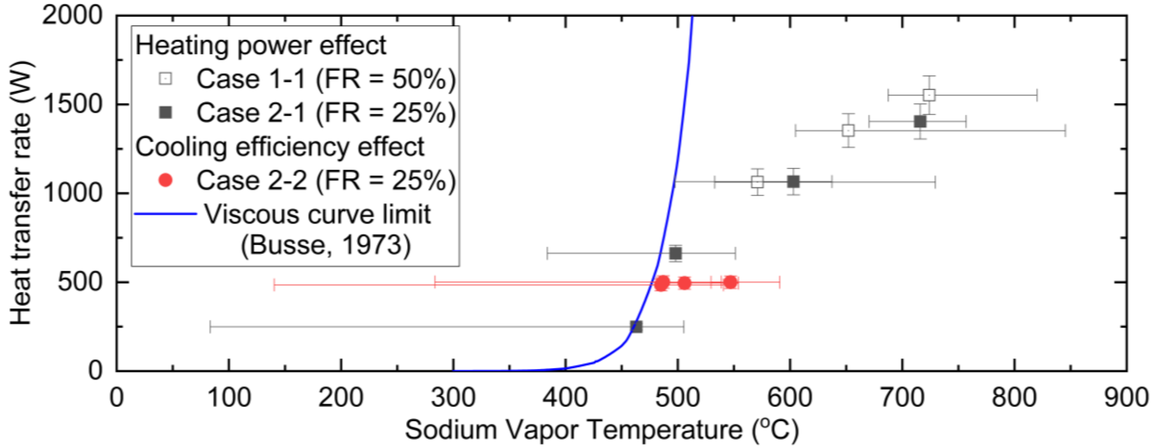
The characteristic plot of HP operation conditions

- The sodium vapor temperature is defined as the average temperature at the adiabatic section; the upper and lower bound of the error bar were referred to the max. and min. heat pipe surface temperature
- The heat transfer rate on the y-axis represents the heat removal rate in the condenser

❖ The cooling conditions and heater input power effects on two HPs with different filling ratios (FR)

- The operation condition of heat pipe is confined by the theoretical viscous curve limitation
- Significant end-to-end temperature differences of heat pipe as the operation condition approach to the viscous curve limitation
- Temperature oscillated in the case of HP with 50% FR unless the power increased above 1500 W

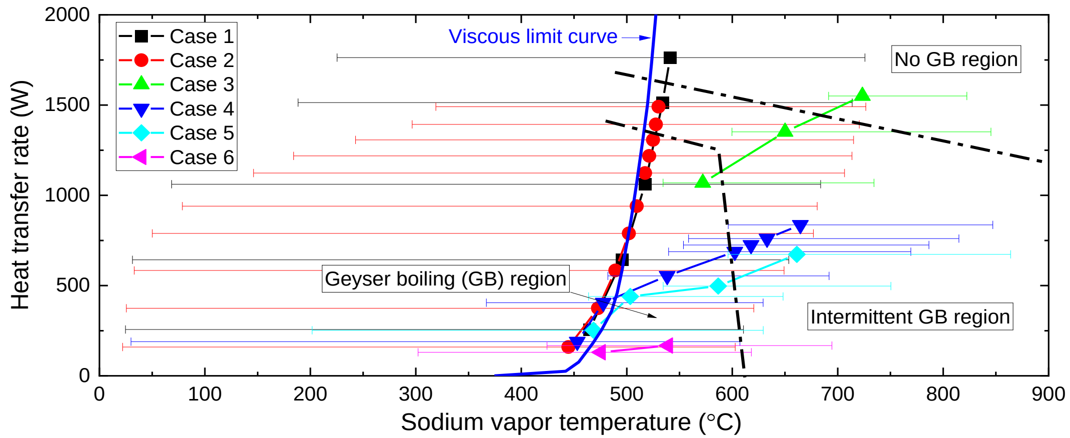
Test	Filling ratios (%)	Filler materials	Water flow rates (g/s)	Air flow rates (g/s)	Heating power (W)
Case 1-1	50	SiC powder	0	6.4	1,500 – 2,250
Case 2-1	25	SiC powder	10	4	500 – 2,000
Case 2-2	25	SiC powder	10	0.48 - 7	800



❖ The cooling conditions and heater input power effects on geyser boiling phenomenon of heat pipe with 50% FR

- As the cooling efficiency decreases, the vapor temperature tends to increase under the given heat transfer condition, facilitating the isothermal operation of the heat pipe.
- The geyser boiling usually occurred in the region near the viscosity limit, and completely disappeared under high heat transfer rate and sodium vapor temperature.
- In between, there is a transition region where intermittent geyser boiling occurs

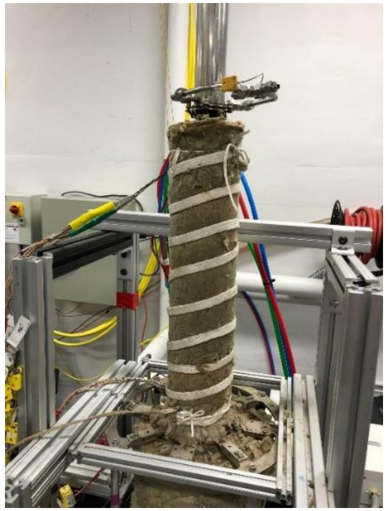
Tests	Filler material	Cooling fluids	Flow rates (g/s)	Cooling efficiency	Heater power range (kW)
Case 1	SiC powder	Water	27 – 28	Highest	500 – 2.25
Case 2	Copper wire	Water	27 – 29	Very high	500 – 2.1
Case 3	SiC powder	Air	6.1 – 6.7	High	1500 – 2.25
Case 4	Copper wire (coarse)	Water	25	Medium	0.5 – 1.5
Case 5	Copper wire	Air	2.2 – 2.9	Low	0.5 – 1.5
Case 6	Copper wire (oxidized)	Air	1.2	Very low	0.5 – 0.75



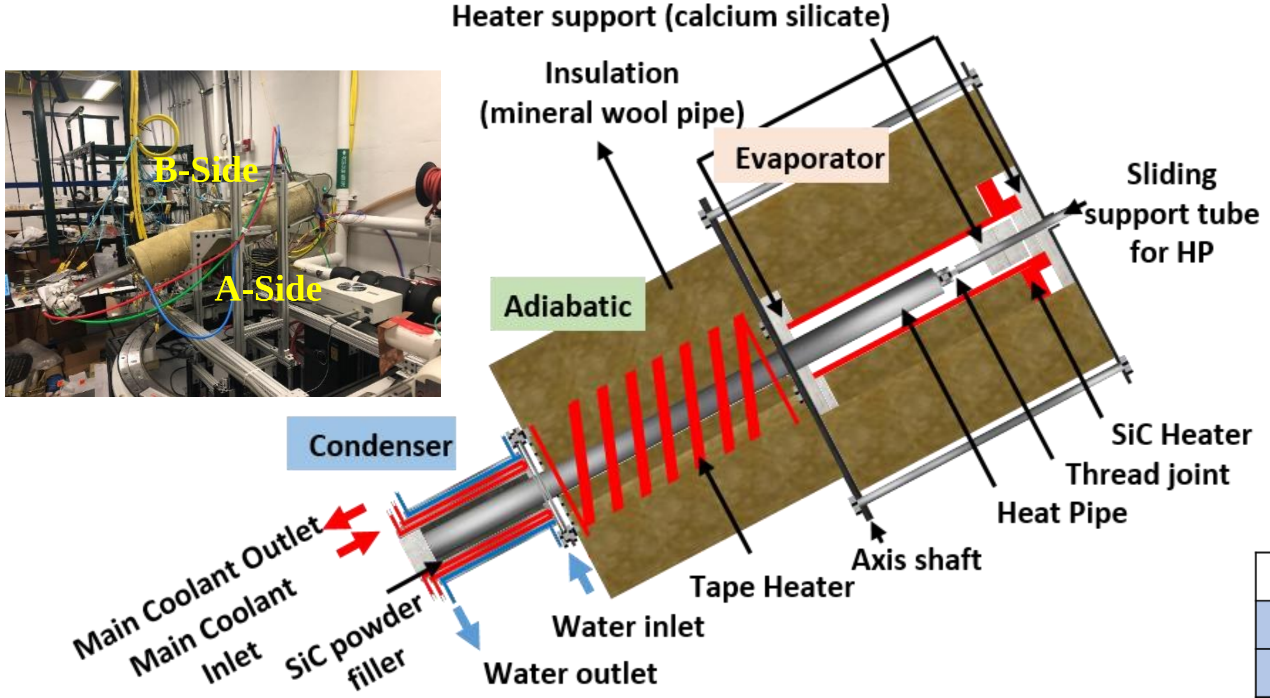
The startup process and performance of a negative orientated heat pipe

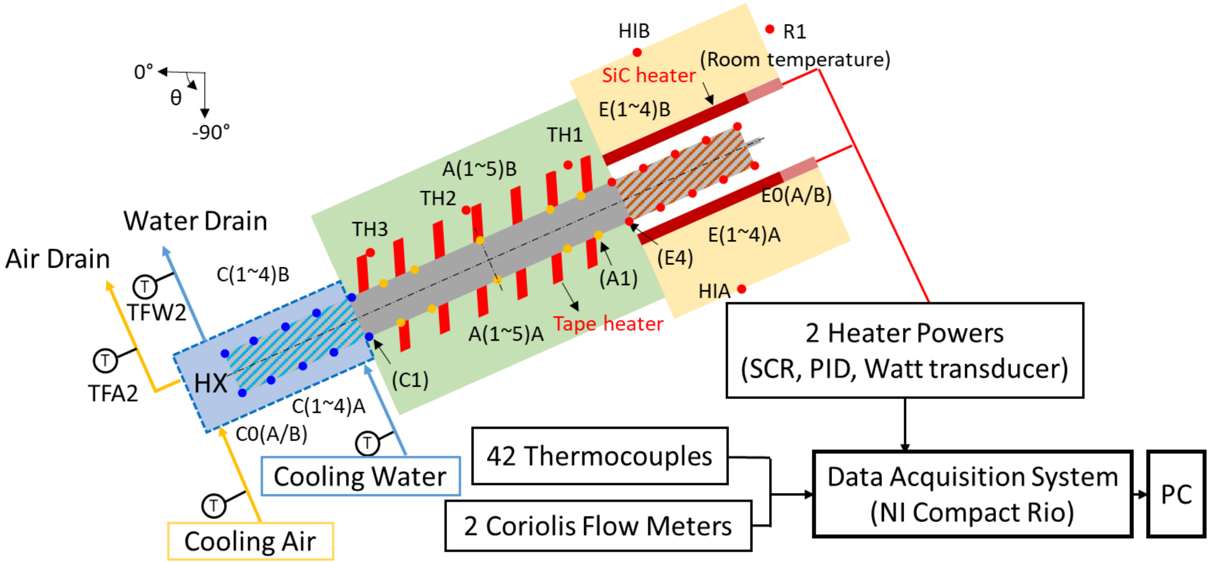
❖ Experimental Apparatus

- B-side was arranged at the top side, which is against the gravity more than A-side
- Trace heater was installed in the adiabatic section and controlled by PID with the setting temperature slightly lower than the minimum temperature in the adiabatic section
- SiC powder was applied between the heat pipe and heat exchanger to enhance the cooling efficiency in the condenser



<Trace heater>

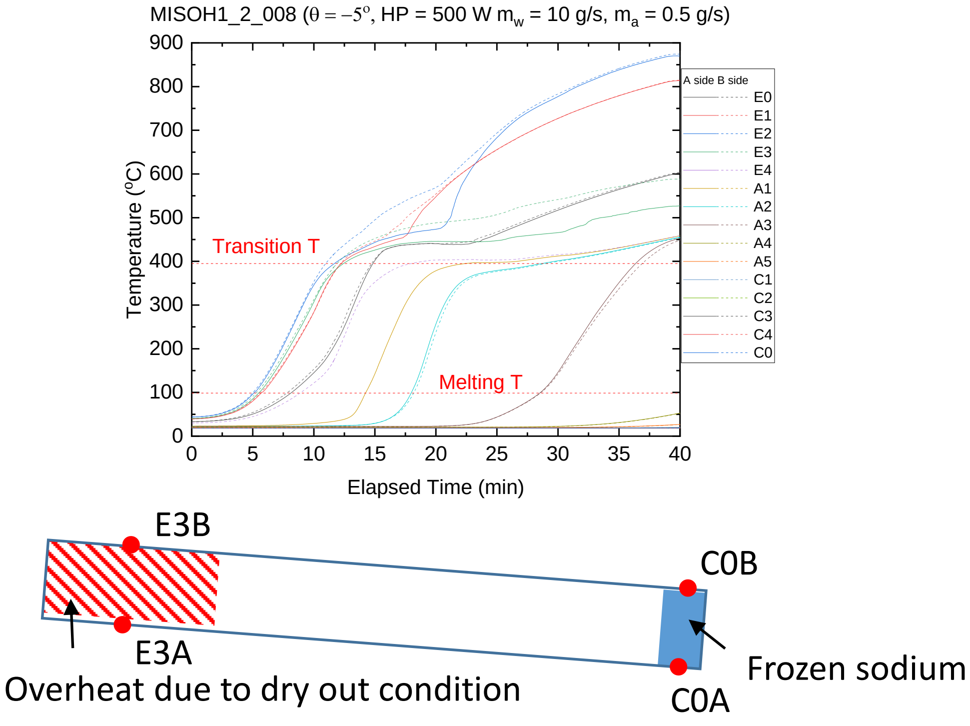




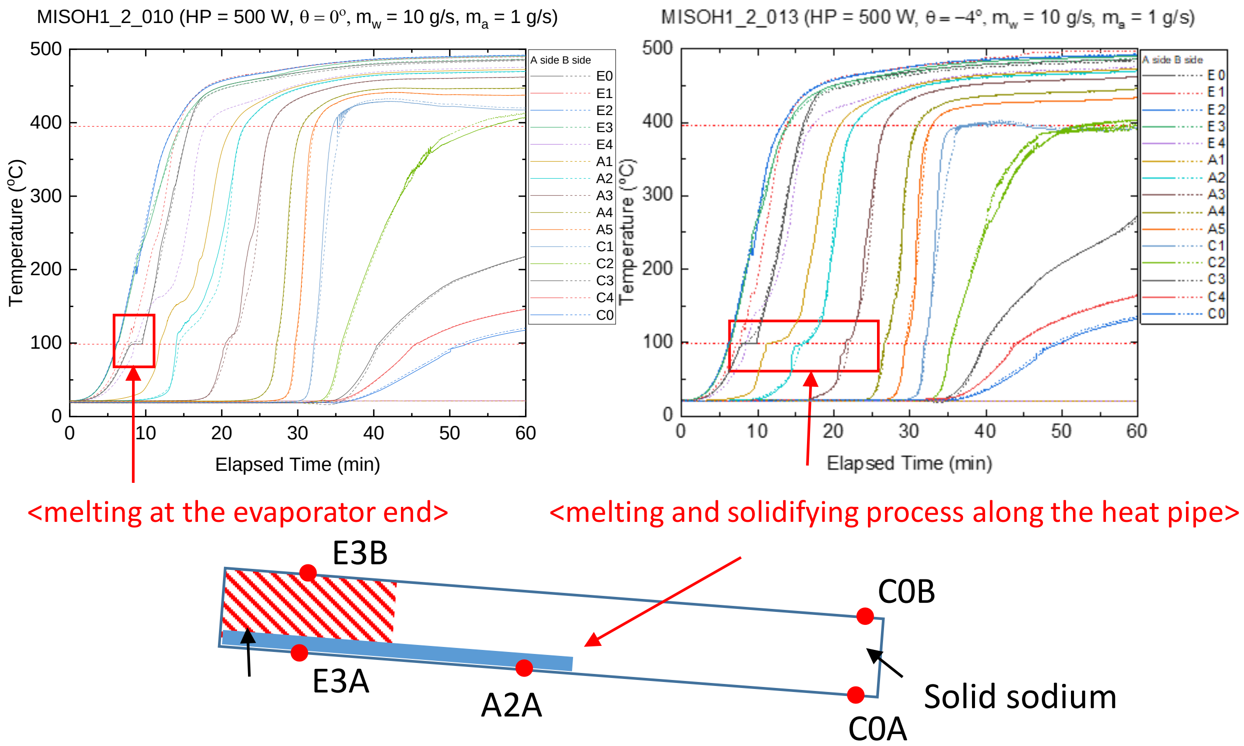
30 TC locations on the heat pipe (mm)														
$T_{w.C}$					$T_{w.A}$					$T_{w.E}$				
C0	C4	C3	C2	C1	A5	A4	A3	A2	A1	E4	E3	E2	E1	E0
1016	952.5	889	825.5	762	698.5	635	508	381	317.5	254	190.5	127	63.5	0

The startup process and performance of a negative orientated heat pipe with 25% filling ratio

❖ The effect of initial sodium location in the heat pipe



❖ The effect of inclination angle on the startup process of the heat pipe

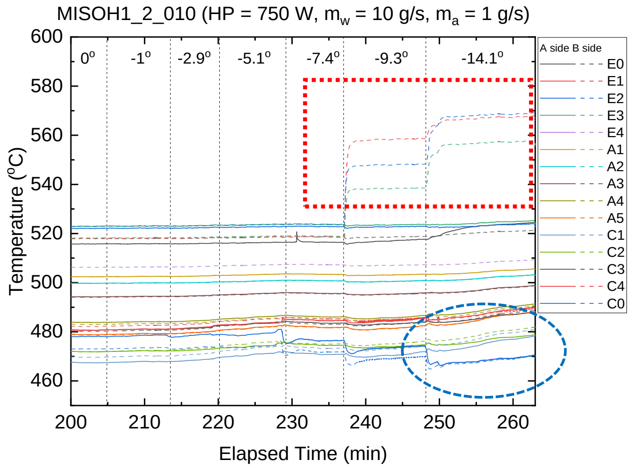


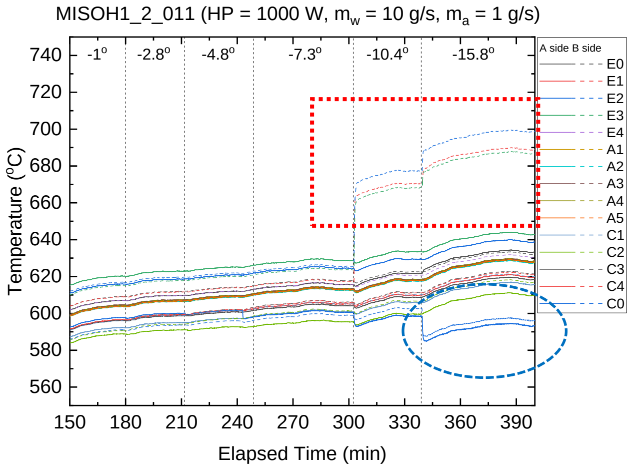
Summaries

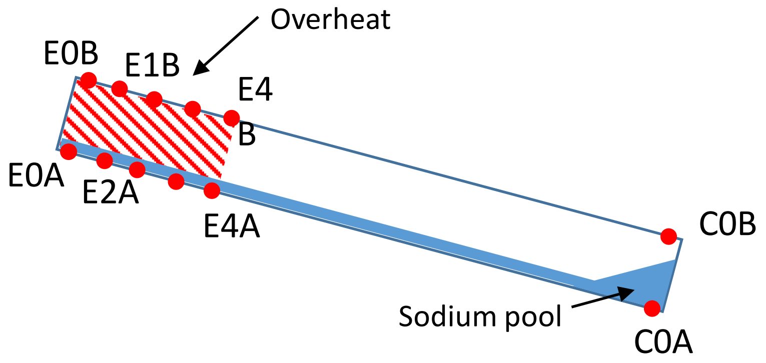
- The initial location of sodium in the heat pipe is crucial for the successful startup of the heat pipe, when solid sodium was initially located at the condenser under slightly negative inclination, fail startup was presented severe overheat in the evaporator region.
- When the solid sodium was initially located in the evaporator, the melting and solidifying process along the heat pipe during startup under negative inclination angles.

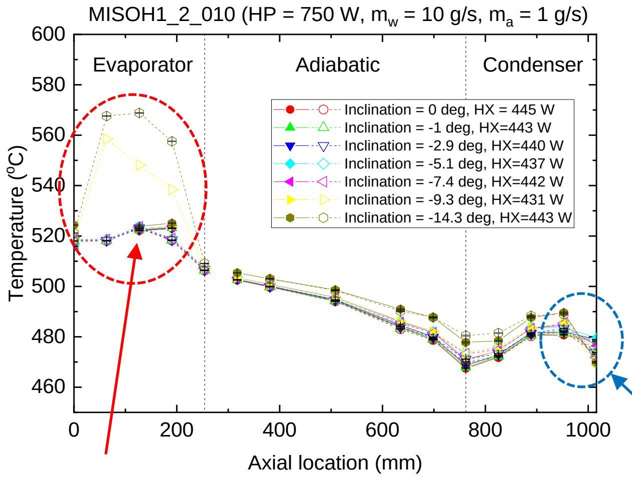
The startup process and performance of a negative orientated heat pipe with 25% filling ratio

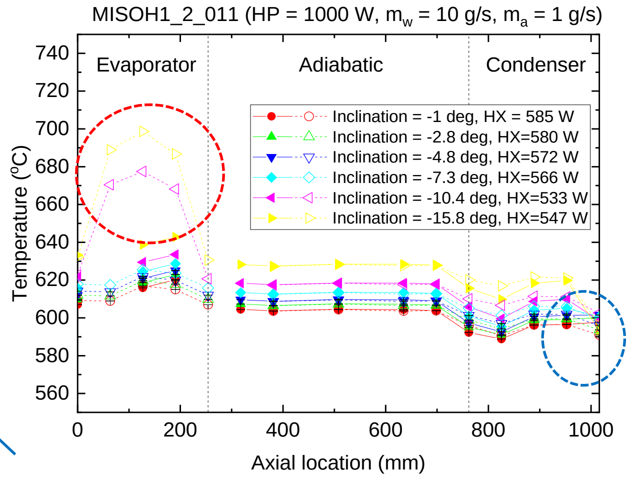
❖ The change of inclination during operation of heat pipe











Overheat at the B-side of evaporator

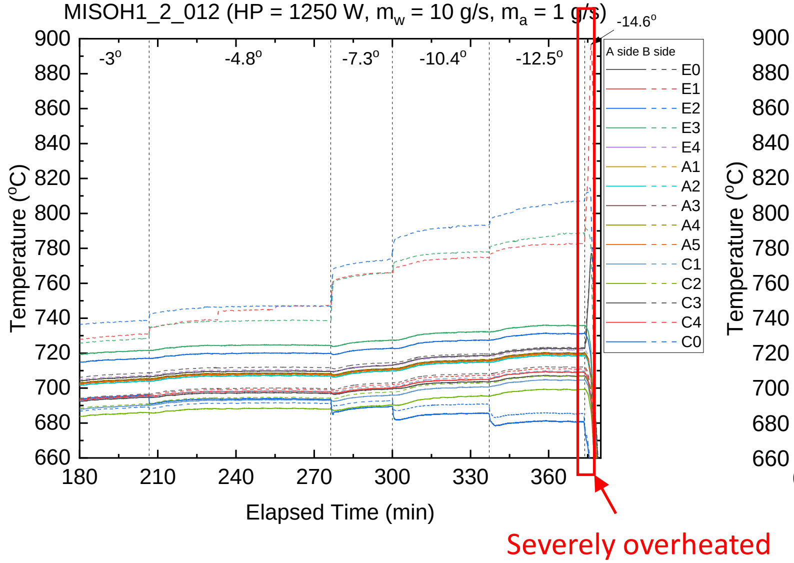
Formation of liquid pool at the A-side of condenser end

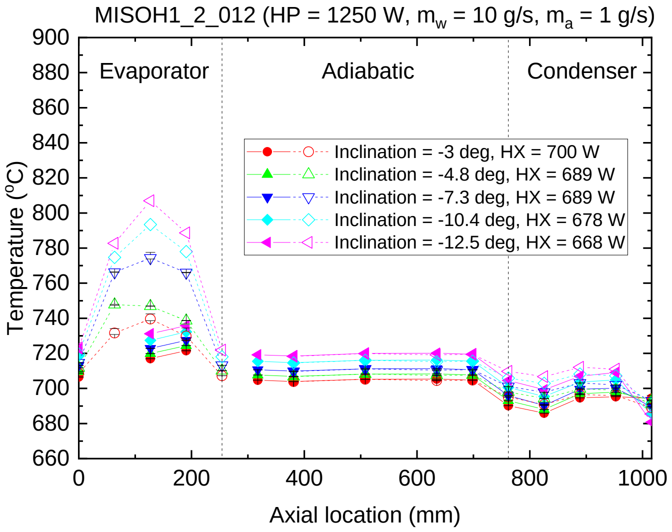
Summaries

- Liquid reservoir formed in the condenser end under the heating power of 750 W with -7.4 deg and heating power of 1000 W with -10.4 deg.
- B-side at the evaporator was overheated under the heating power of 750 W with -9.3 deg and heating power of 1000 W with -10.4 deg.

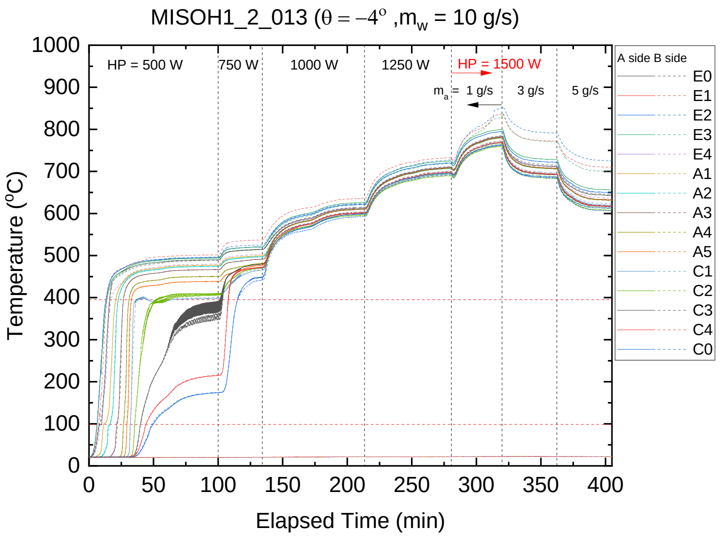
The startup process and performance of a negative orientated heat pipe with 25% filling ratio

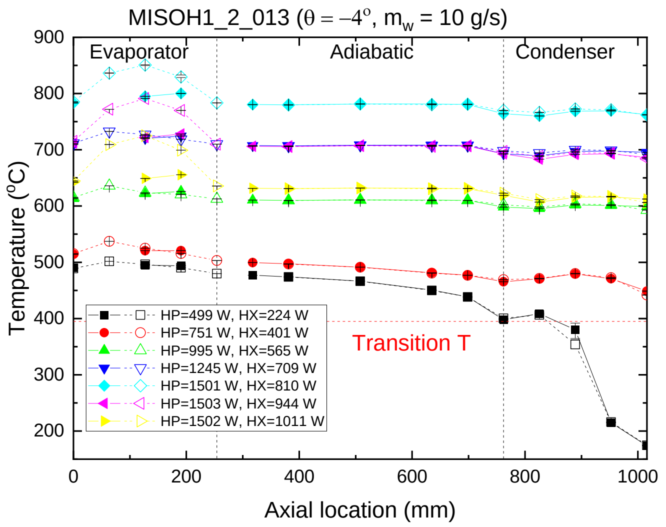
❖ The change of inclination and cooling condition during operation of heat pipe





MISOH1_2_012: As the input power ≤ 1000 W, the heat pipe can be operated under -15 deg, but the temperature becomes not isothermal (overheated at the B side of the evaporator and subcooled at the A side of condenser end). On the other hand, severe overheat occurred as the input power approaches 1250 W under -14.6 deg

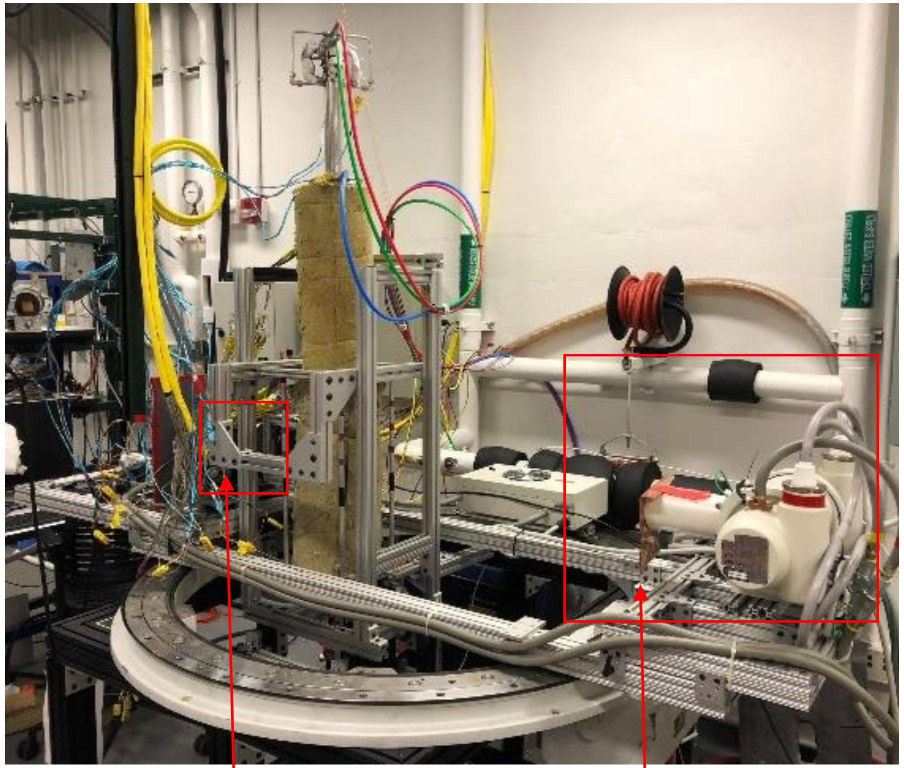




MISOH1_2_013: Comparing the steady-state temperature profile between pink and dark blue and between yellow and green. B side at evaporator was overheated under high heat transport rate with the same sodium vapor temperature. It is because more sodium is needed to support such a high heat transport rate so insufficient liquid sodium at B side lead to overheat

X-ray radiography measurement of a vertical orientated heat pipe with 25% FR

- Experimental Apparatus
  - Test section (MISOH1)
    - Vertical HP (90 deg)
    - m_a= 4 g/s
    - m_w = 10 g/s
  - X-ray radiography system
    - X-ray tube - 150 kV, 80 mA, 500 ms
    - Detector settings - 360 frms, 300 Hz

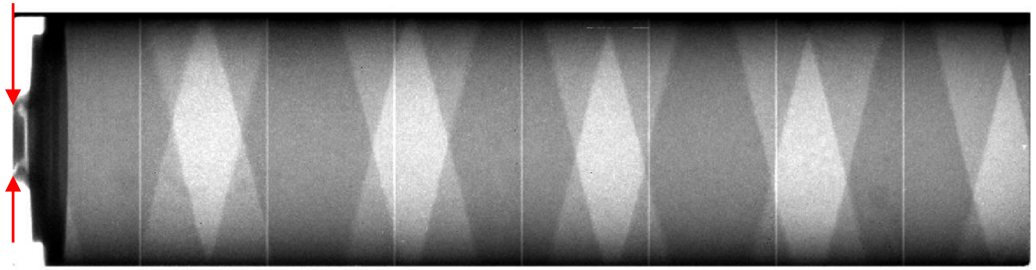


Detector

X-ray tube

- Measurement preparation
  - Magnification factor was estimated based on the known dimension of injection tube on the heat pipe

Digitalization: 8.11 mm
(Real: 8 mm)

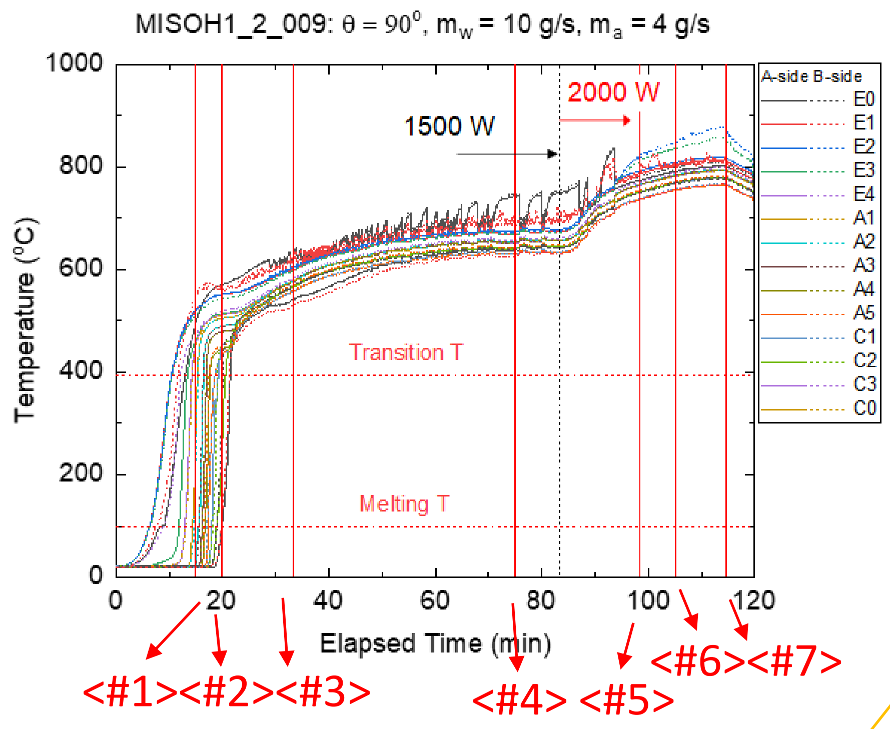


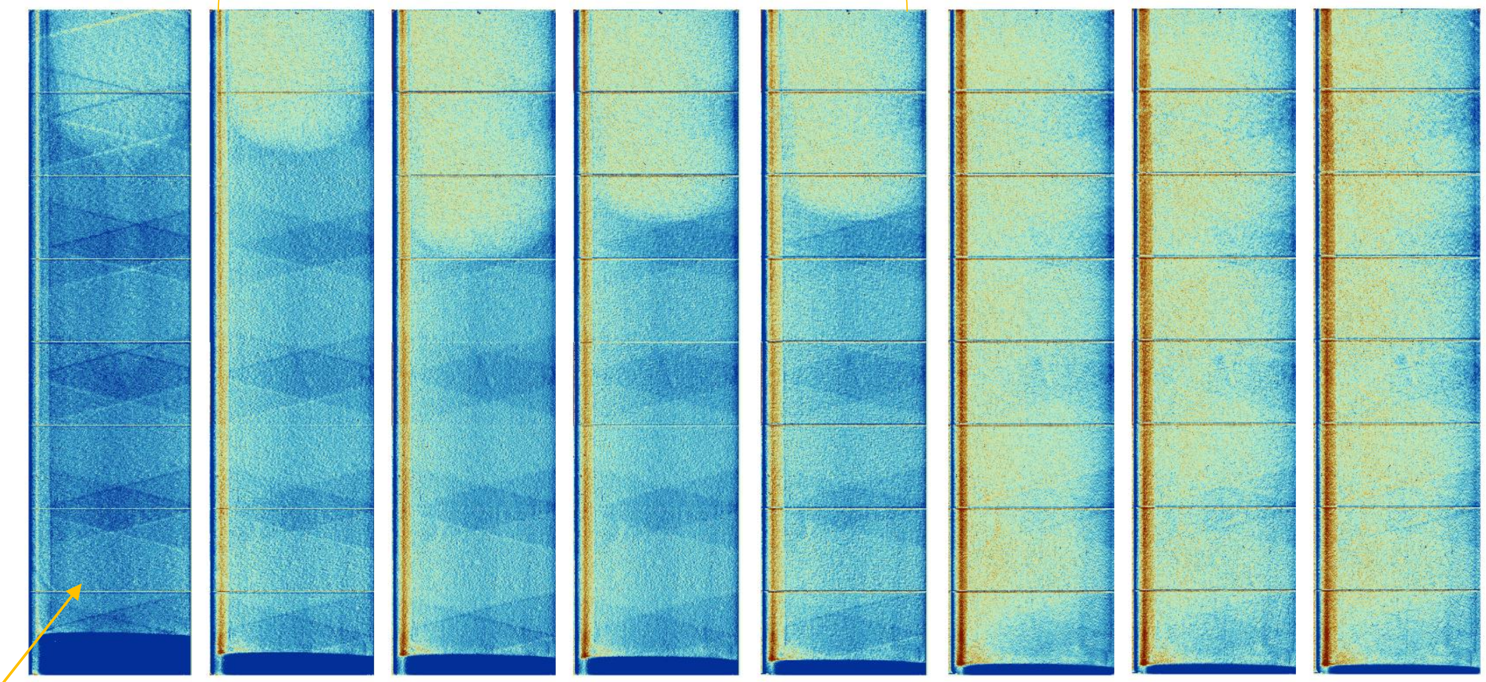
Magnification factor (MF) = 1.01315

  - Calibration image was acquired by measuring a dummy tube with the same dimension of the heat pipe container

Dummy tube

X-ray radiography measurement of a vertical orientated heat pipe with 25% FR





<Averaged images>

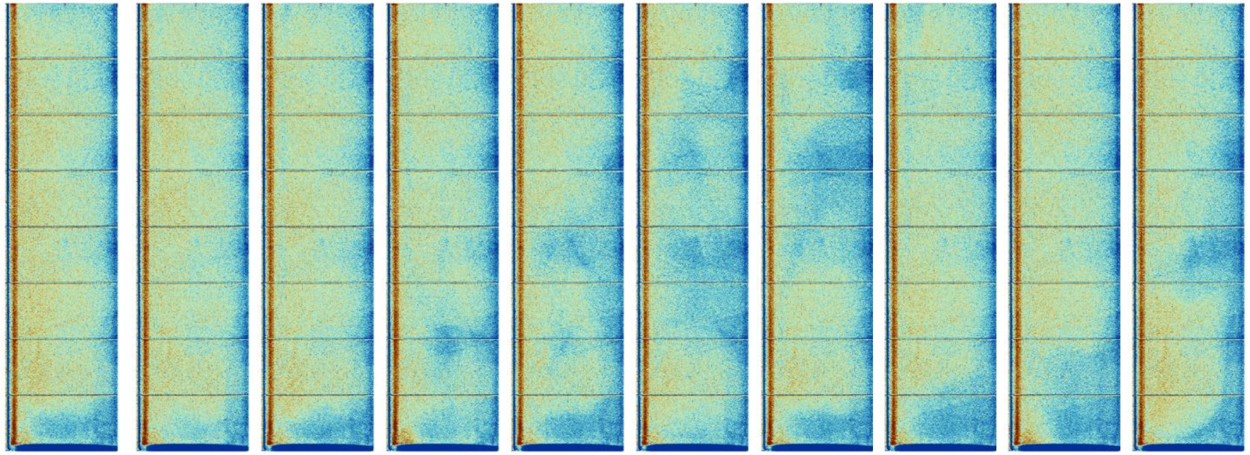
Summaries

- No two-phase flow was observed under the heating power of 1500 W (only liquid pool presented)
- Intense two-phase flow was captured as the heating power proceeded to 2000 W

X-ray radiography measurement of a vertical orientated heat pipe with 25% FR

❖ Transient flow images

<#5>



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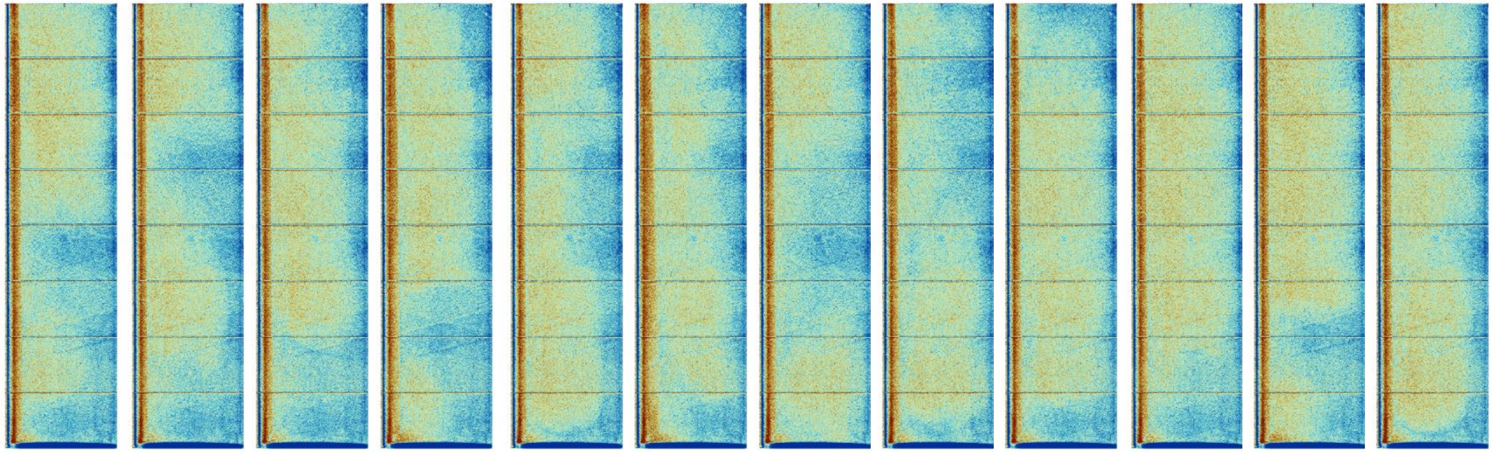
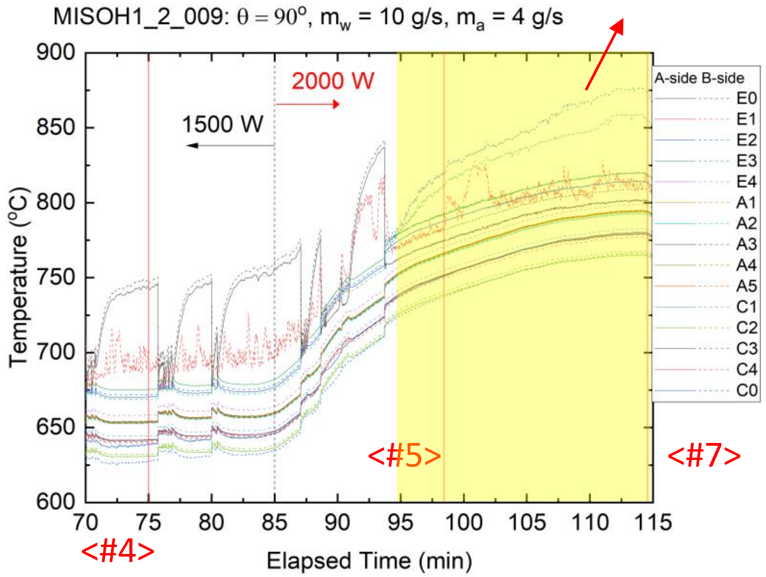


<Around 50^{o}C overheat at B side (left side on the images) under 2000 W where intense two-phase slug flow observed>



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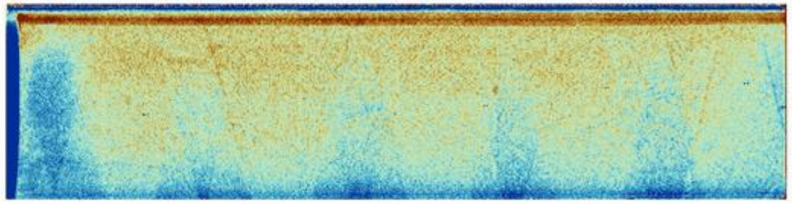

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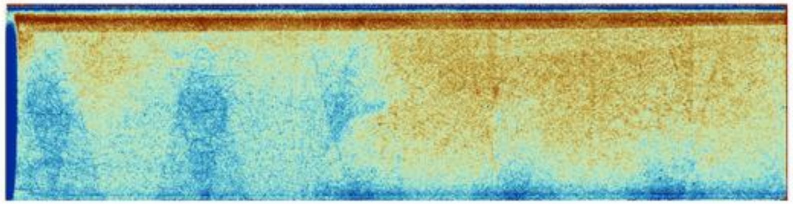
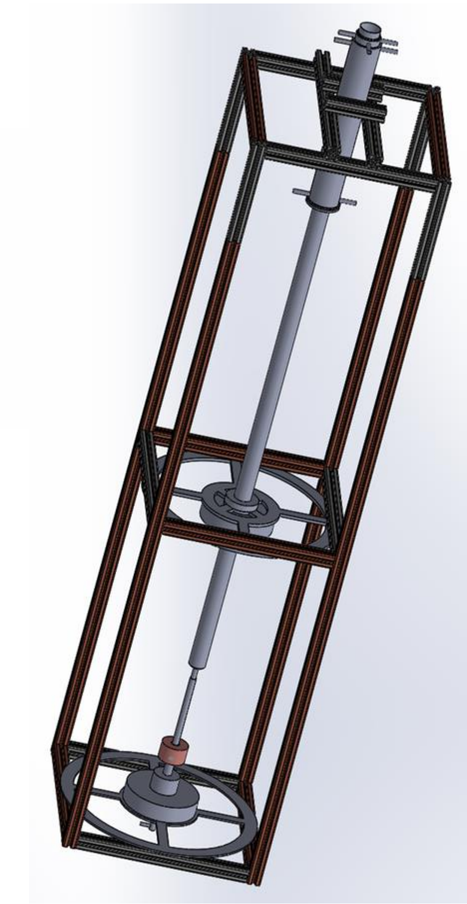


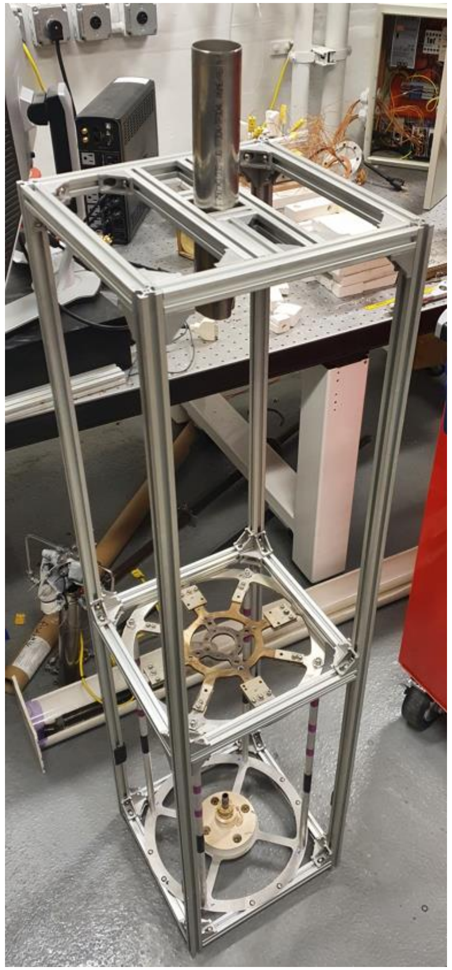
The sodium vapor was mostly generated from the B-side during the transient process, which matches with the temperature readings (B side temperature was higher than A side in the evaporator)

Test section upgrade

❖ Structural upgrade

- Additional Aluminum profiles were installed on the test section to enhance the integrity of the structure and prevent the heat pipe from touching the heater during operation





❖ New split (UX type) SiC heater for X-ray radiography measurement

- Although the heater strip artifacts presented on the X-ray images had been mitigated upmost by the developed image morphing tool in the Matlab environment, the heater with uniform surface is desirable because it makes the analysis of void fraction becomes possible

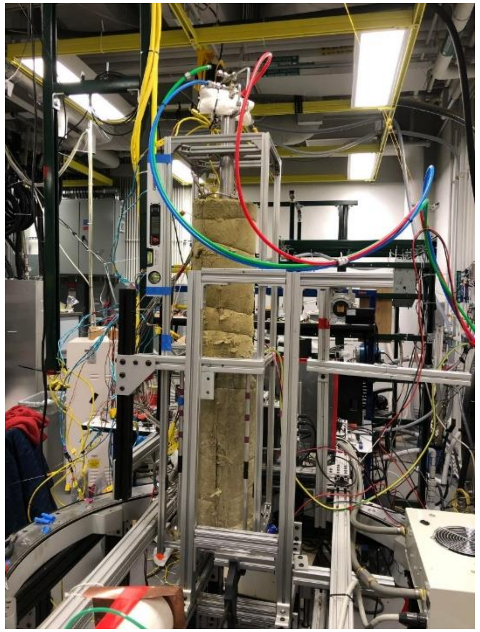
For that, a DC power supply is required for controlling because of the difference of resistance range.

The new heaters had arrived, and the DC power supply had been ordered.

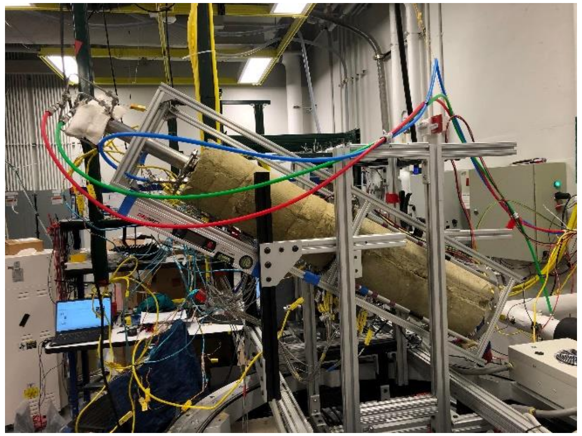
New experimental campaign (In progress)

- Experimental Apparatus
- Trace heater was installed in the adiabatic section and controlled by PID with the setting temperature slightly lower than the minimum temperature in the adiabatic section
- SiC powder was applied between the heat pipe and heat exchanger to enhance the cooling efficiency in the condenser
- Experimental purpose
- Investigate the heat pipe performance under highest cooling efficiency with upgraded test section
- Boundary conditions:
- Air mass flow rate = 7.5 g/s, Water mass flow rate = 10 g/s, HP inclination angle = 90, 30, 15, 0 deg with HP#31 (similar filling ratio as HP#13)

<Upgraded test section>



<90 deg>

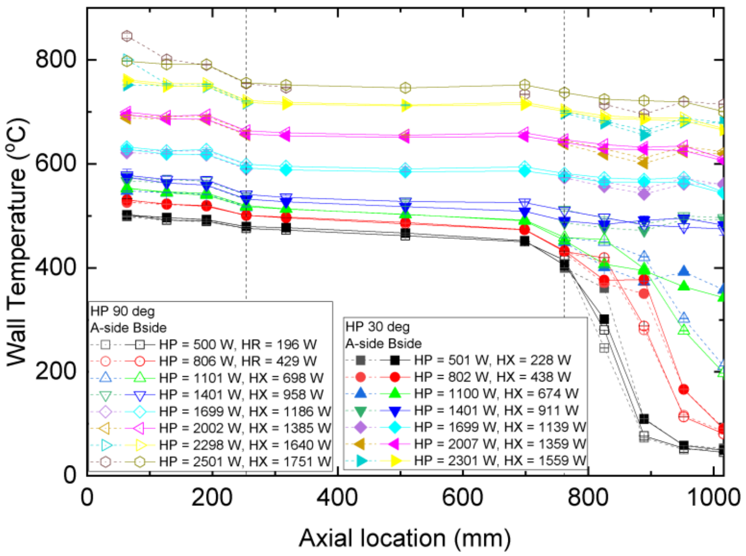


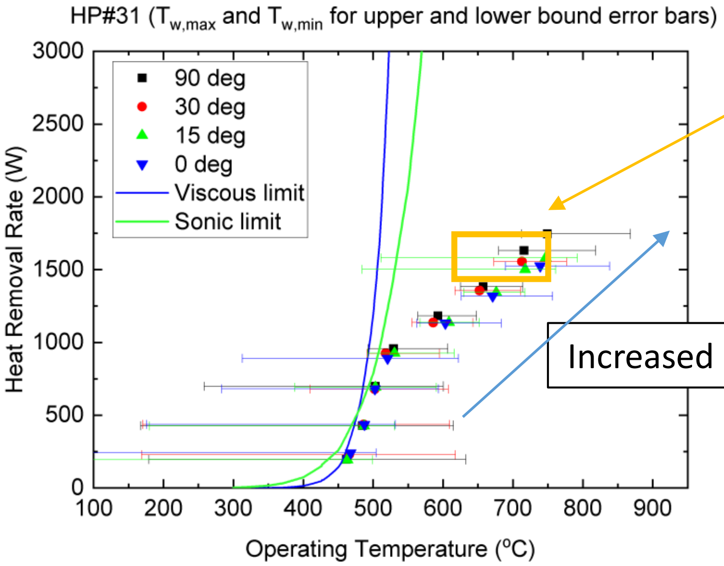
<30 deg>

Results

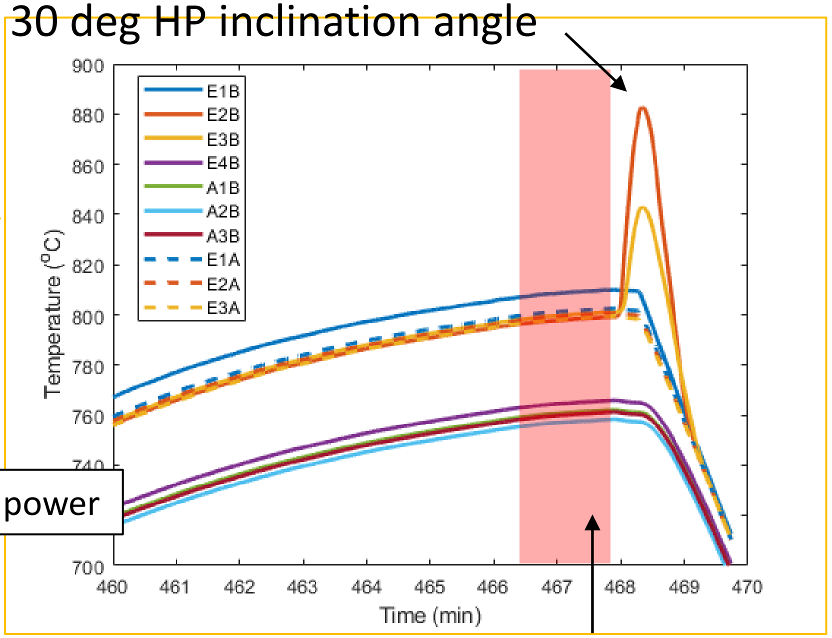
sudden temperature peak under high heat transfer rate with 30 deg HP inclination angle

MISOH1_3_002



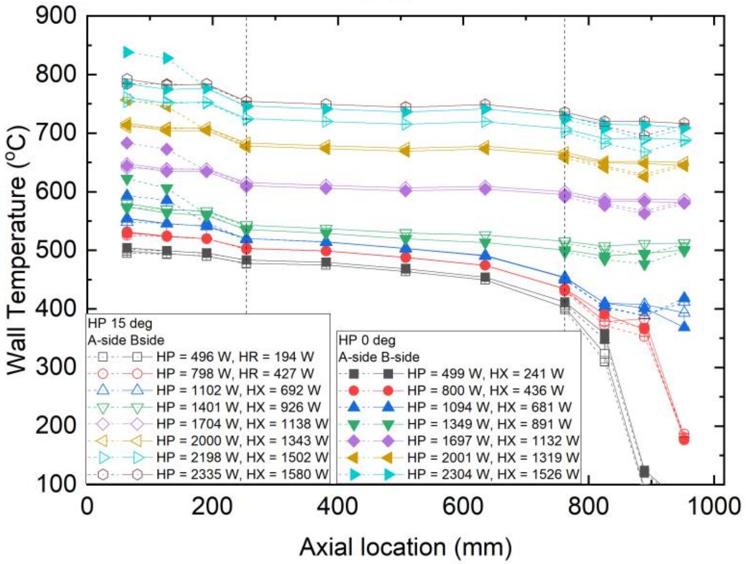


Increased input power



Acquired quasi steady-state data

MISOH1_3_003 - 004

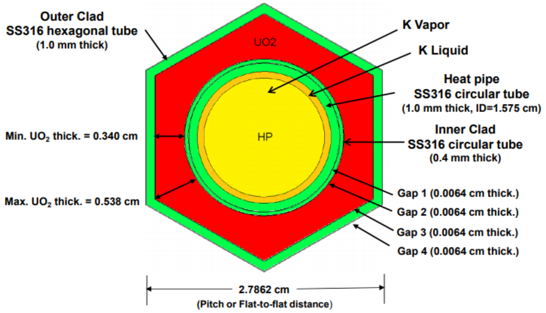


Summaries

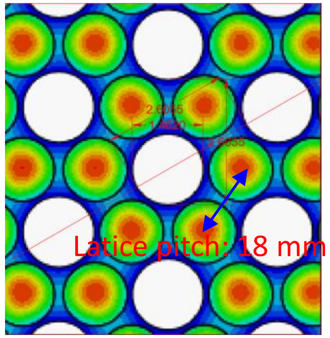
- The operating temperature of the heat pipe follows similar operation curve regardless of the inclination angle
- Large end-to-end temperature differences of the heat pipe as operating near viscous curve
- A sudden temperature surge at B-side of heat pipe (top side) under high heat transfer rate with 30 deg of hp inclination angle, which is possibly resulting from the CHF or local dry-out

Heat pipe mini-core design

❖ Design of the evaporator



<Design A>
P/D = 1.570

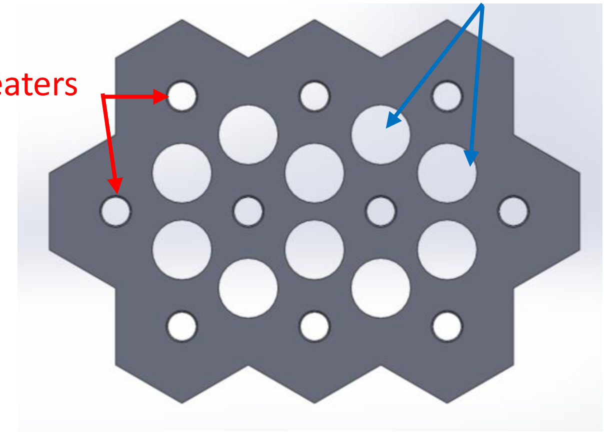


<Design B>
P/D = 1.756
(Sterbentz et al. 2018)

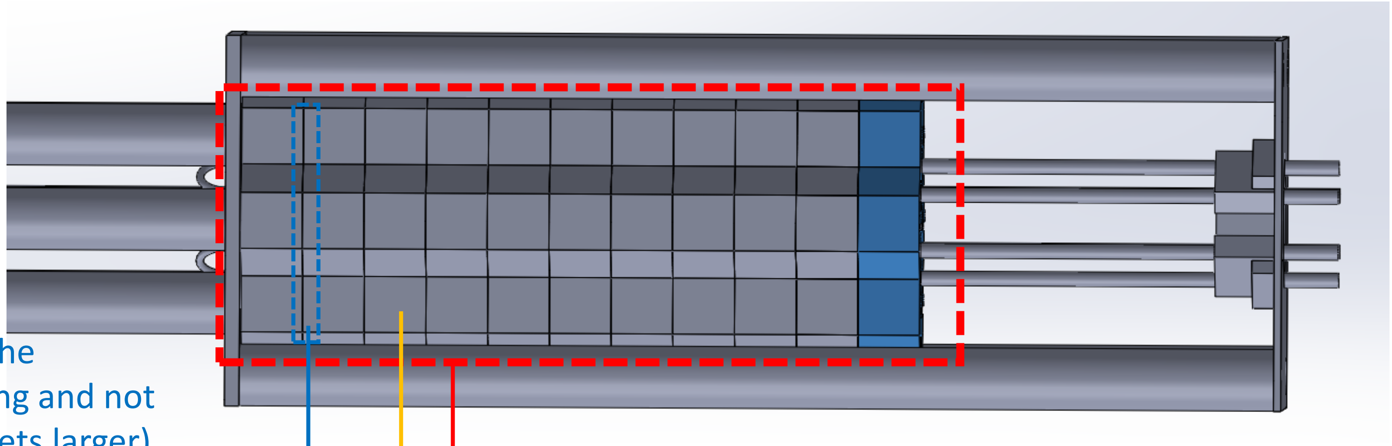
<Top View>

Holes for Heat pipes

Holes for MoSi2 heaters



<Side View>



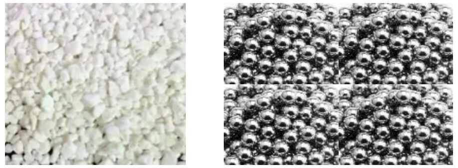
<Heating element>

MoSi2 Heating element
(3 mm OD (HZ) x 6 mm OD (CZ))

Potential issues and solutions

Contact resistance between the blocks
- Using larger blocks (2” or more), but the machining will be somehow challenging and not precise (enlarged error as the depth gets larger)
- Applying high temperature thermal paste between slabs

<Conductive powder>



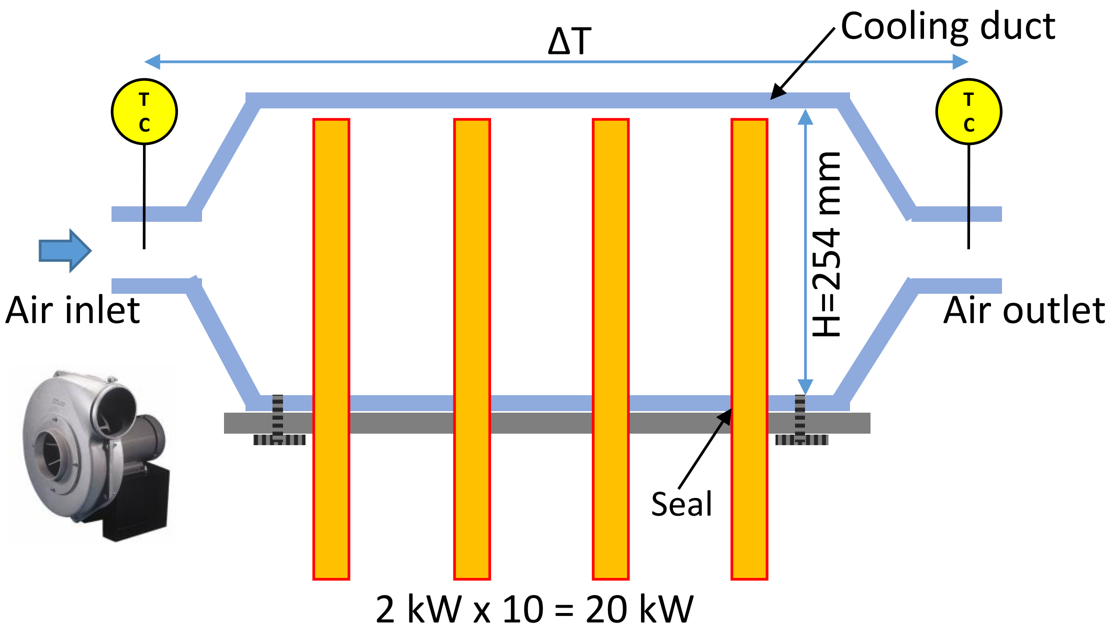
<Alternative: coarse pebble or beads>

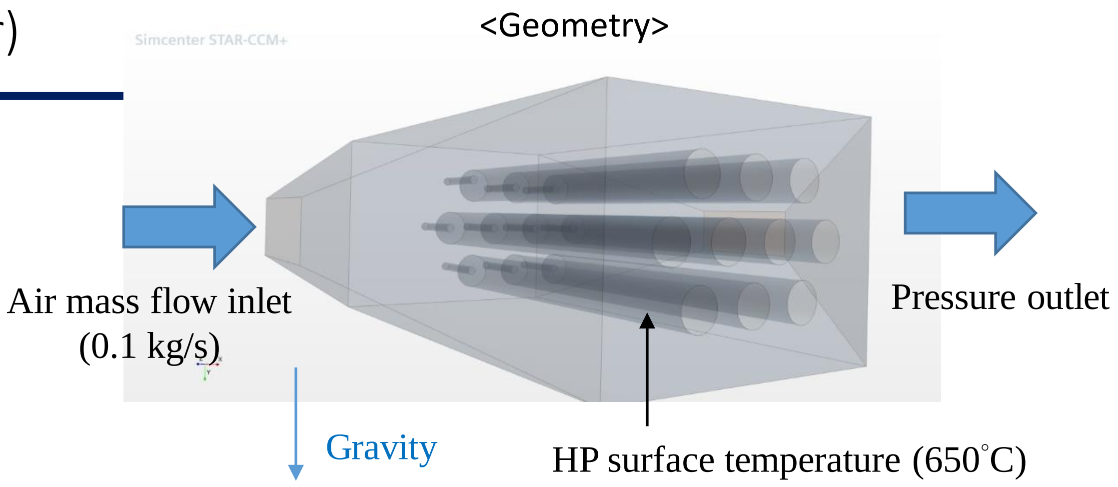
Weight of the hex block
- Strong bottom insulation support
- Angle adjustment by two different height support at the condenser and evaporator sections

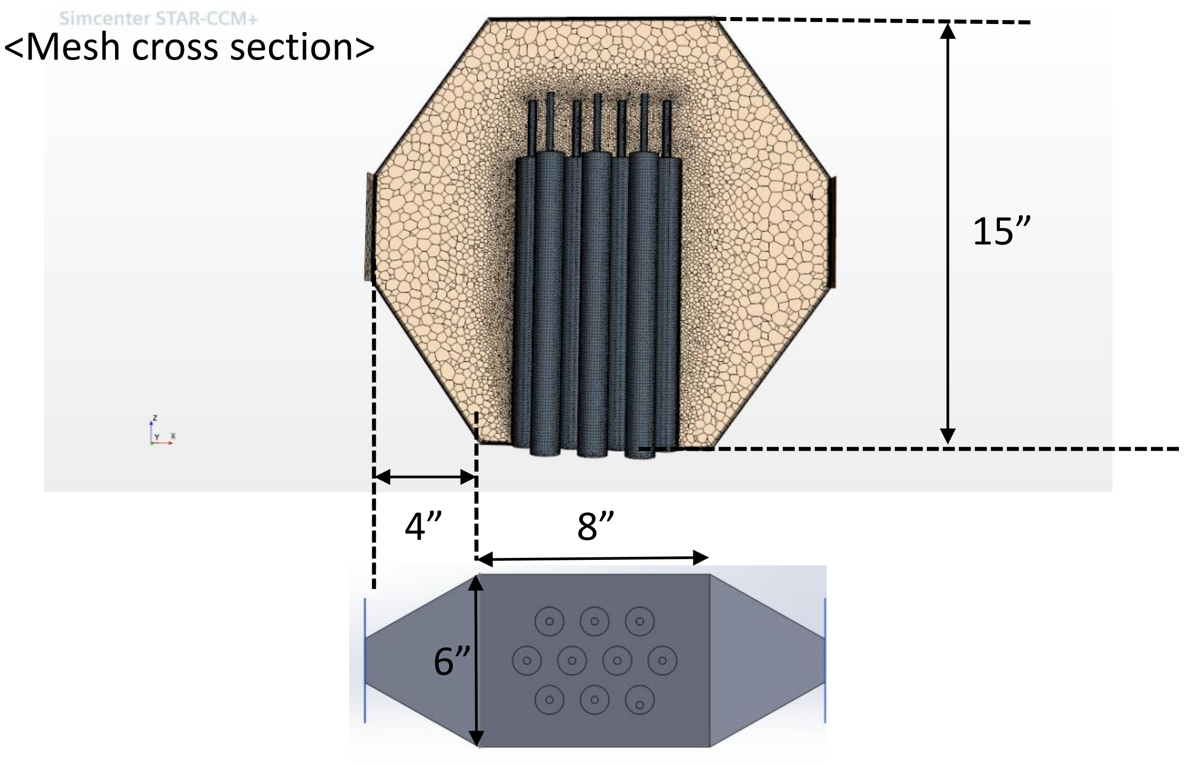
Thermal stress of the hex block and HPs
- Sliding support at the right side for HPs to allow thermal expansion

Heat pipe mini-core design (1st design for the condenser)

❖ Design of the condenser







Geometry specifications:

- HP-HP pitch = 1.57”
- Inlet & Outlet: 1.5” x 3.75” rectangular channel
- Wind tunnel: 8” x 6” x 15”

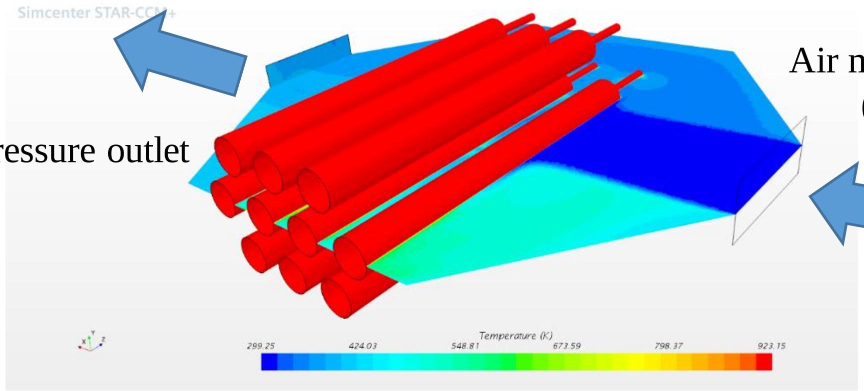
Assumptions:

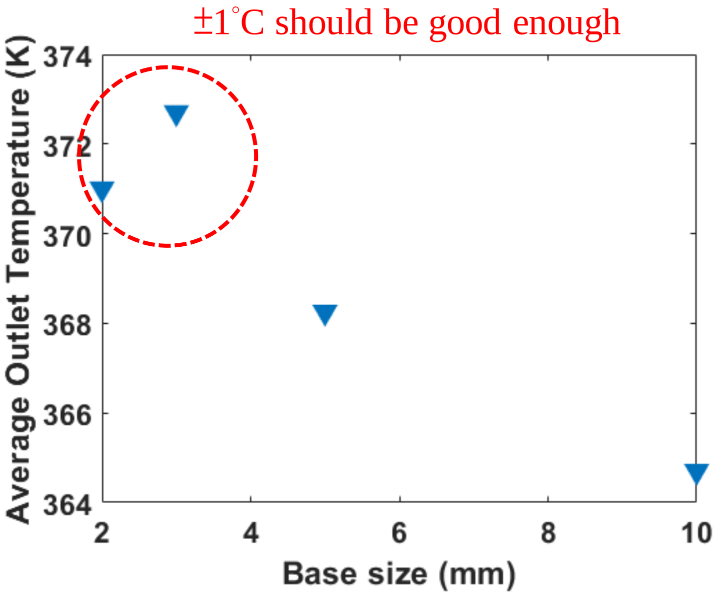
- Ignore radiation heat

Mesh conditions:

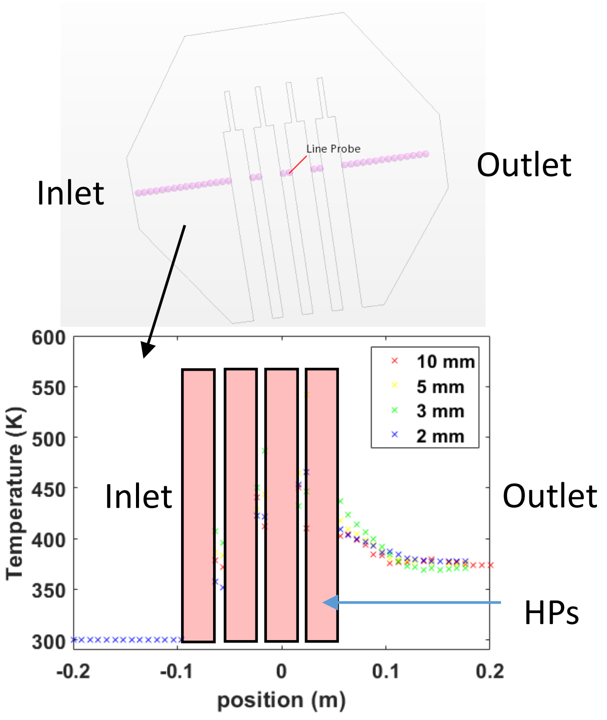
- 5 prism layers with total thickness of 1 mm is applied near boundaries
- 4 different base sizes were tested

Heat pipe mini-core design





<Mesh sensitivity study>



<Temperature profile at the central line>

Summaries

- Although it was not converged very well from the central line temperature profile, especially near the gaps between the HPs, the average outlet temperature is not sensitive to the mesh base sizes
- The average outlet temperature is estimated to be around 372 K, based on the energy balance equation, the heat removal rate is calculated as follows:

$$\dot{Q} = \dot{m}C_p\Delta T = 0.1\left(\frac{kg}{s}\right) * 1006\left(\frac{J}{kgK}\right) * (372 - 300)(K) = 7243.2(W)$$

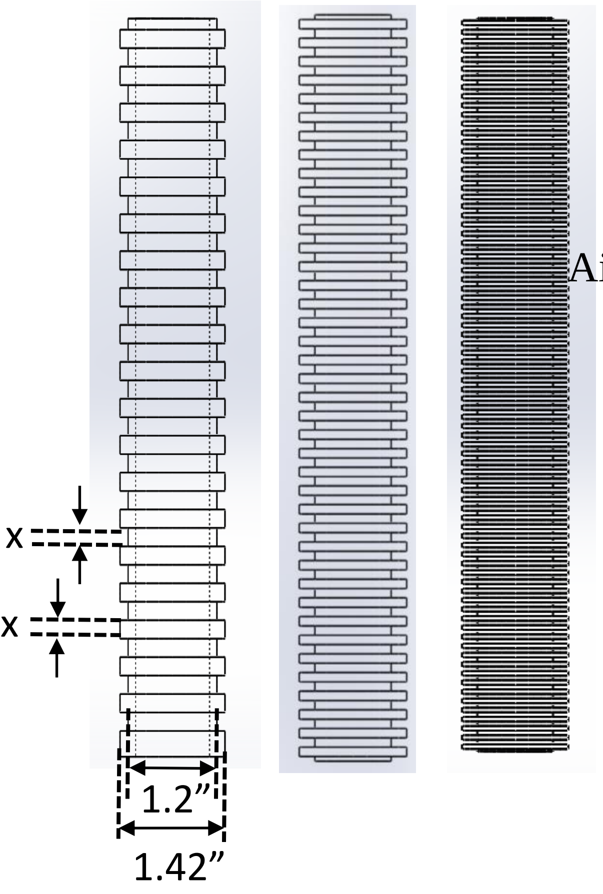
- The maximum required heat removal rate under horizontal HP is around 800 (W)*10 (HPs) = 8000 W, the result shows slightly insufficient heat transport capacity
- Another issue is the HP where directly facing the air inlet may be too cold for successful startup

Heat pipe mini-core design (2^{nd} design for the condenser)

❖ 2^{nd} design of the condenser

- Apply fins on the surface of the heat pipe to enhance the heat transfer rate

<Fin geometry>

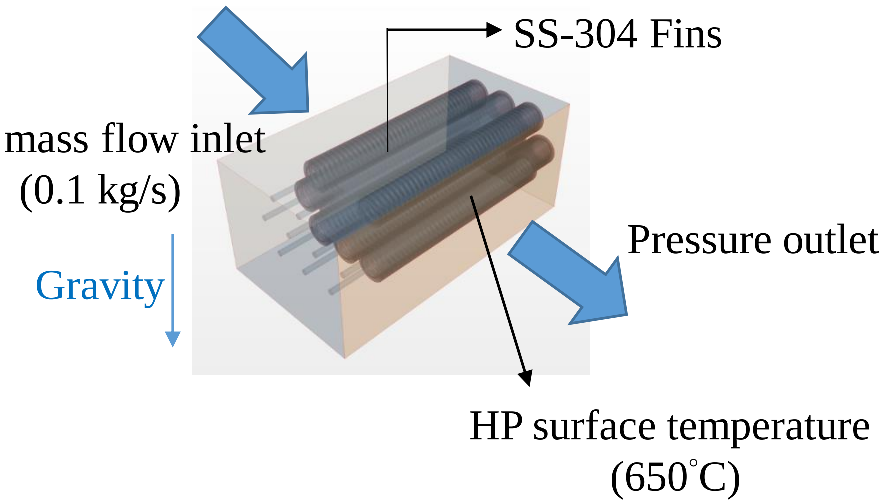


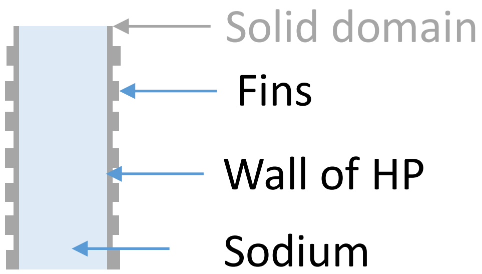
x = 0.25” 0.125” 0.0625”

Unit: inches

<Geometry condition>

The size of wind tunnel was reduced for efficiency





<fin on HP>

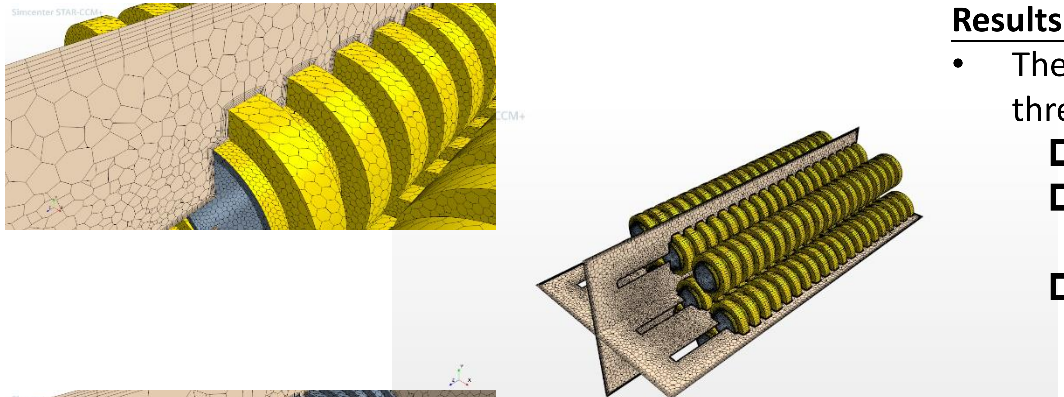
Mesh conditions:

2-3 mm base size for solid fins, prism layers were applied in the solid-fluid interface, the mesh information of fluid domain are as follows:

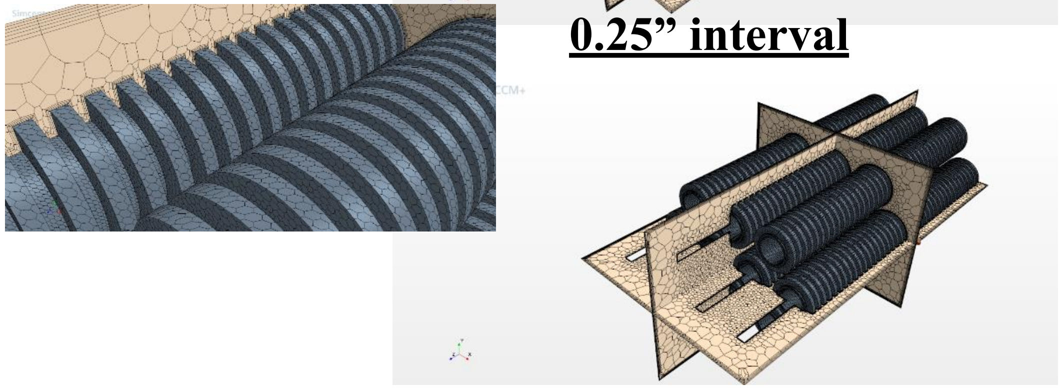
	Base size	Cell #	Faces #	Vertices #
0.25” interval	10 mm	746321	3169672	1913267
	5 mm	1132014	4944705	3078931
	3 mm	1572237	7589406	5151847
0.125” interval	10 mm	4347786	19549956	13195943
	5 mm	5811361	26079798	17450696
	4 mm	5949960	26865336	18053038
	3 mm	6344471	29239130	19927031
0.0625” interval	10 mm	2099786	9221106	5831188
	7.5 mm	3462920	15584816	10105716
	5 mm	6219812	28248596	18482155
	4 mm	19487903	87808358	58642545

<Large cost to make fine enough mesh>

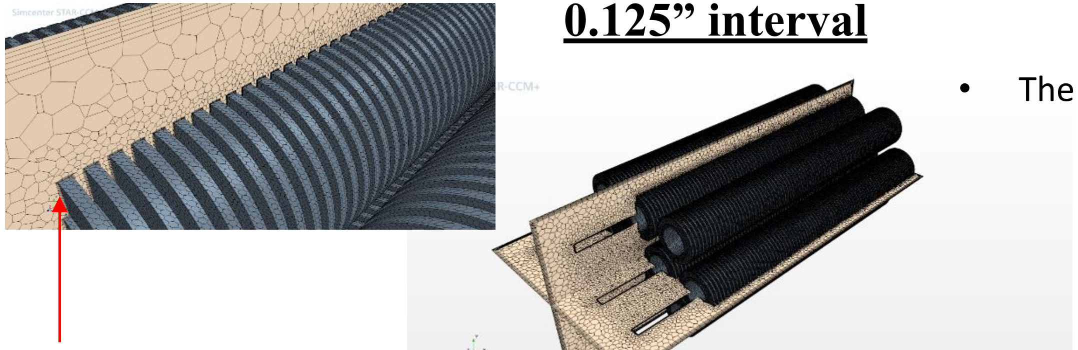
Heat pipe mini-core design (2nd design for the condenser)



0.25” interval



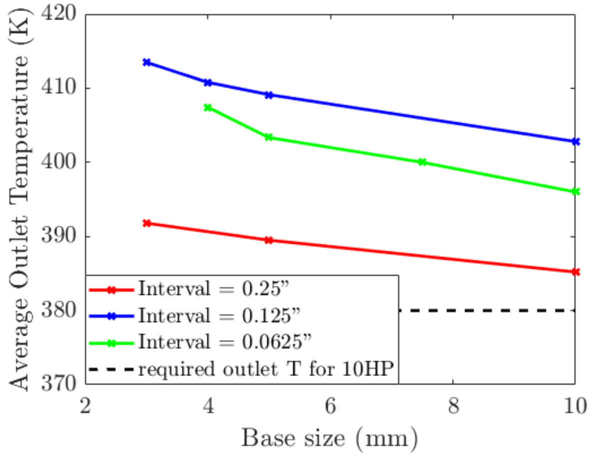
0.125” interval



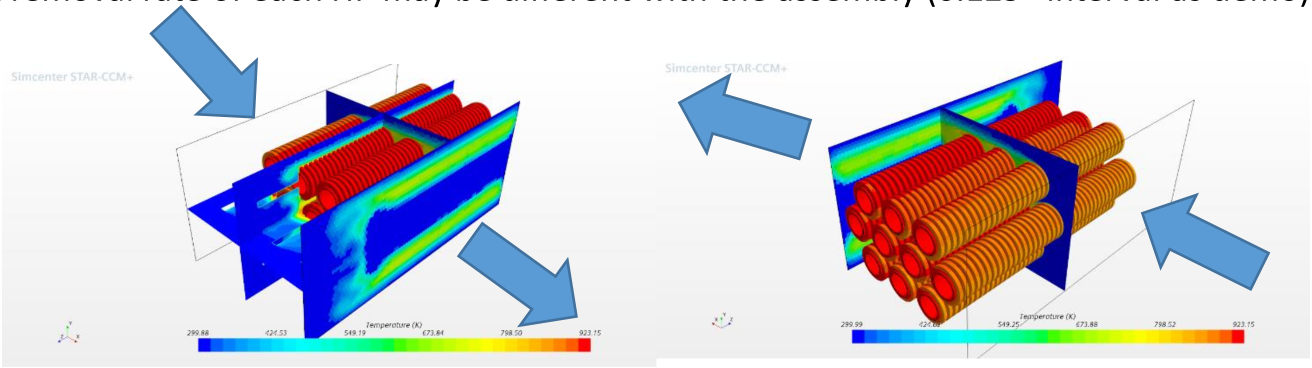
0.0625” interval

Results:

- The mesh average outlet temperature versus the mesh base size of fluid domain along with these three fin geometries shows:
  - ☐ More mesh is needed for interval = 0.0625” because of the complex geometry
  - ☐ The heat removal rate increases a lot as the interval of fins reduce from 0.25” to 0.125”, but the effect become not significant as the interval from 0.125” to 0.0625”
  - ☐ Anyway, the required heat transfer rate can be achieved with the applied fins on HPs



- The heat removal rate of each HP may be different with the assembly (0.125” interval as demo)



Conclusion

- The data analysis for the experimental campaign of HP#1 (FR = 50%) and HP#13 (FR = 25%) indicates:
  1. the isothermal behavior of heat pipe is sensitive to the cooling efficiency as the operation condition approached the viscous limit curve
  2. Geyser boiling induced temperature oscillation increased the end-to-end temperature of the heat pipe. The geyser boiling, intermittent geyser boiling, and ideal regions were classified on the heat pipe performance characteristic plot
- The study of the startup process and performance of heat pipe under negative orientation shows:
  1. When the solid sodium was initially located in the condenser, the heat pipe failed startup as the inclination angles are close to horizontal
  2. When the inclination angle of the heat pipe decreased up to around -10 deg during isothermal operation, the B-side at the evaporator overheated and the liquid pool at the condenser end formed, heat pipe completely failed under -15 deg of inclination angle with the heating power of 1250 W
- The intense two-phase (slug) flow was observed in a vertical orientated heat pipe under 2000 W heating power through X-ray radiography measurement
- Aluminum profiles were utilized to enhance the structural integrity of the test section, new (UX type) split heater is going to be used for future X-ray radiography measurement to reduce the image artifact
- The $MoSi_2$ heaters are planned to be used for the heat pipe mini-core facility (MISOH2), the concept of the design had been performed, in the design 10 heat pipes are arranged under horizontal orientation. The condenser capacity analysis was conducted, showing the required heat transfer rate of the system (8000 W) can be realized