DOE-NE Microreactor Meeting–

Sodium heat pipes; design and failure mode assessment for micro-reactor applications (NEUP 24-31551)

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Contents

Project Collaborators and Background

- Collaborative effort between:
  - **University of Wisconsin-Madison (UWM)**
    - Mark Anderson (PI), Paul Brooks, Nikona Rousseau, Erik Tillman, Peter Beckman, Tiago Moreira (Former Co-PI)
  - **Texas A&M University (TAMU)**
    - Yassin Hassan (Co-PI), Joseph Seo, Hansol Kim
  - **Westinghouse (WEC)**
    - Michael Shockling (Co-PI), John Lojek, Rachel Riley, Harold Maguire, Jennifer Sassaman, Hayley Wagreich
  - **Los Alamos National Laboratory (LANL)**
    - Martin Ward, Bob Reid, Katrina Sweetland (Former Co-PI)
- Collaborators meet monthly to disseminate information and provide progress updates

- Goal: ***Understand the performance of sodium heat pipes with the following conditions to support Westinghouse eVinci development***
  - Physical failures (pinhole breech, weld failures, manufacturing flaws, etc.)
  - Prescence of high oxygen concentration
  - Prescence of non-condensable gases

Project Goals & Timeline

Tasks/Milestone:	Deliverable	Responsible	2024		2025						2026						2027				
			10	12	2	4	6	8	10	12	2	4	6	8	10	12	2	4	6	8	10
	Final Report	UW-THL																			
Failure modes and their effects on heat pipes	Construction of instrumented sodium heat pipes	UW-THL/WEC and LANL																			
	Characterization of theoretical heat pipe performance through numerical modelling and CFD	UW-THL/ TAMU/WEC and LANL																			
	Characterization of the performance and limits of the sodium heat pipes	UW-THL/ TAMU/WEC and LANL																			
	Assessment of heat pipe failure modes and their effects on heat pipe performance	UW-THL/ TAMU/WEC and LANL																			
Performance degradation with different non-condensable gases	Design and construction of liquid sodium heat pipes with access for vacuum level control	UW-THL/WEC and LANL																			
	Characterization of the effects different non-condensable gases have on heat pipe performance	UW-THL/ TAMU/WEC and LANL																			
Effect of sodium oxygen content on heat pipe performance	Corrosion assessment of heat pipe candidate materials in liquid sodium at different oxygen concentrations	UW-THL/ TAMU/WEC and LANL																			
	Evaluation of the effect that sodium oxygen concentration has on heat pipe performance	UW-THL/ TAMU/WEC and LANL																			
Wick optimization and heat pipe performance	Development of optimized wicks based on CFD and water experiments considering water-sodium scaling methodologies	TAMU/ UW-THL/WEC and LANL																			
	Construction and testing of heat pipes with optimized wicks from start-up up to their limits of operation	UW-THL/WEC and LANL																			

Heat Pipe Development – Task 1

- ***Design and manufacture sodium heat pipes with reasonably prototypic dimensions and performance***

First Generation Heat Pipe Parameters

- Dimensions
  - OD: 0.75”
  - Condenser Length: 9”
  - Adiabatic Length: 17.7”
  - Evaporator Length: 9”
- Materials
  - Tube: Inconel 625
  - Wick: Stainless 316
- Wicks
  - Porous sintered tube
  - Wrapped Mesh
  - Sintered Mesh
- Fill ratio Target
  - 100% - 120%

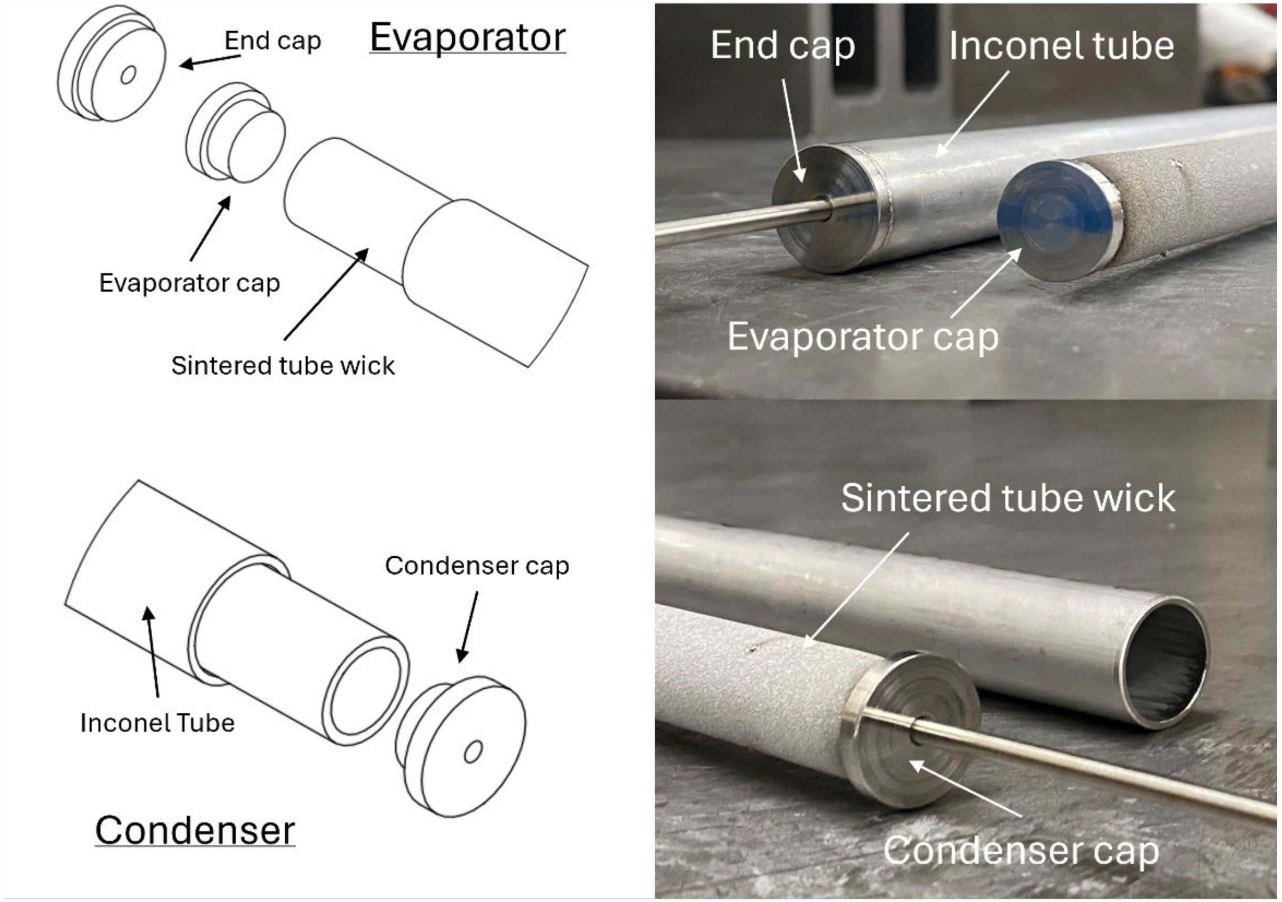


Figure 1. Heat pipe design.

Wick Development – Task 1

- Two wick design options
- Wick 1: Porous Sintered Tubes:
  - Specifications
    - 14 μm pore radius
    - 0.063" thick
    - 0.625" OD (0.014" gap size)
- Wick 2: Hand Wrapped Mesh
  - Specifications
    - Stainless 316 – 250 Square Mesh
    - 60 μm pore radius
    - 0.028" thick
    - 0.625" OD
- Wick 3: Mesh (In Development)
  - Specifications
    - Stainless 316 – Dutch Weave Mesh
    - Opening size: 20 μm
    - 0.020" thick
    - 0.600" OD (0.026" gap size)

Figure 2. Porous sintered wick.

Figure 3. Sintered mesh wick.

Wick Characterization – Task 2

- ***Bubble test characterizes pore size***
- Relates pressure to pore size:

$$\frac{2\sigma}{r_{pore}} = P_{gas} \text{ (Young-Laplace)}$$

- Visual observation of largest pore location
  - Determines condenser end of wick
- Proper characterization improves modeling and limit calculations
- Effective Pore Size:
  - Porous Sintered Wick: 19 μm
  - Wrapped Mesh Wick: 60 μm
  - Sintered Mesh Wick: 20 μm

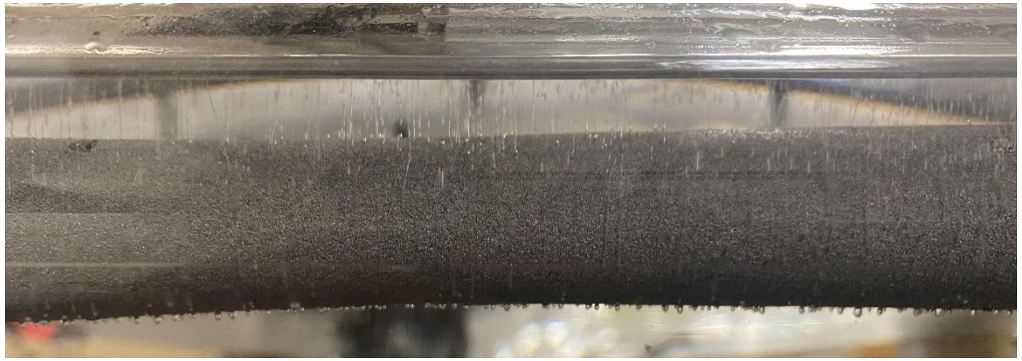


Figure 4. Porous sintered tube wick bubble test.

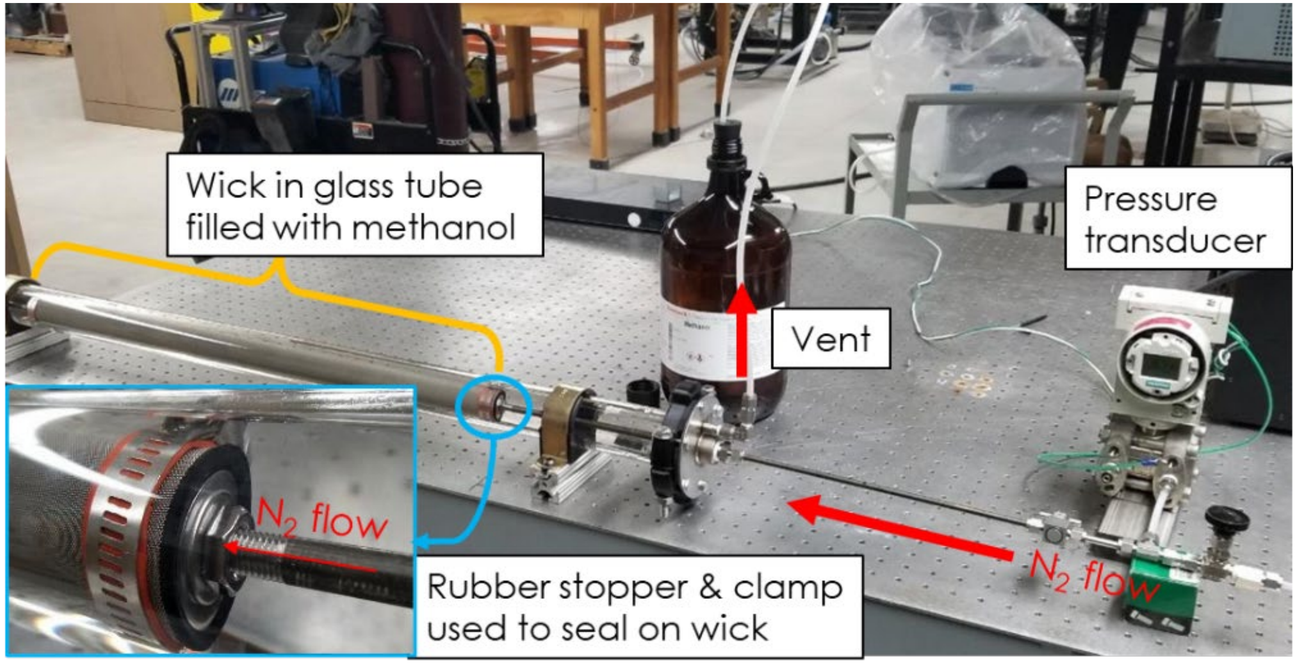


Figure 5. Bubble test setup.

Limits of wicks – Task 2 & 9

- ***Applied heat pipe theoretical limits to design wick geometry***:
  - Thickness
  - Gap size (OD)
  - Pore size
- Chose geometry that maximized operating limits
- Compared analytical limits to numerical models
  - HTPIPE
  - NASA GLENN
- Targeting reasonable heat pipe limits for microreactor applications
  - ~ 5 kW
- Capillary limit is typically the most difficult limit for microreactor scale heat pipes

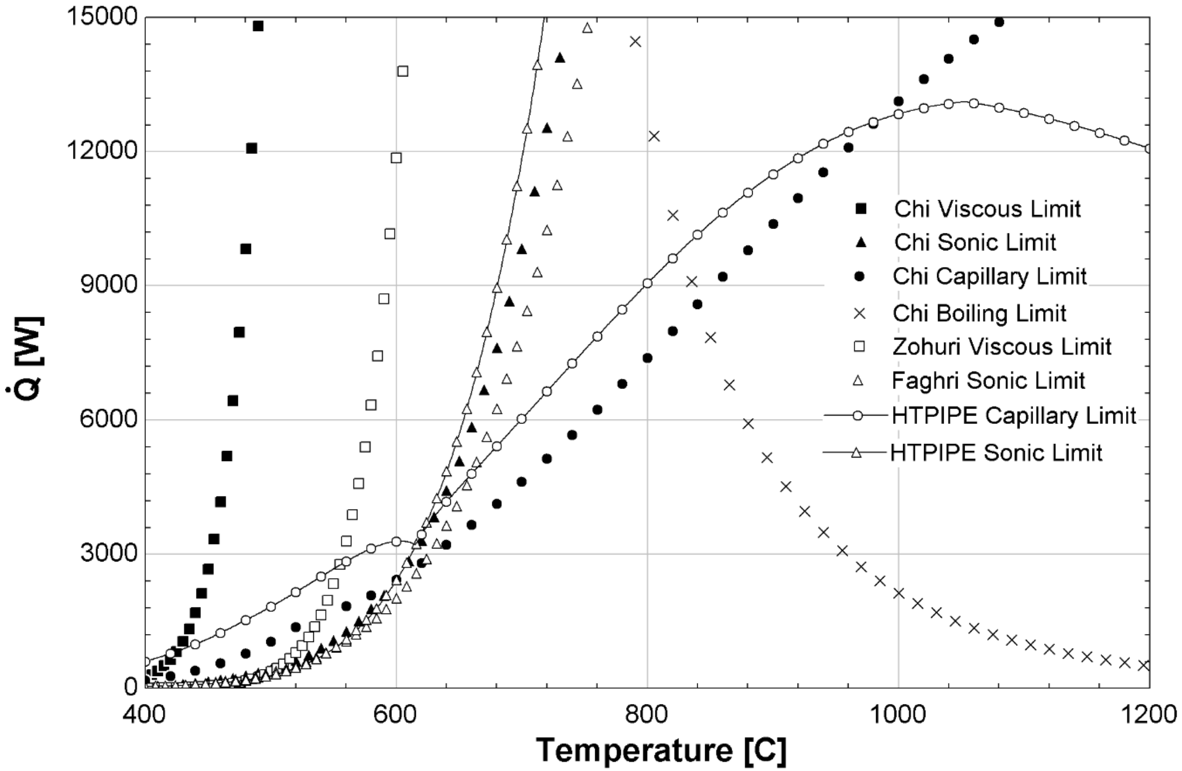


Figure 6. Porous sintered wick heat pipe limits.

TAMU Permeability Measurements – Task 2 & 9

- ***TAMU measuring wick structure permeability***
  - Important for modelling and predicting heat pipe behavior
- Using ethanol as a baseline fluid
- Mass measurements over time to capture capillary rise rate
- Applied relationship between porosity, pore size and permeability.

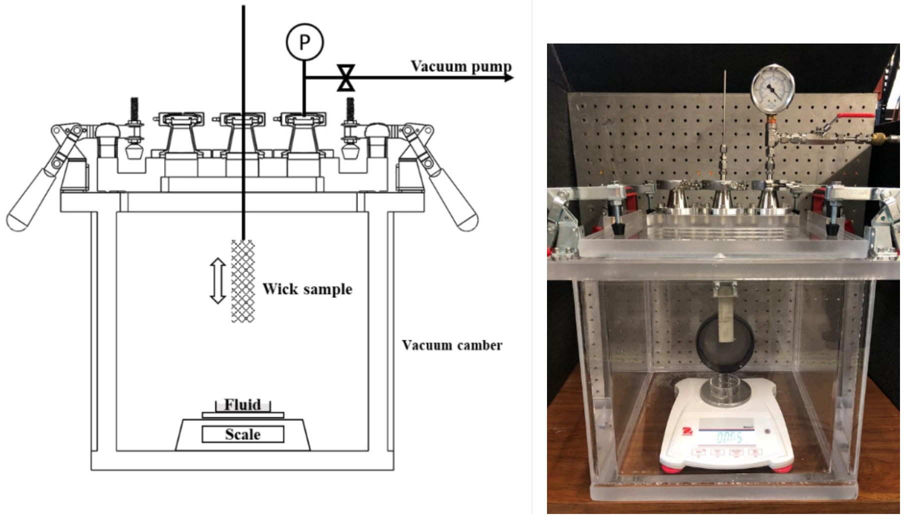


Figure 7. schematic (left) and picture (right) of the wick characterization experimental setup.

$$t_{Holley\,\&\,Faghri} = f(K, r_{eff}, m_{exp}) = -\frac{\varepsilon \mu_l}{\rho_l^2 g^2 K}\left[\frac{2\sigma}{r_{eff}} * \ln\left(1 - \frac{g r_{eff}}{2\sigma A_{wick}\varepsilon} m_{exp}\right) + \frac{g}{A_w \varepsilon} m_{exp}\right]$$

TAMU Contact Angle Measurements – Task 9

- ***TAMU measuring fluid-porous media contact angles***
  - Important for modelling and predicting heat pipe behavior
- Using water as a baseline fluid prior to using sodium
- Visual measurements of contact angle between fluid and wick material
- Also taking X-ray images of sodium-porous media interactions
  - Challenges in making sure we achieve similar wetting characteristics as an operational heat pipe

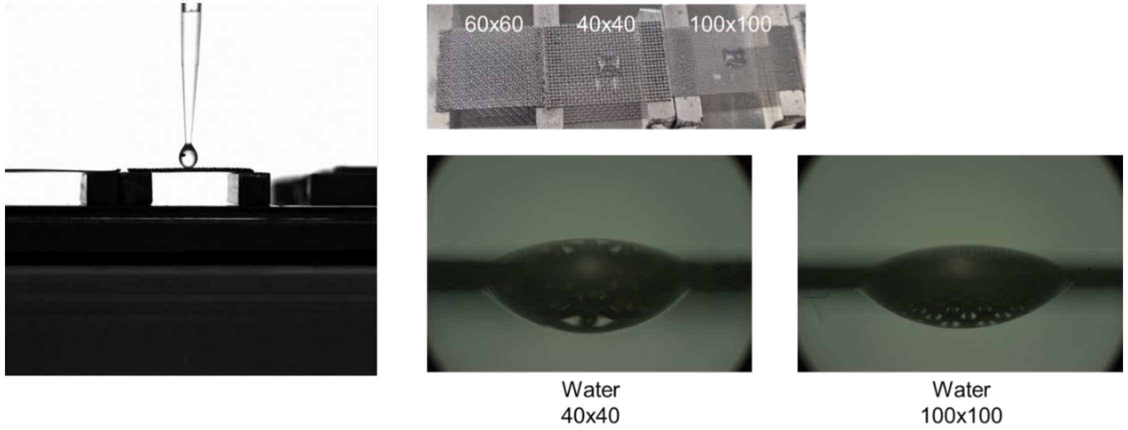


Figure 8. Water-mesh contact angle measurements.

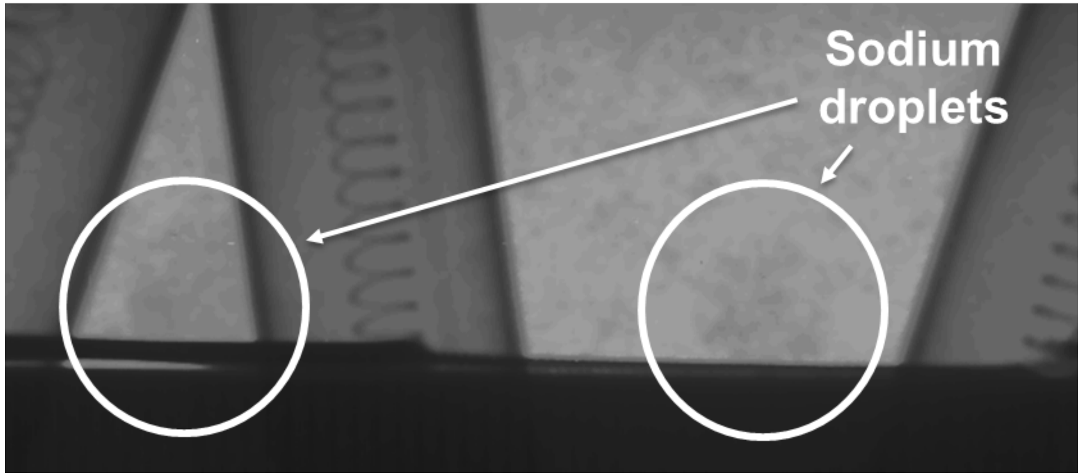
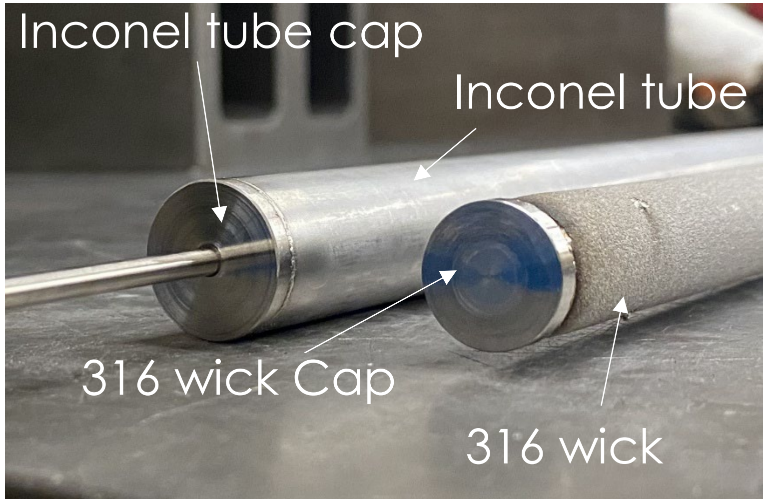


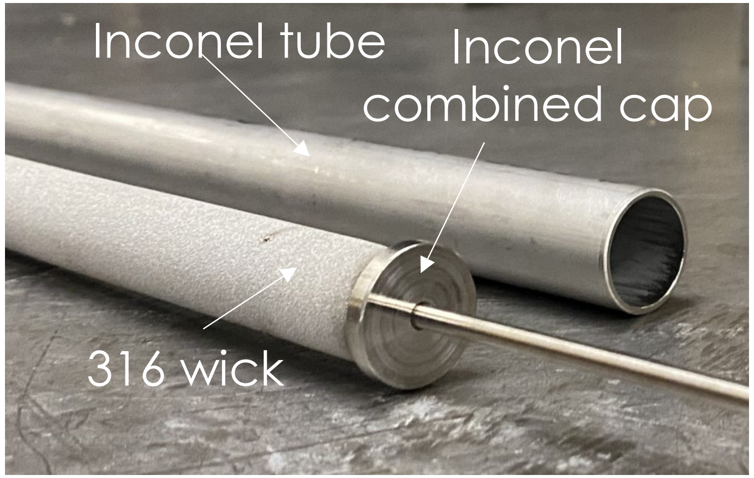
Figure 9. X-ray images of sodium-mesh interaction.

Heat Pipe Fabrication – Task 1

- Bubble test to identify condenser end
- Clean wick with ethanol and vacuum bake
- Laser weld heat pipe assembly
- Clean with ethanol
- Vacuum bake in fill loop

Evaporator





Condenser

Sodium Fill – Task 1

1. Vacuum bake Heat Pipe
2. Circulate sodium through heat pipe and cold trap to wet and reduce any oxide presence in heat pipe
3. Set desired sodium fill level
4. X-ray verification
5. Scale verification
6. Conduct XRCT to verify sodium fill volume and obtain as fabricated complete 3D model

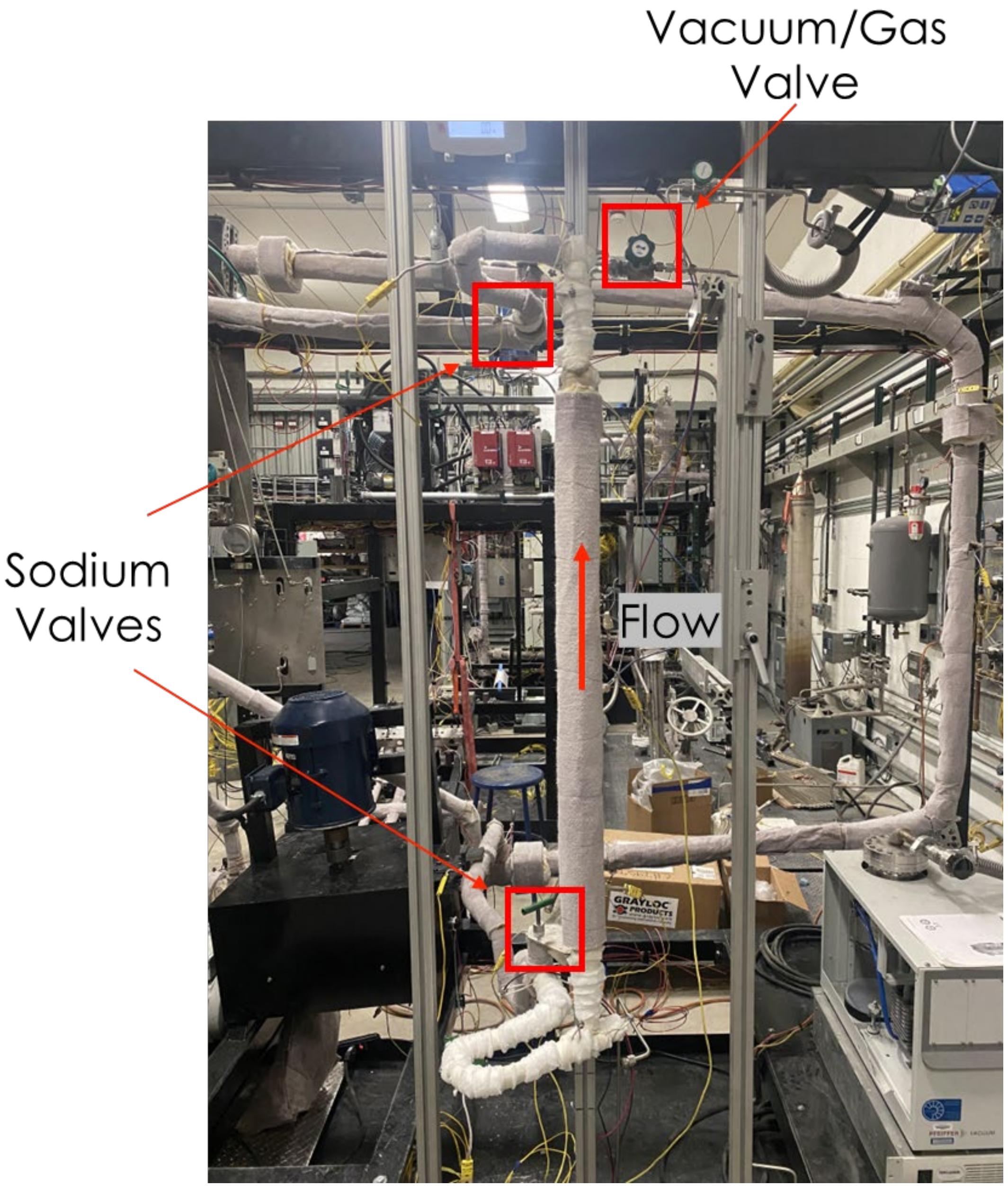


Figure 10. Sodium fill loop.

Heat Pipe Sealing – Task 1

- ***Developed repeatable sealing technique***
  - In-line diffusion bond
- Leak proof against:
  - 30 psi helium leak detection
  - 5000 psi of H_2O
- Heat pipe sealed in fill-loop
- Quick and repeatable filling and sealing of heat pipes

Figure 11. Microscope image of seal.

X-ray Fill Verification – Task 1

- In-situ X-ray imaging to identify fill meniscus during filling
- Post-fill full CT scan to verify heat pipe internal geometry and sodium volume
- Fill ratio between 105% and 130%
  - Each gram ~1.5% fill ratio

*Fill ratio defined as void volume in wick and gap

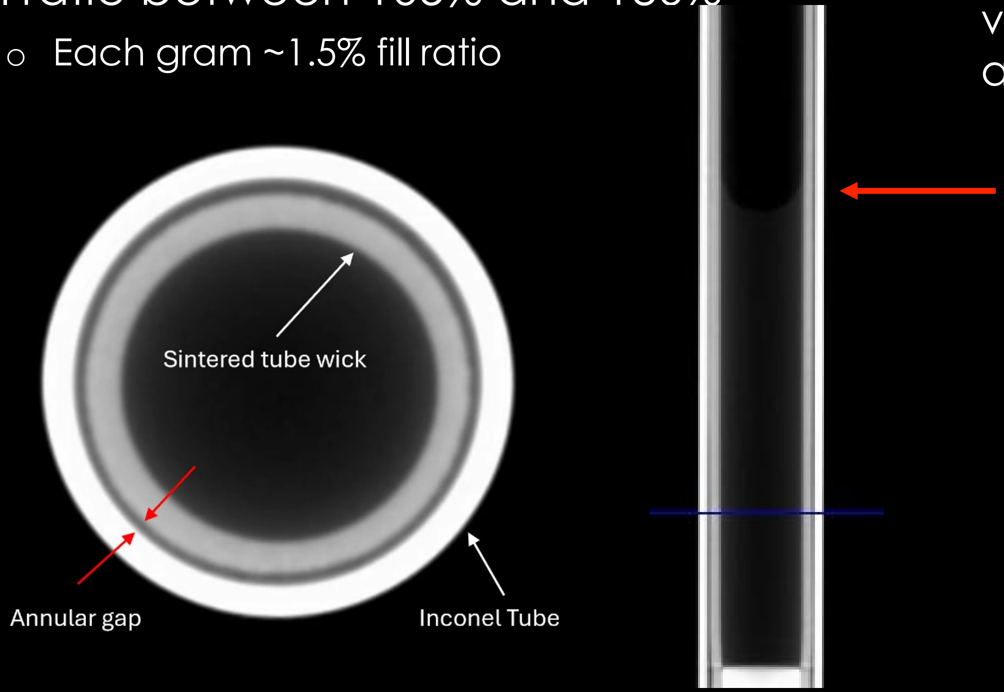


Figure 12. CT scan results.

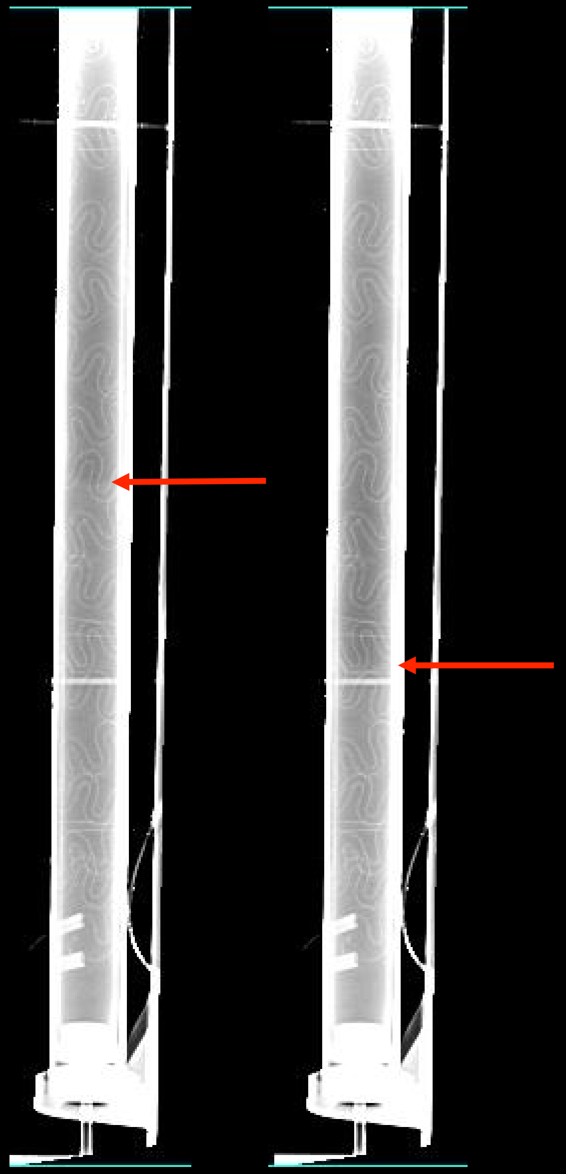


Figure 13. Heat pipe sodium meniscus.

Summary of Heat Pipe Development – Tasks 1, 2, 5 & 9

- Development of a repeatable heat pipe manufacturing process.
- Initial design of heat pipe with two different wick geometries.
    - Designed wicks to maximize theoretical performance
    - Manufactured wicks and characterized performance with bubble test.
    - Fabricated heat pipes
    - Filled to desired volume
    - Developed repeatable and effective sealing method
- Filling procedure allows for controlled delivery of NCGs

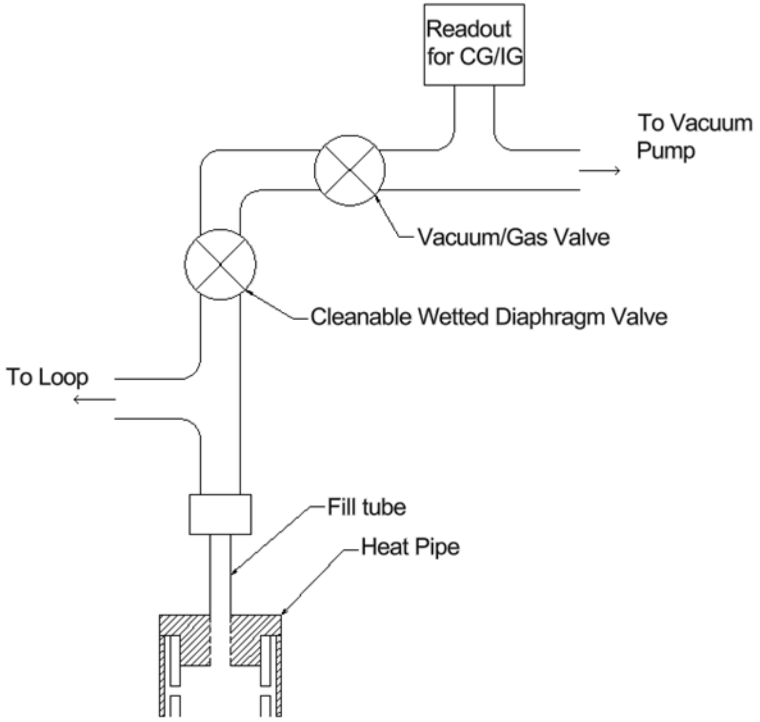
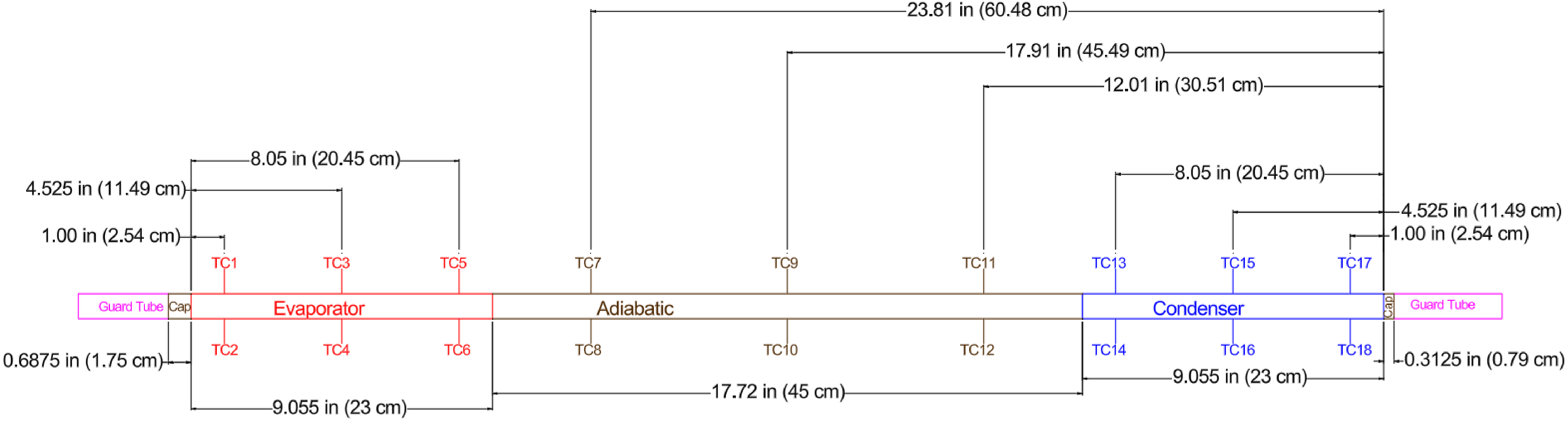


Figure 14. Vacuum control schematic.

Now to initial testing

Heat Pipe TC Locations– Tasks 3 & 10



Preliminary Testing Instrumentation – Tasks 3 & 10

- Initial testing (Low Power)
  - Kanthal ribbon heated evaporator
  - Air flow cooling jacket condenser
  - Thermocouple wall temperature measurements
  - X-ray imaging
- Test Conditions:
  - Natural convection cooling (blower off) at 350 W steady state
  - 15% Blower Speed (17 m^3/hr) at 450 W steady state
  - 30% Blower Speed (40 m^3/hr) at 520 W steady state
  - Kept average evaporator temperature between 600 and 700 C

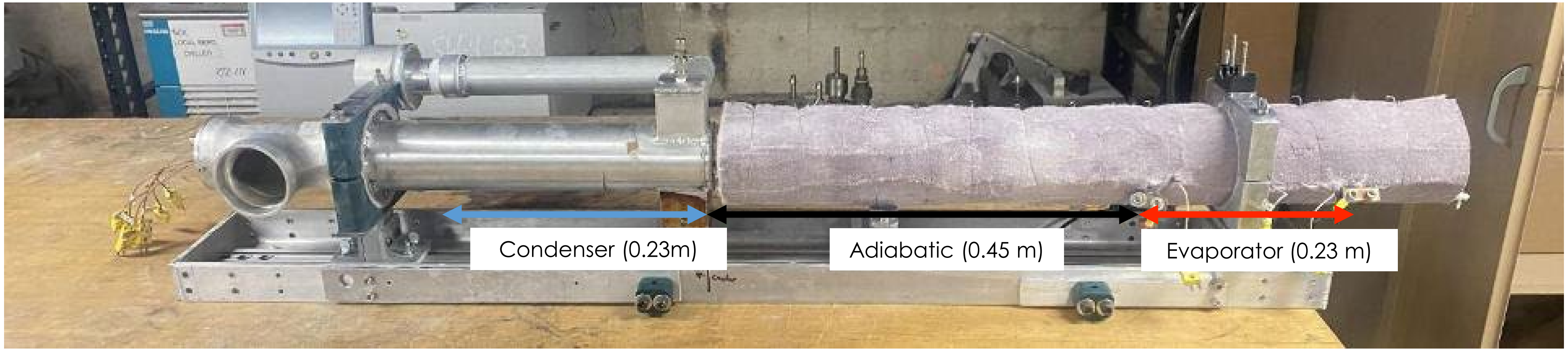


Figure 15. Heat Pipe testing sled.

Verification of Startup Behavior – Tasks 3 & 10

- Vapor flow transitions from molecular to continuum
  - o HTC goes way up
- Used the relationship defined by Faghri to verify transition temperature

$$T^* = \left(\frac{\pi}{2E-4}\right)\left(\frac{M}{R_{univ}}\right)\left(\frac{\mu}{\rho D_v}\right)^2$$

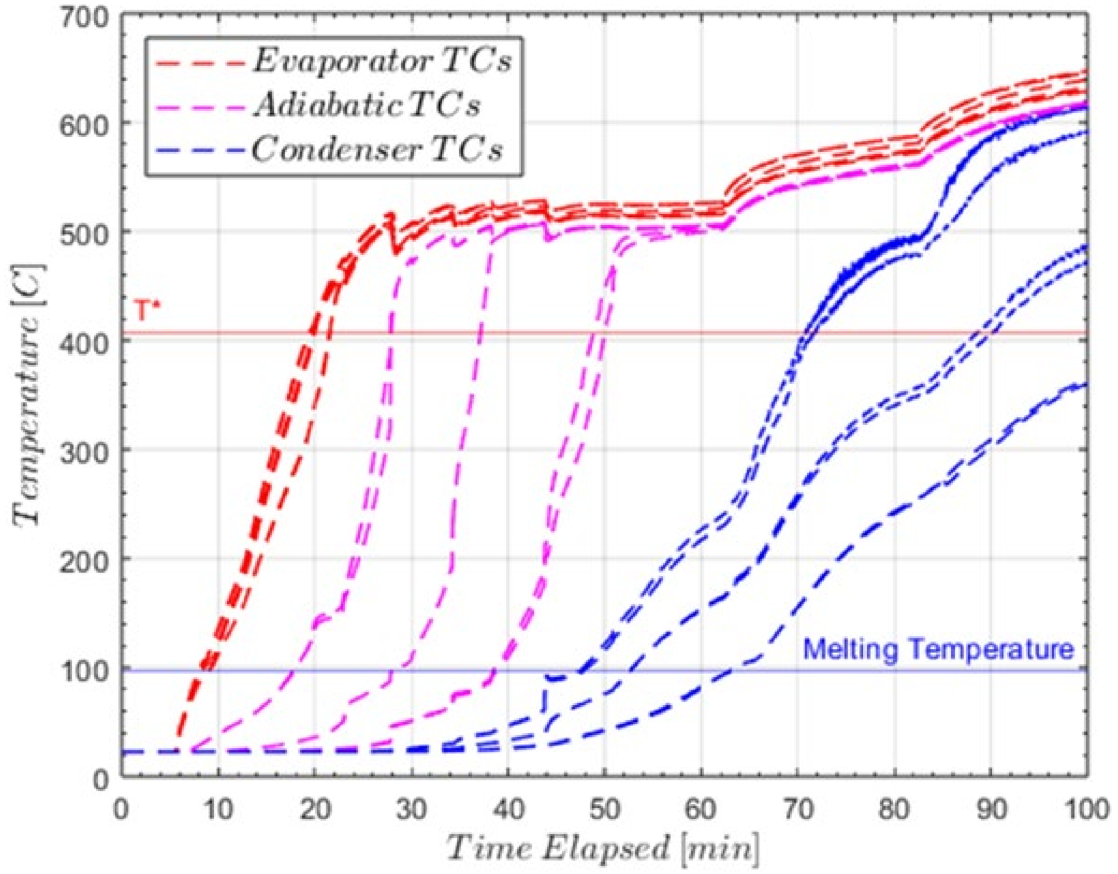
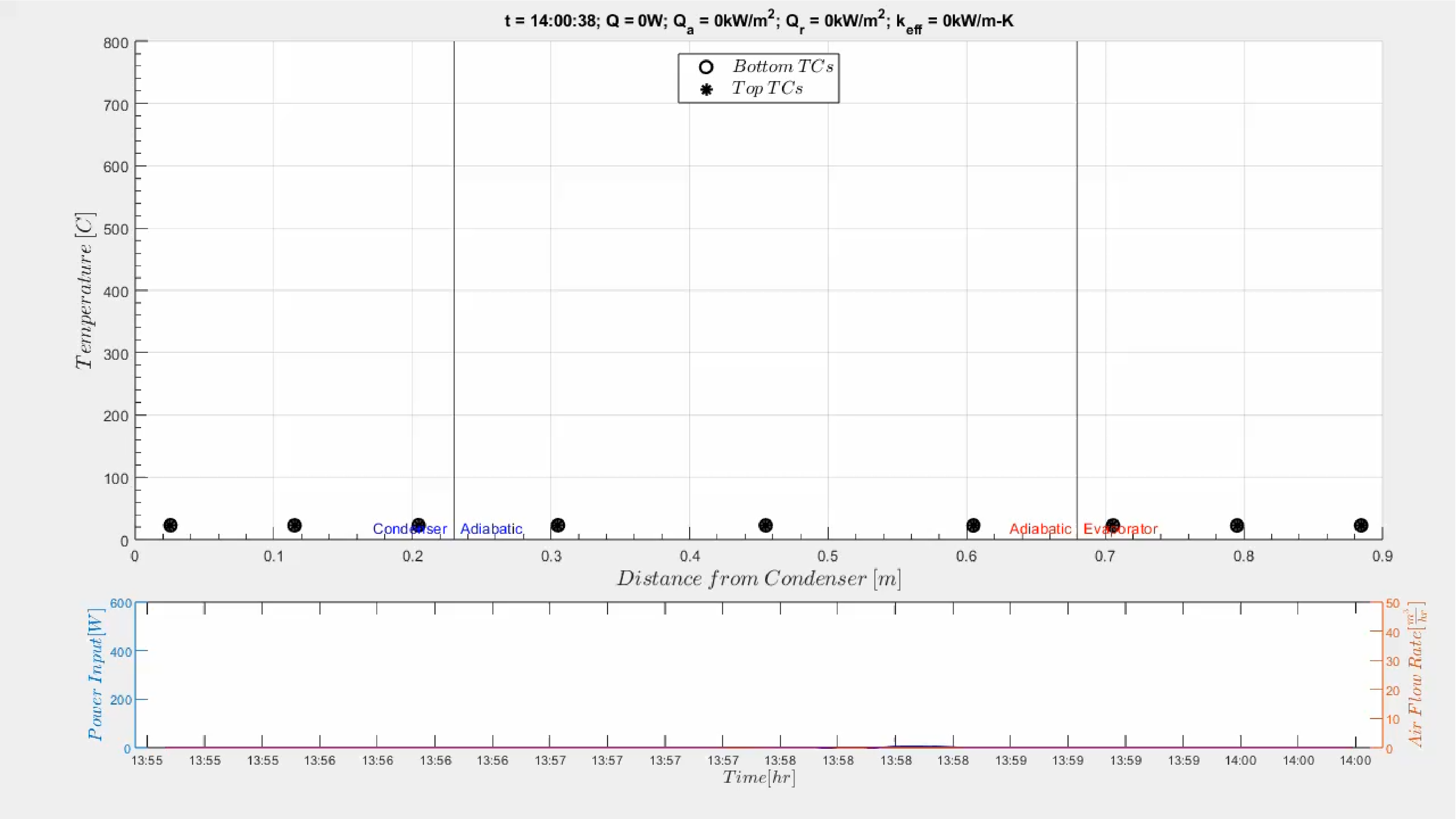


Figure 16. Startup TC data of wrapped mesh heat pipe.

Startup to Steady State – Tasks 3 & 10



Startup to Steady State – Tasks 3 & 10

- Heat pipe installed in 450 kV X-ray facility for imaging
  - Up to 30 fps acquisition speed
  - 2048 x 2048-pixel array (41 cm x 41 cm)

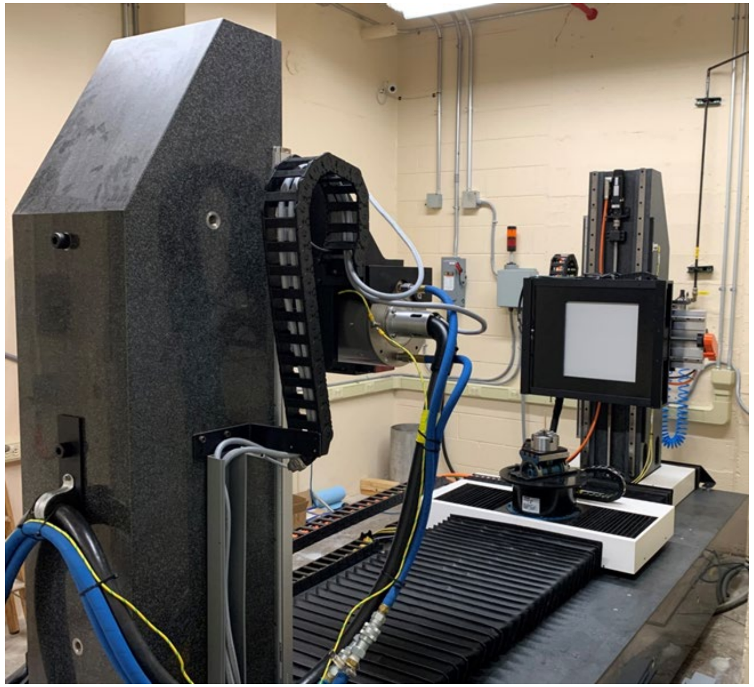
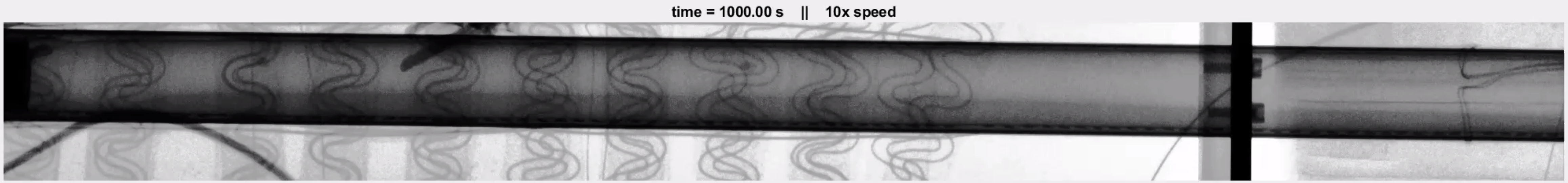


Figure 17. 450 kV X-ray facility.



Steady State & Effective Thermal Conductivity – Tasks 3 & 10

- Considering only active heat pipe length
  - Region where temperature profile is isothermal
- Applying Fourier's Law:
- $\dot{Q} = k_{eff} A_c \frac{dT}{dx}$
  - A_c = cross sectional area using tube outer diameter
  - dT = Temperature difference between avg evaporator TC temperature and avg temperature of the farthest set of condenser TC's (top and bottom avg)
  - dx = axial distance from center of heat zone to farthest set of active condenser TC's.
  - $\dot{Q}$ = power input

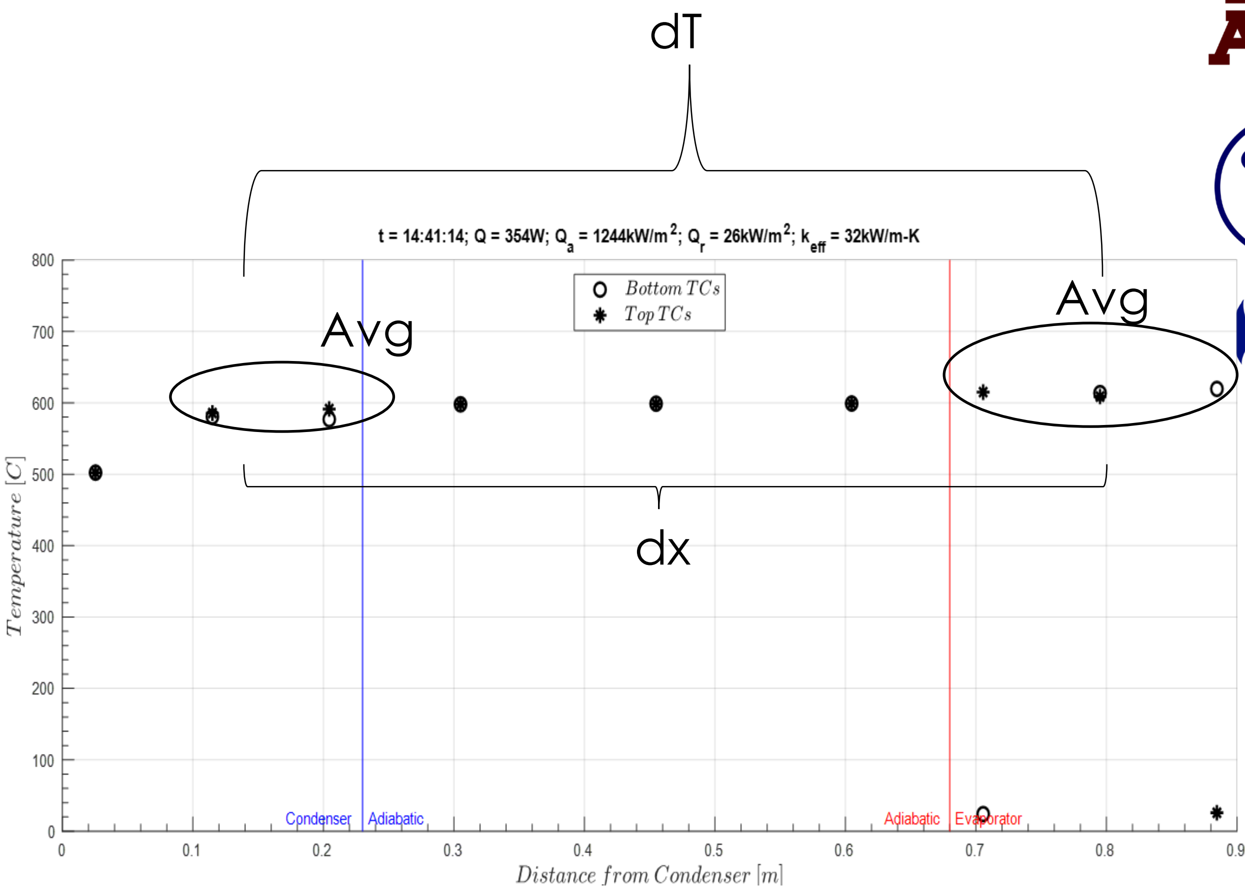


Figure 18. Steady state TC data of wrapped mesh heat pipe.

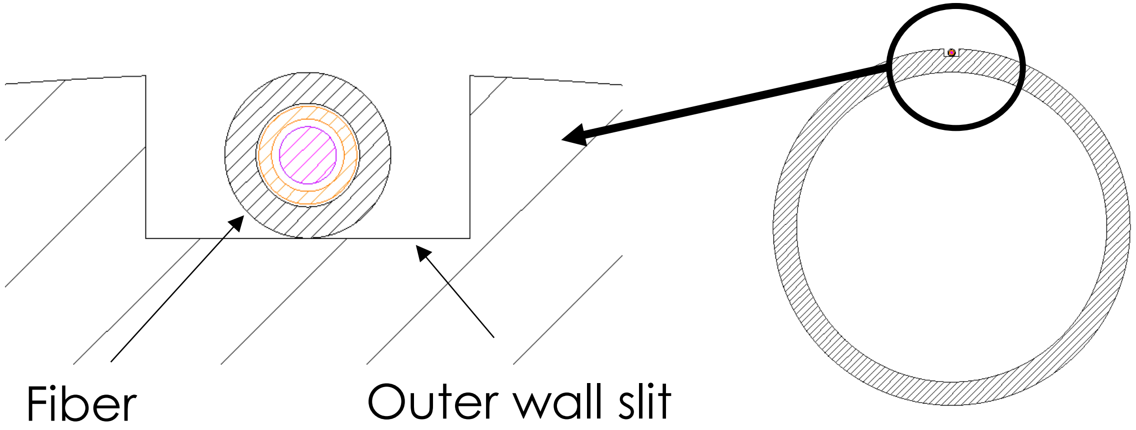
Verification of Startup Behavior – Tasks 3 & 10

- Observations:
  - Mesh wick heat pipe saw slightly higher effective thermal conductivity at lower powers
  - Mesh wick saw significant dry out at higher heat flux
    - Sintered wick wetted better
  - Effective thermal conductivities ranged 8-32 kW/m-K
    - Copper ~0.4 kW/-m-K

Heat Pipe	Heating Setpoint [W]	Cooling Blower Speed [%]	Max Temp [C]	ΔT [C]	Effective Conductivity [kW/m-K]	Axial Heat Flux [kW/m^2]	Radial Heat Flux [kW/m^2]
Sintered Wick	350	0	696	32	25	1213	25
	440	15	682	64	17	1545	32
	520	30	694	129	10	1833	38
Mesh Wick	350	0	620	31	32	1244	26
	440	15	652	63	17	1537	32
	520	30	729	166	8	1820	38

Expanding Testing Facilities – Task 3

- Testing heating capabilities of our induction heating system.
- Determining accuracy of measuring surface temp w/ fiber optic temp sensors.
  - Skin effect on metal capillary may skew measurements
- Verifying surface temperature w/ IR camera



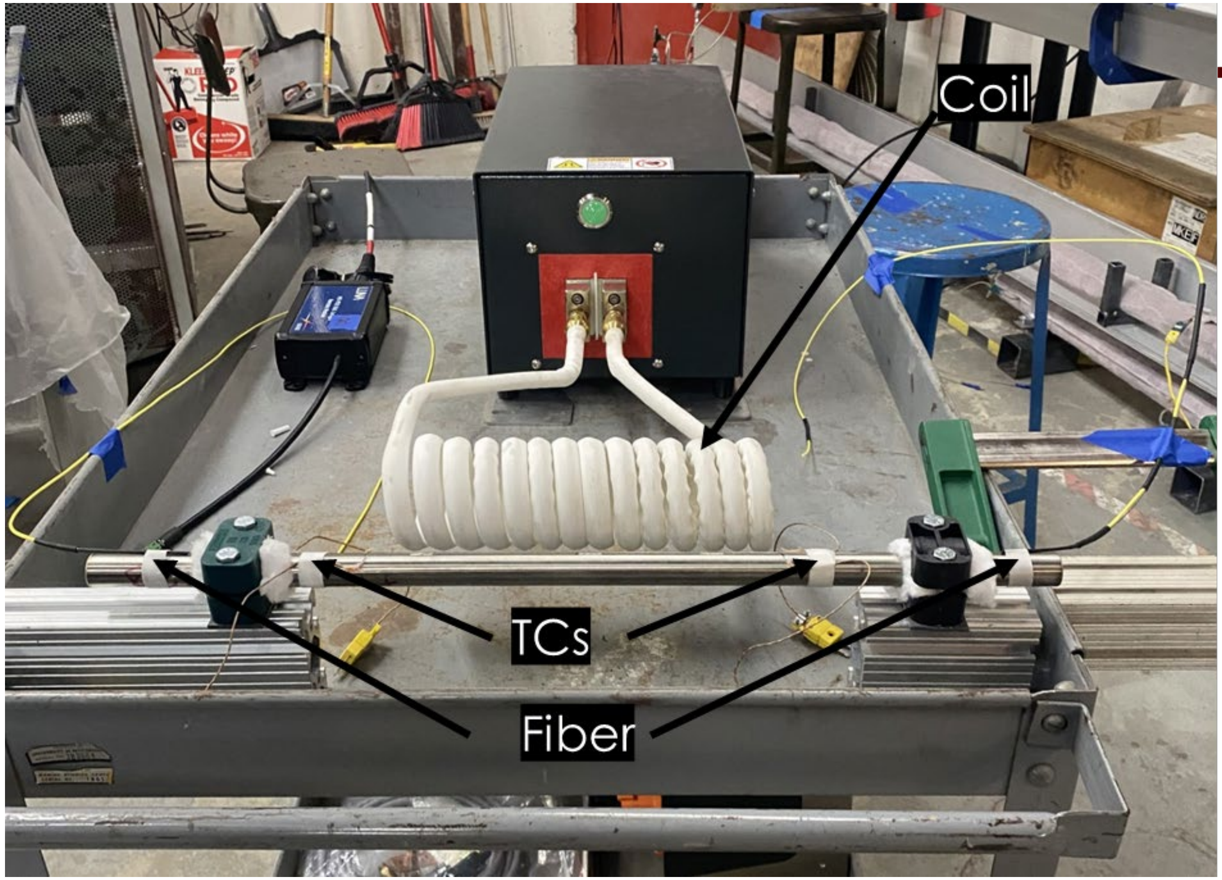
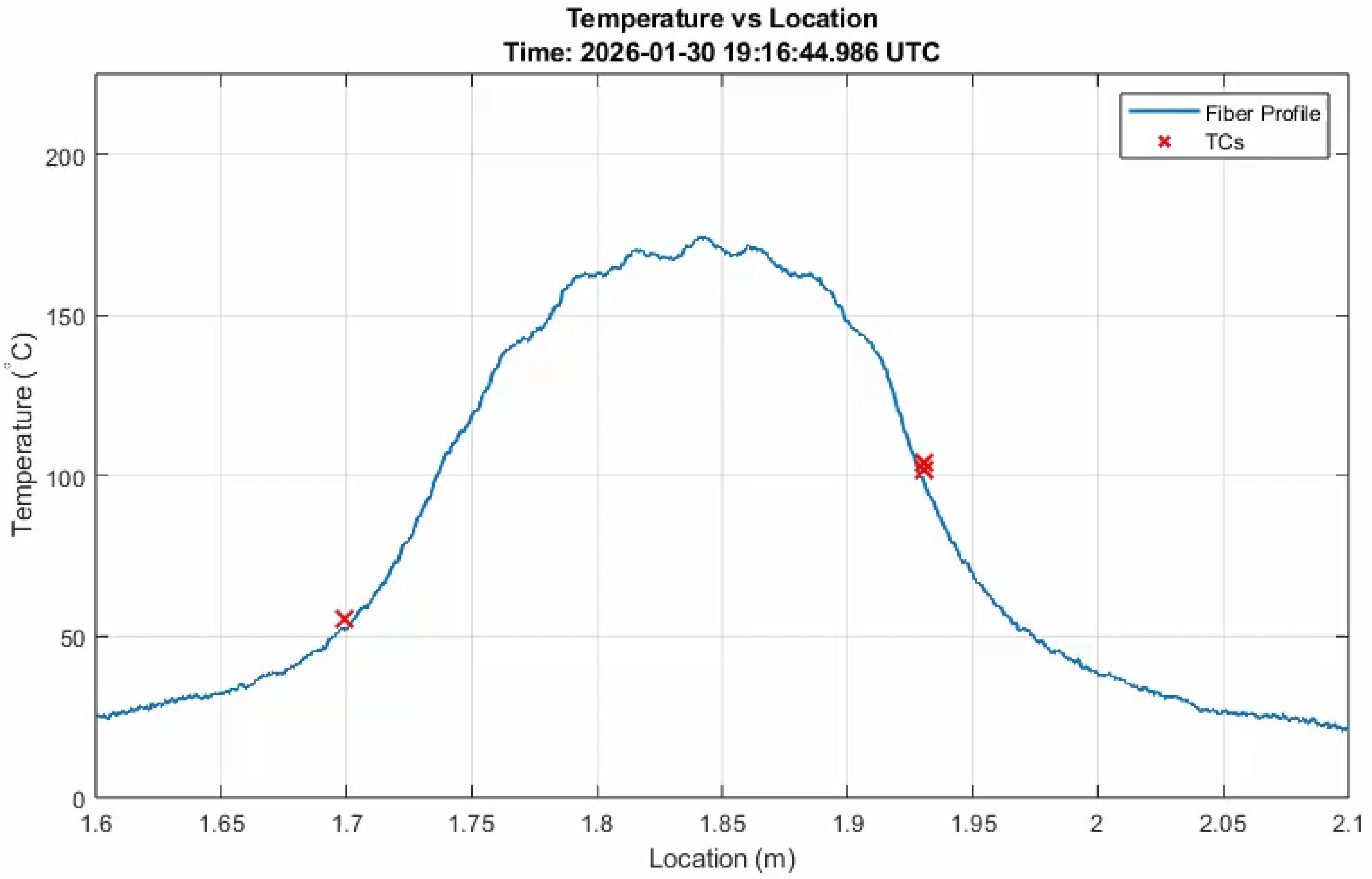


Figure 19. Experimental configuration of fiber sensor and induction heater.

Expanding Testing Facilities – Task 3



Next steps

- Expand heat pipe testing facility
  - Induction heated evaporator
  - Helium gas-gap calorimeter condenser
- Perform corrosion tests on heat pipe candidate materials – Task 7
  - Materials likely used for microreactor heat pipes (Inconel, Kanthal, FeCrAl, etc.)
- Develop methodology to test heat pipes during failure – Task 4
  - Laser induced pinhole breach
- Further explore performance degradation from
  - Non-condensable gases – Task 6
  - High oxygen content – Task 8

Publications

- Journal papers

E. Tillman, T. Moreira, G. Nellis, & M. Anderson. "High-Resolution Internal Temperature Measurements and X-Ray Imaging of Sodium Heat Pipes." *Applied Thermal Engineering*, 2025 [submitted, under revision]

- Conference Papers:

E. Tillman, T. Moreira, G. Nellis, & M. Anderson. "High-Resolution Temperature Measurements on Sodium Heat Pipes Applied to Microreactors." Presented at the ANS Winter Meeting 2024.

E. Tillman, G. Nellis, & M. Anderson. "X-ray Imaging of Flow Phenomena Within Sodium Heat Pipes for Microreactor Applications." *Transactions of the American Nuclear Society,* 2023. doi.org/10.13182/T128-42068

E. Tillman, G. Nellis, & M. Anderson. "Manufacturing and X-ray Imaging of Kilowatt-Scale Sodium Heat Pipes for Microreactor Applications." *Proceedings of the ANS Winter Meeting 2022*. doi.org/10.13182/T127-39763

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Thank you!

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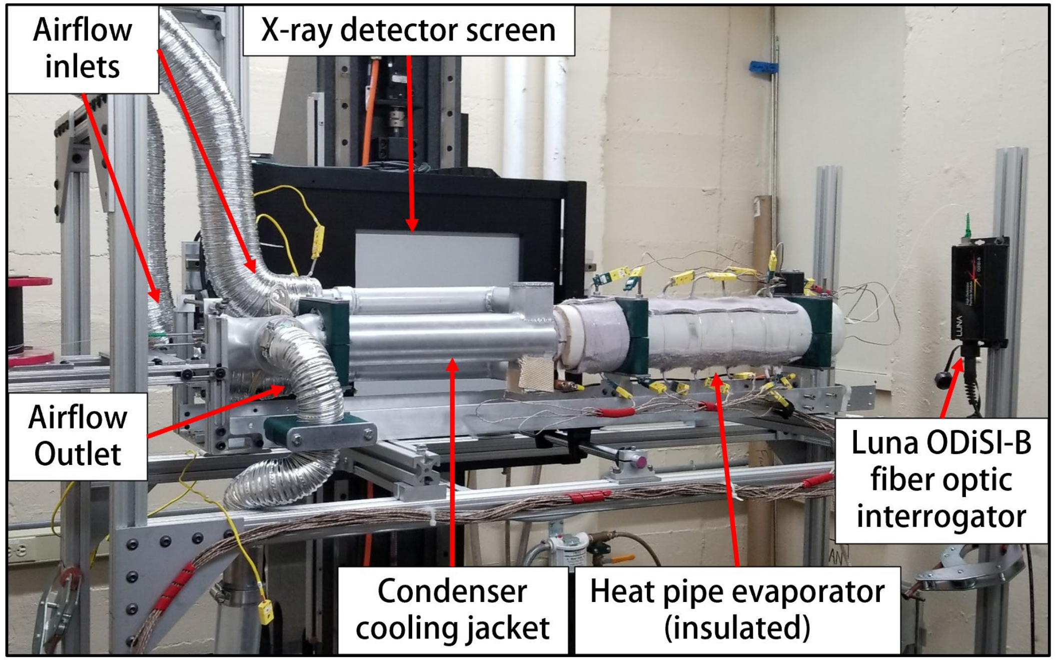
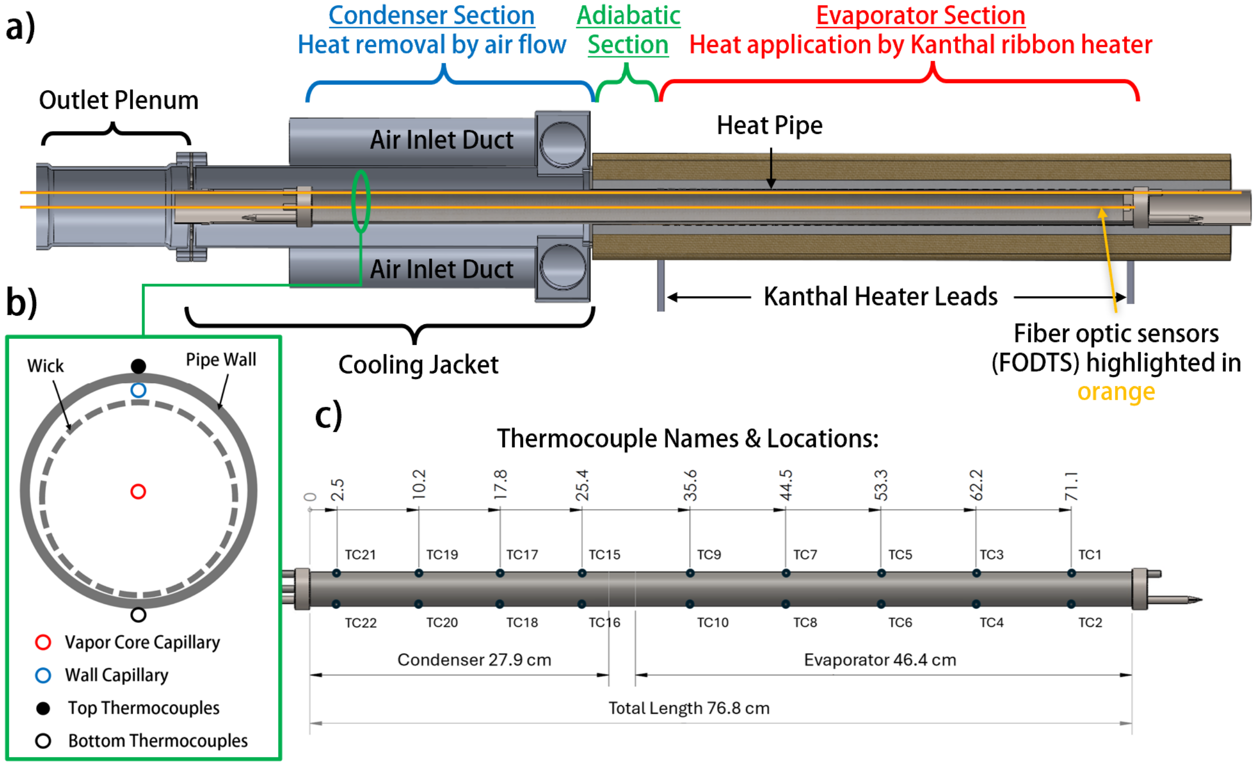
Supporting Slides Start Here!

Heat Pipe Testing and Characterization Facility

- Heat pipe installed in 450 kV X-ray facility for imaging
  - Up to 30 fps acquisition speed
  - 2048 x 2048 pixel array (41 cm x 41 cm)
- TCs measure external evaporator and condenser temperatures
- Luna ODiSI B system records internal FODTS temperature data
  - 0.5mm gauge length
  - Up to 100 Hz acquisition frequency
- Evaporator heated using resistive heating element (measure DC power input)
- Condenser cooled by forced airflow (measured using hotwire anemometer)





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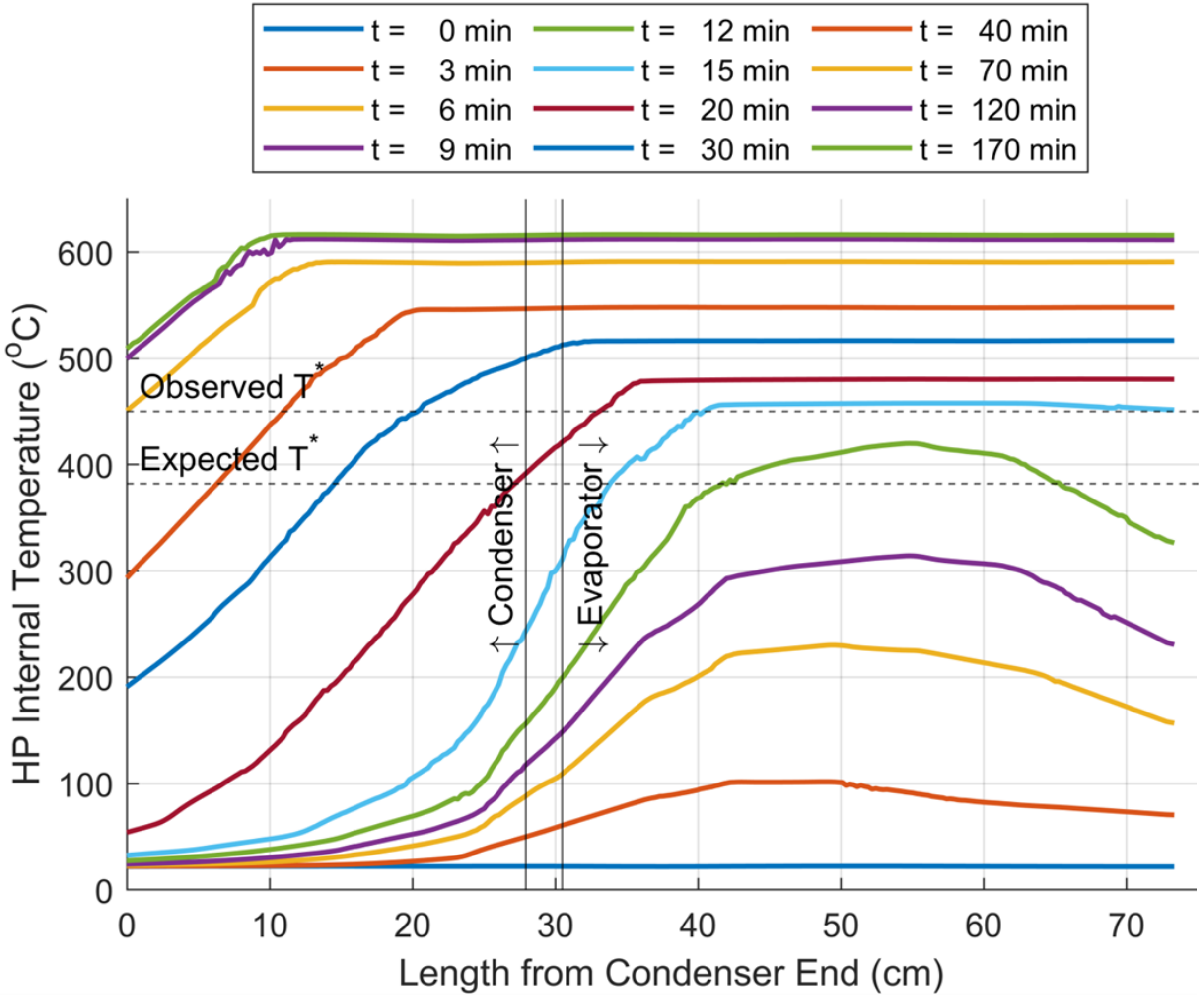
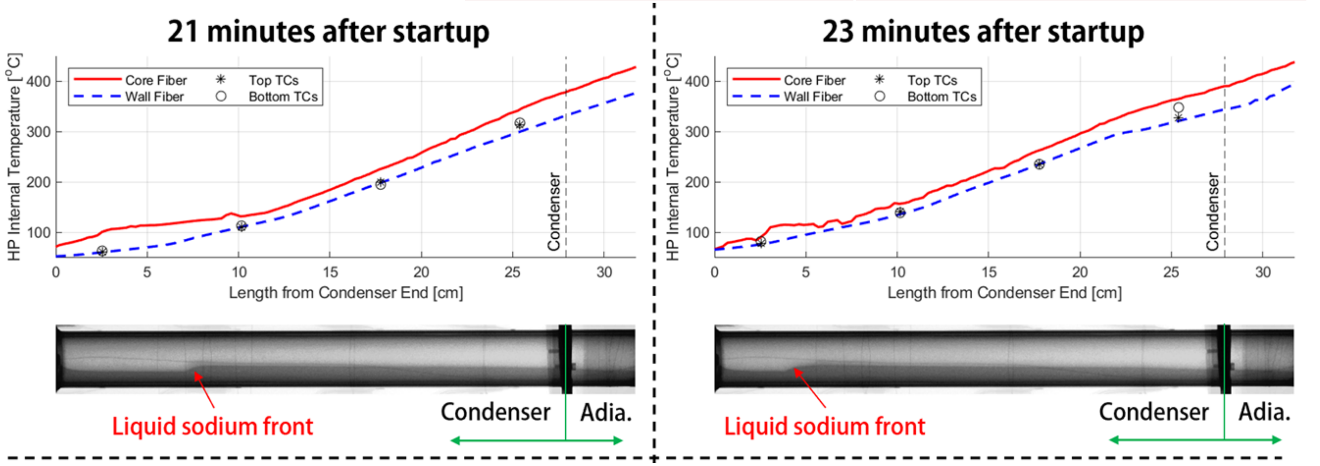
Example: Startup Characteristics

Vapor Core FODTS measurements, 500W startup



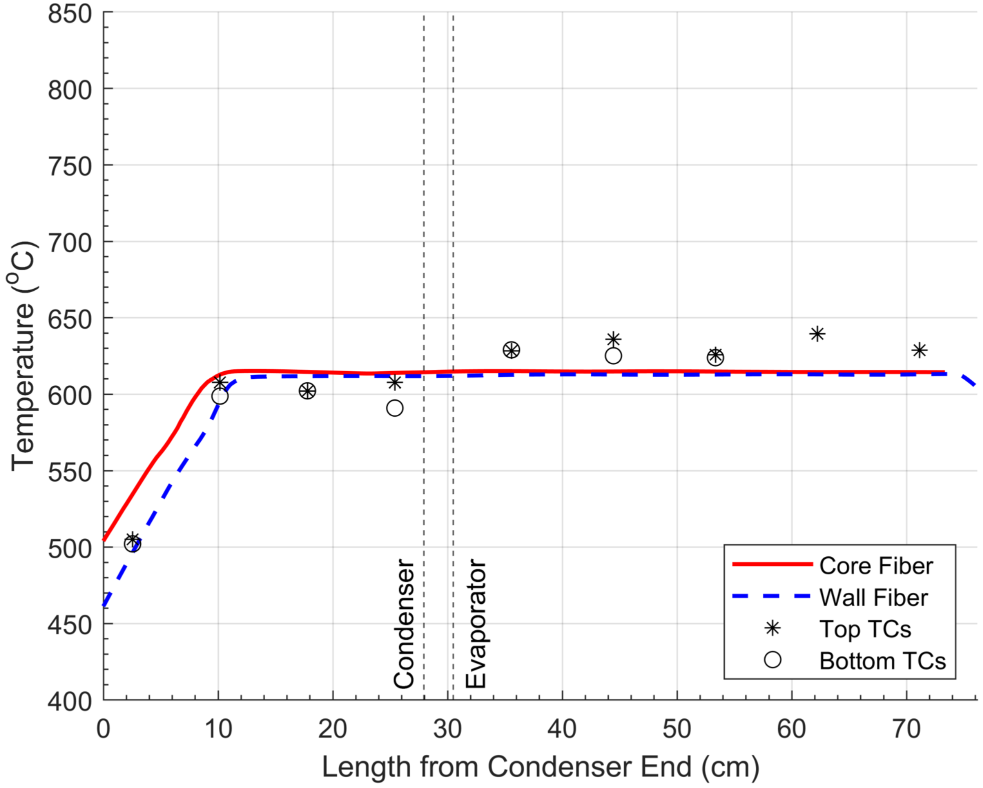
Parameter	Value
Pipe OD / ID	1.25 [in] / 1.12 [in]
Vapor Core Dia.	1.00 [in]
Evaporator Length	18 [in]
Adiabatic Length	1 [in]
Condenser Length	11 [in]
Wick Thickness	0.045 [in]
Wick Composition	6 Layers of 316 mesh: Inside: 1x 100x100 Middle: 3x 400x400 Outside: 2x 60x60
Max. Annular Gap	0.030 [in]
Sodium Fill	150% of wick + gap volume



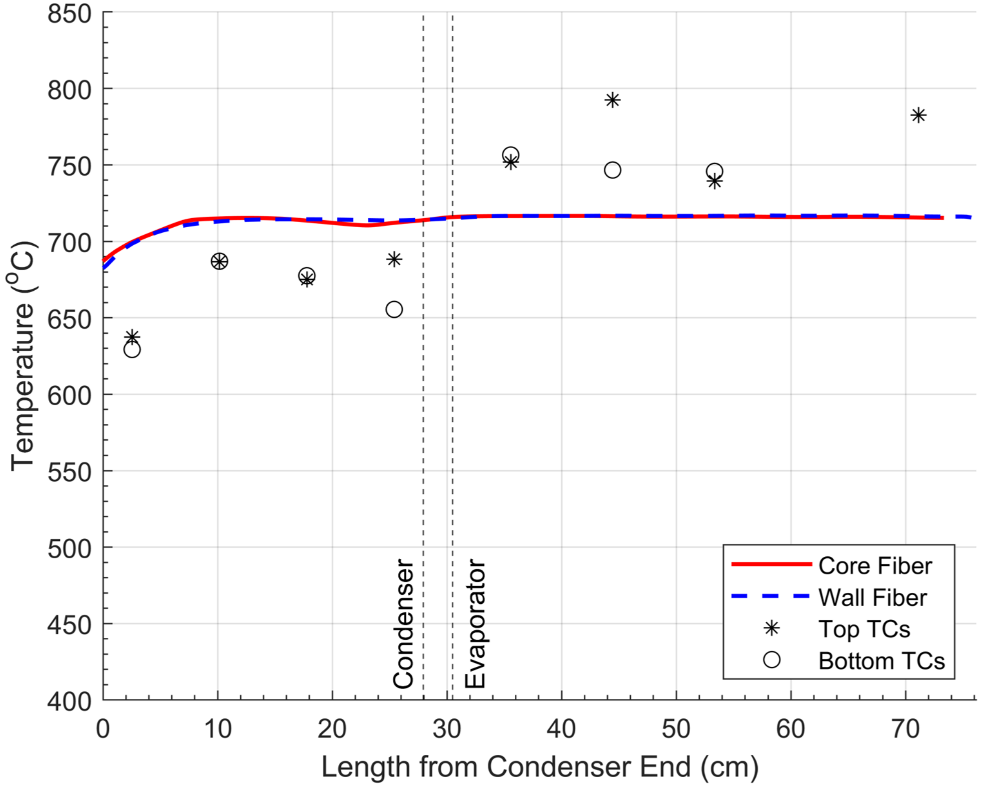
E. Tillman, T. Moreira, G. Nellis, & M. Anderson. "High-Resolution Internal Temperature Measurements and X-Ray Imaging of Sodium Heat Pipes." Applied Thermal Engineering, 2025 [submitted, under revision]

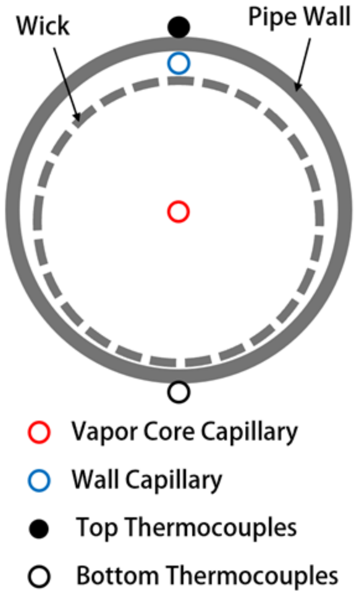
Steady-State Operating Conditions

a) 500 W, no airflow
(60 W/cm^2)



b) 1500 W, 42 m^3/hr airflow
(185 W/cm^2)

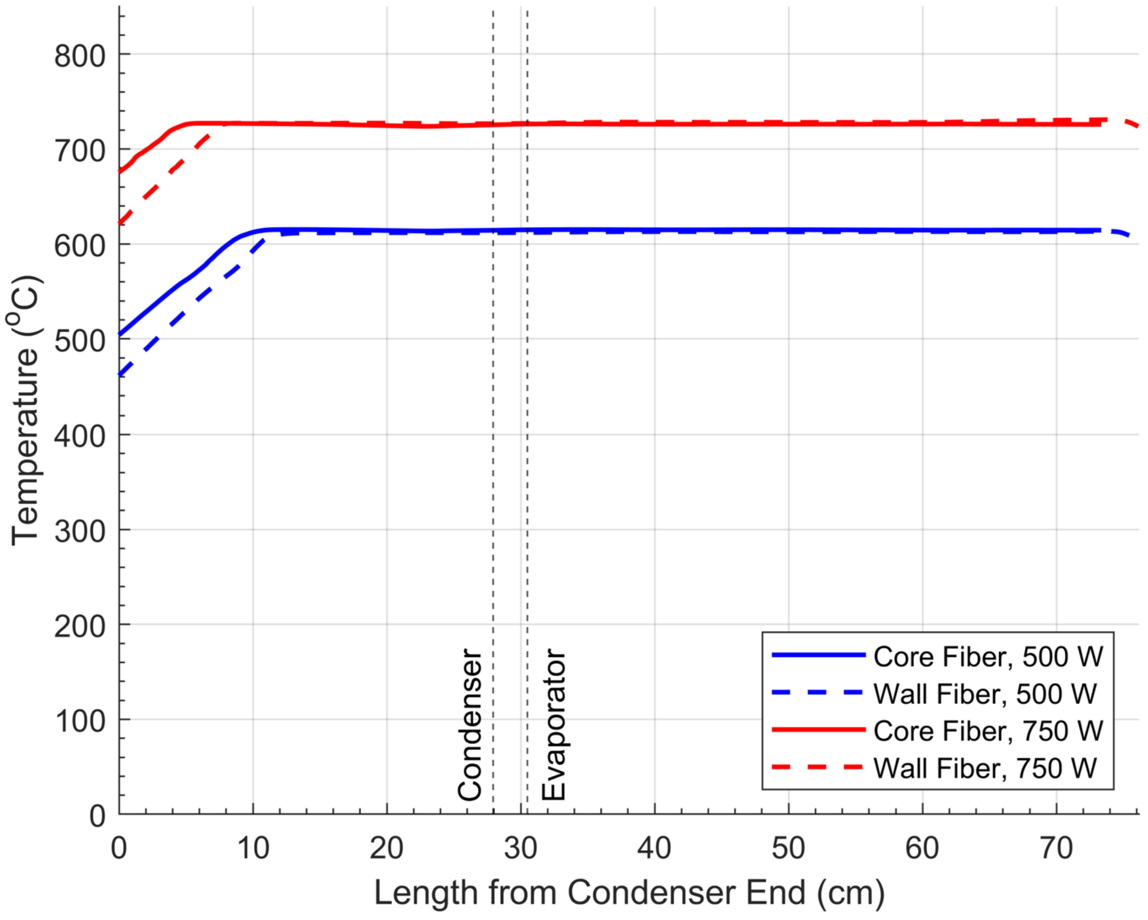




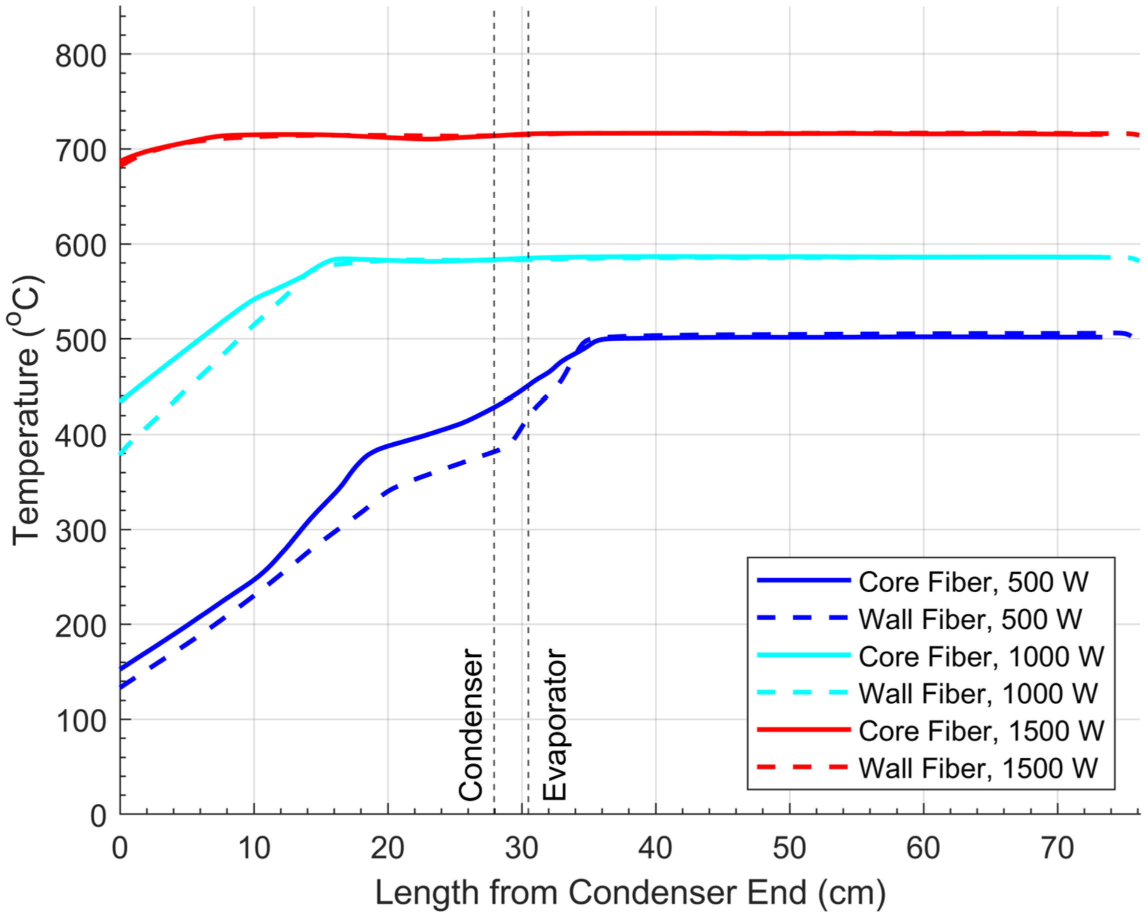
E. Tillman, T. Moreira, G. Nellis, & M. Anderson. "High-Resolution Internal Temperature Measurements and X-Ray Imaging of Sodium Heat Pipes." Applied Thermal Engineering, 2025 [submitted, under revision]

Effect of Heat Flux on Steady-State Operating Conditions

a) No condenser airflow



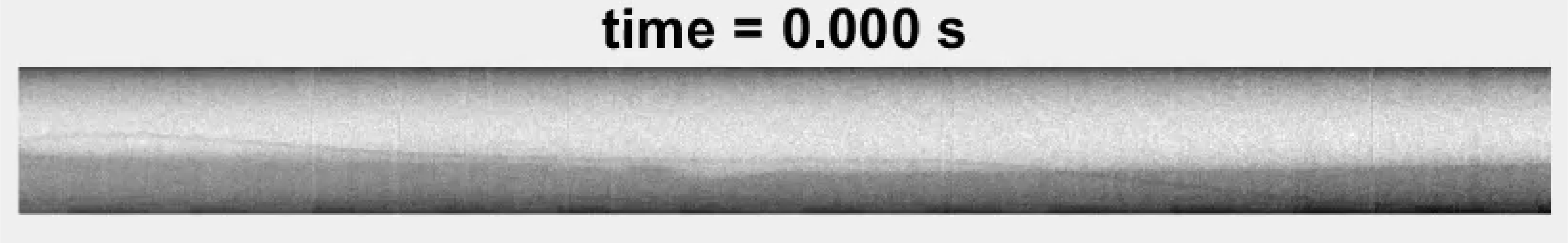
b) Condenser airflow of 42 m^3/hr

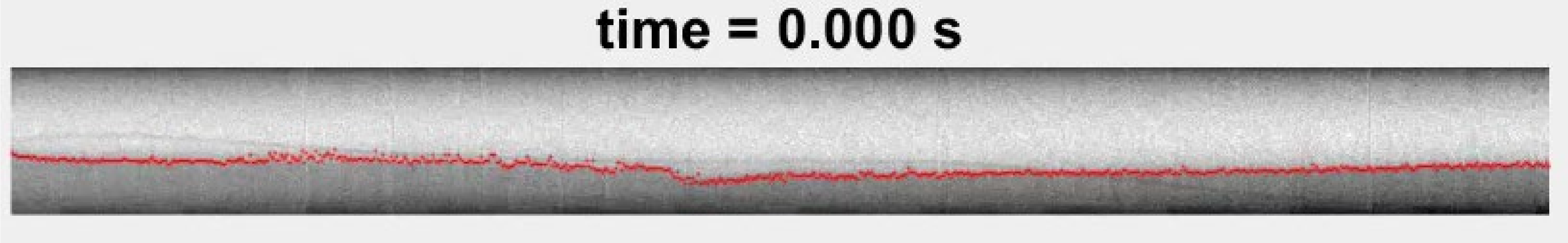


E. Tillman, T. Moreira, G. Nellis, & M. Anderson. "High-Resolution Internal Temperature Measurements and X-Ray Imaging of Sodium Heat Pipes." Applied Thermal Engineering, 2025 [submitted, under revision]

Time-Resolved X-ray Imaging

- Developed algorithm to track the liquid-vapor interface for every axial position





Both videos show condenser, 1000 W steady-state, 1/3x speed

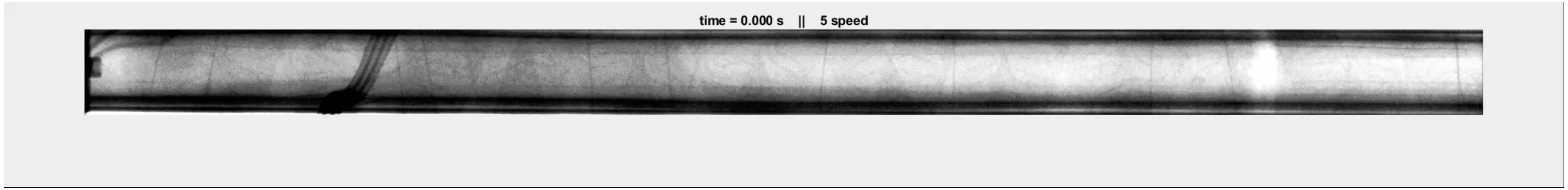
E. Tillman, T. Moreira, G. Nellis, & M. Anderson. "High-Resolution Internal Temperature Measurements and X-Ray Imaging of Sodium Heat Pipes." Applied Thermal Engineering, 2025 [submitted, under revision]

Effects of non-condensable gas in an overfilled heat pipe

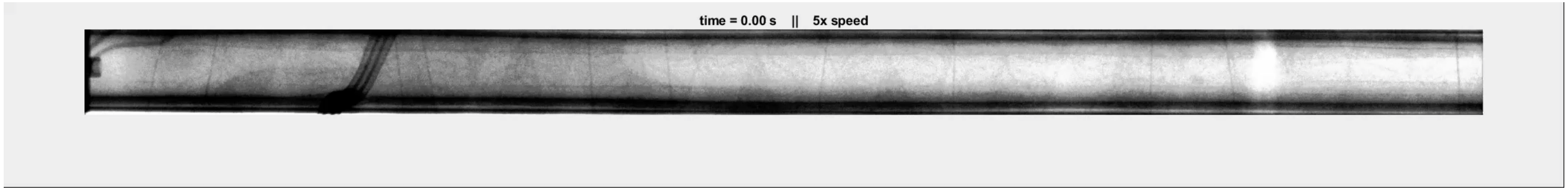
- Present NCG's raised sodium boiling temperature
- NCG's built up in condenser region
  - Shortened effective condenser length

To Condenser

To Evaporator



Power Increase



Shutdown

Induction Heater

- 16 kW, 480 V/ 3-phase
- Custom coil design and efficiency calculations
  - ~70%
- Frequency adjustment via switching capacitors/ adjusting transformer ratios
- 0-10V/4-20mA signal control
- Good control down to ~400W (before coil efficiency losses)
- Currently going through purchasing process
- Drawing new test stand for custom coil design

Milestones

- **Task 1: Failure modes and their effects on heat pipes:**
  - Major:
    - Characterization of the performance and limits of the sodium heat pipes
      - **UW** (lead), TAMU, Westinghouse and LANL
    - Assessment of heat pipe failure modes and their effects on heat pipe performance
      - **UW** (lead), TAMU, Westinghouse and LANL
  - Minor:
    - Construction of instrumented sodium heat pipes
      - **UW** (lead), Westinghouse and LANL
    - Characterization of theoretical heat pipe performance through numerical modelling and CFD
      - **UW** (lead), TAMU, Westinghouse and LANL

- **Task 2: Performance degradation with different non-condensable gases:**
  - Major:
    - Characterization of the effects different non-condensable gases have on heat pipe performance
      - **UW** (lead), TAMU, Westinghouse and LANL
  - Minor:
    - Design and construction of liquid sodium heat pipes with access for vacuum level control
      - **UW** (lead), Westinghouse and LANL

Milestones

- **Task 3: Effect of sodium oxygen content on heat pipe performance:**
  - Major:
    - Evaluation of the effect that sodium oxygen concentration has on heat pipe performance
      - **UW** (lead), Westinghouse and LANL
  - Minor:
    - Corrosion assessment of heat pipe candidate materials in liquid sodium at different oxygen concentrations
      - **UW** (lead), Westinghouse and LANL

- **Task 4: Wick optimization and heat pipe performance:**
  - Minor:
    - Development of optimized wicks based on CFD and water experiments considering water-sodium scaling methodologies
      - **TAMU** (lead), UW, Westinghouse and LANL
  - Major:
    - Construction and testing of heat pipes with optimized wicks from start-up up to their limits of operation
      - **UW** (lead), Westinghouse and LANL

Measurement Technologies

- Fiber-Optic Distributed Temperature Sensing (FODTS)
- Change in temperature causes optical fiber to expand
- This causes a change in refractive index
- Reference key allows calculation of temperature profile along the fiber length
- Spatial resolution of ~0.5mm
- Measurement frequency up to 100 Hz

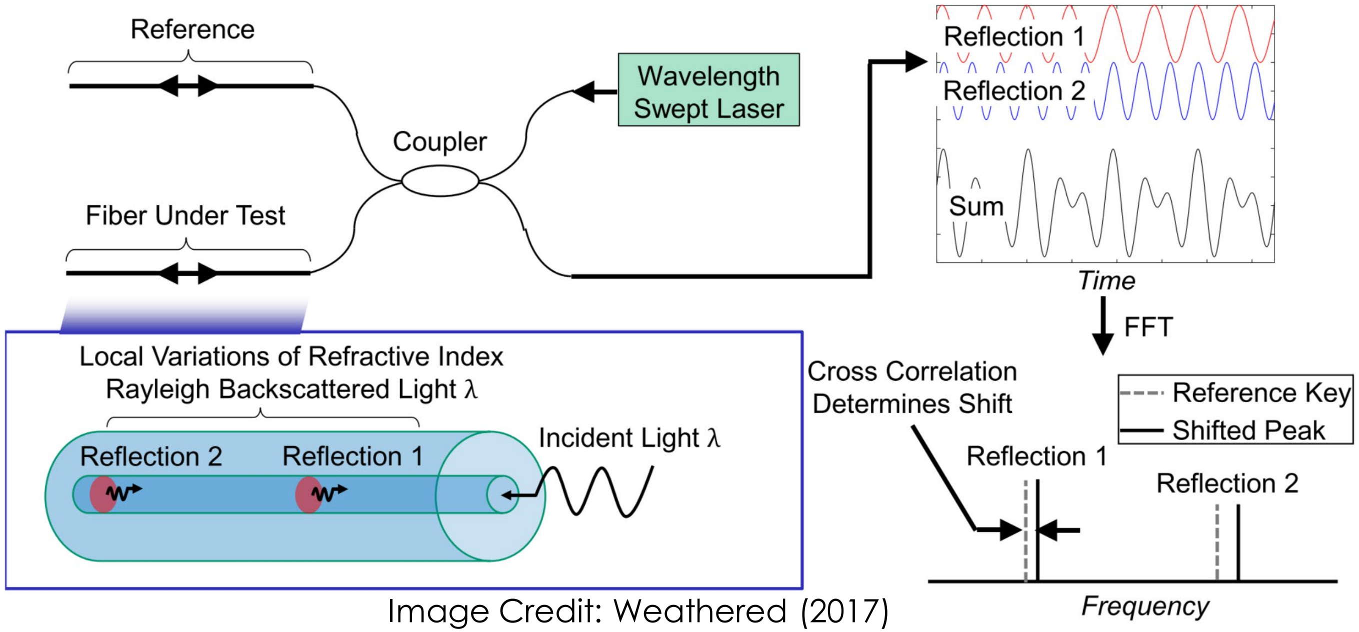


Image Credit: Weathered (2017)

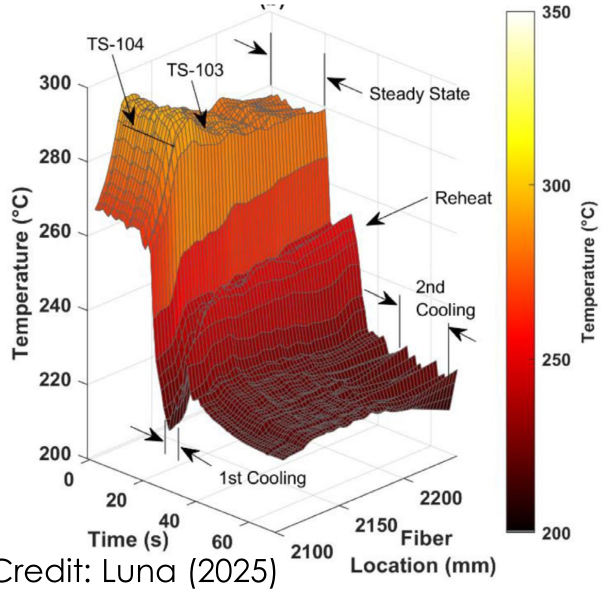
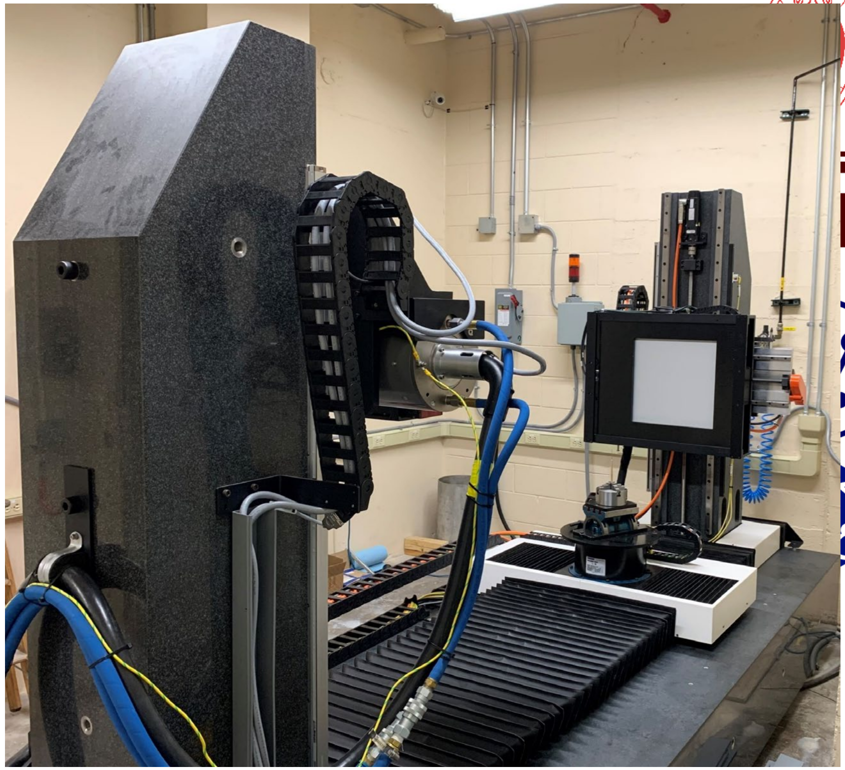


Image Credit: Luna (2025)

Thermal Hydraulics Laboratory

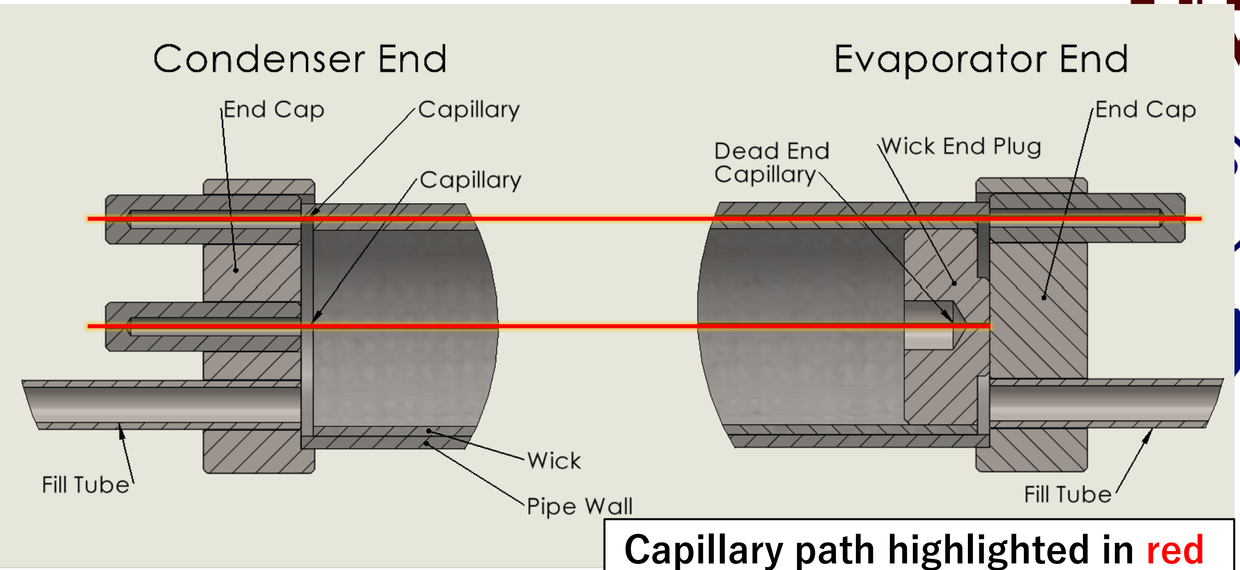
Measurement Technologies

- High-power (450 kV) industrial X-ray imaging system
  - Designed for imaging of steel components
- Can be used to acquire 3D images (CT scans) or series of 2D images
- Detector characteristics:
  - Pixel size: 2048 x 2048
  - Pixel pitch: 200 μm
  - Image acquisition rate of 15 Hz or 30 Hz with 2 x 2 binning

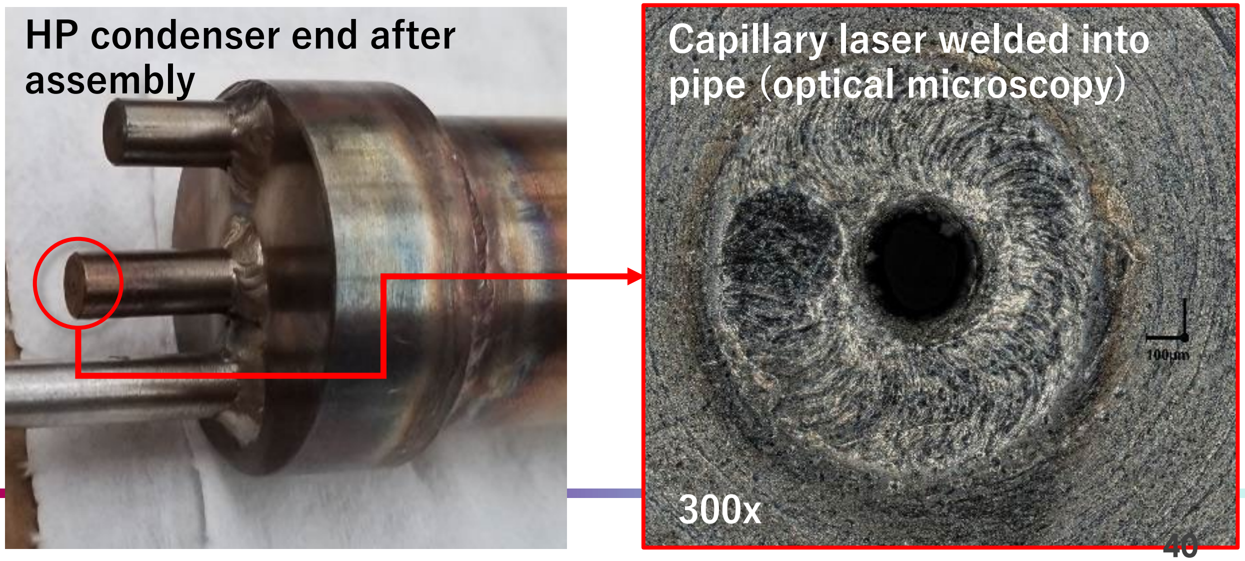


Capillaries for Internal FODTS Measurements

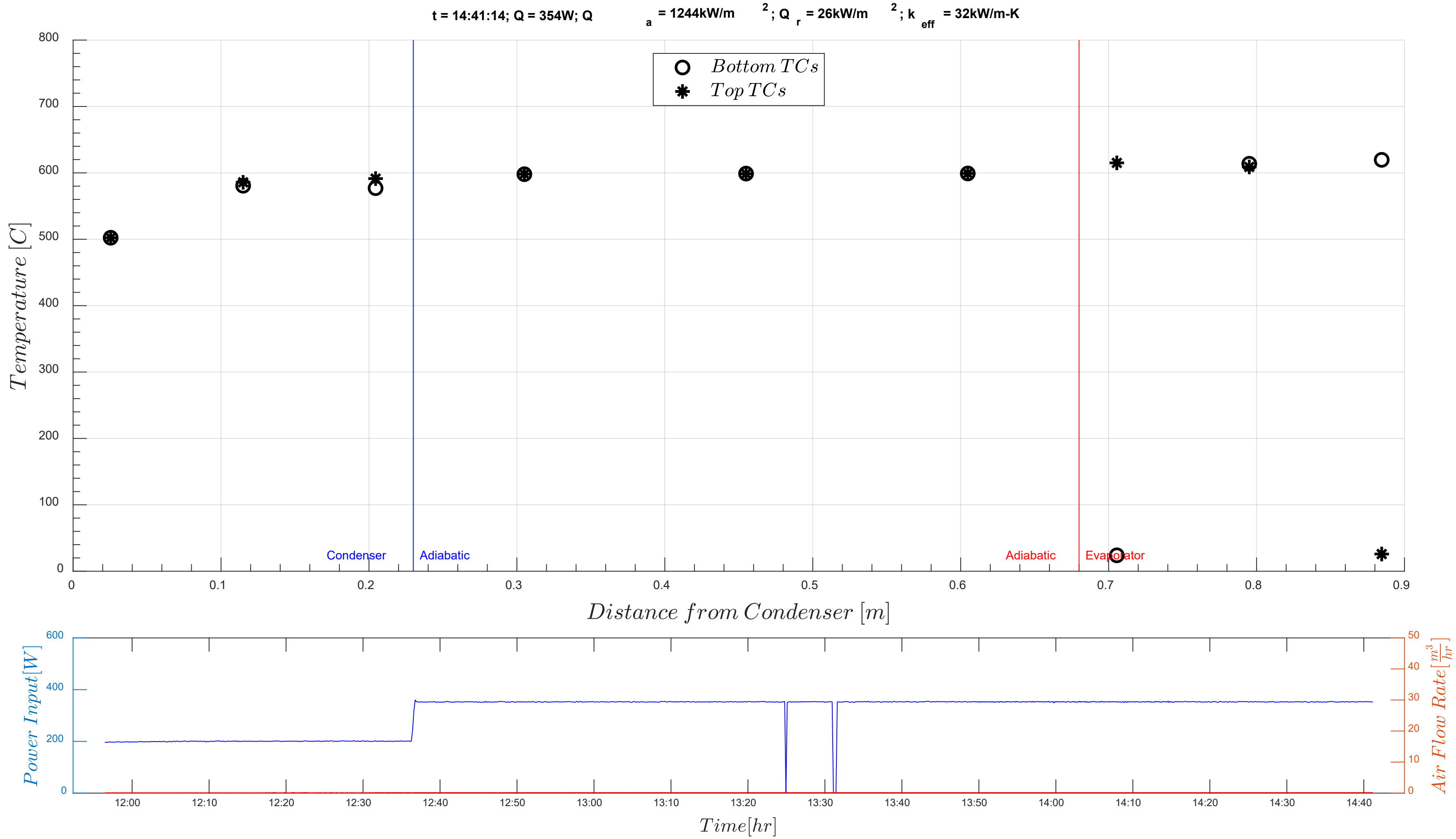
- <u>Goal:</u> use FODTS to get internal temperature data
  - Spatial resolution: 0.5mm
  - Temporal resolution up to 100 Hz
- Designed heat pipe with two embedded capillary tubes
- CNC laser weld to seal capillaries into pipe without leaking
- Tested with helium leak sniffer to verify hermetic seal



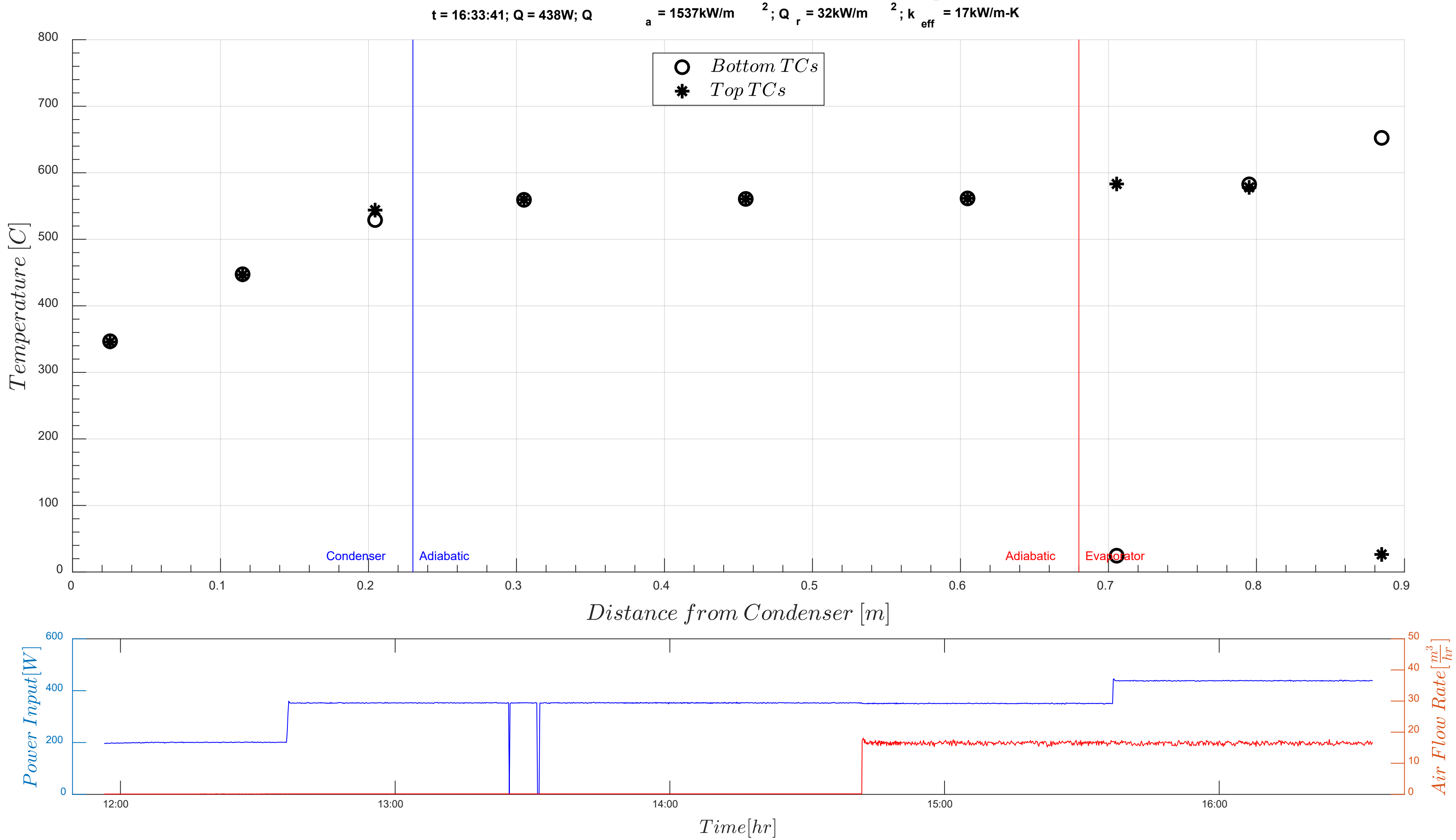
Capillary path highlighted in red



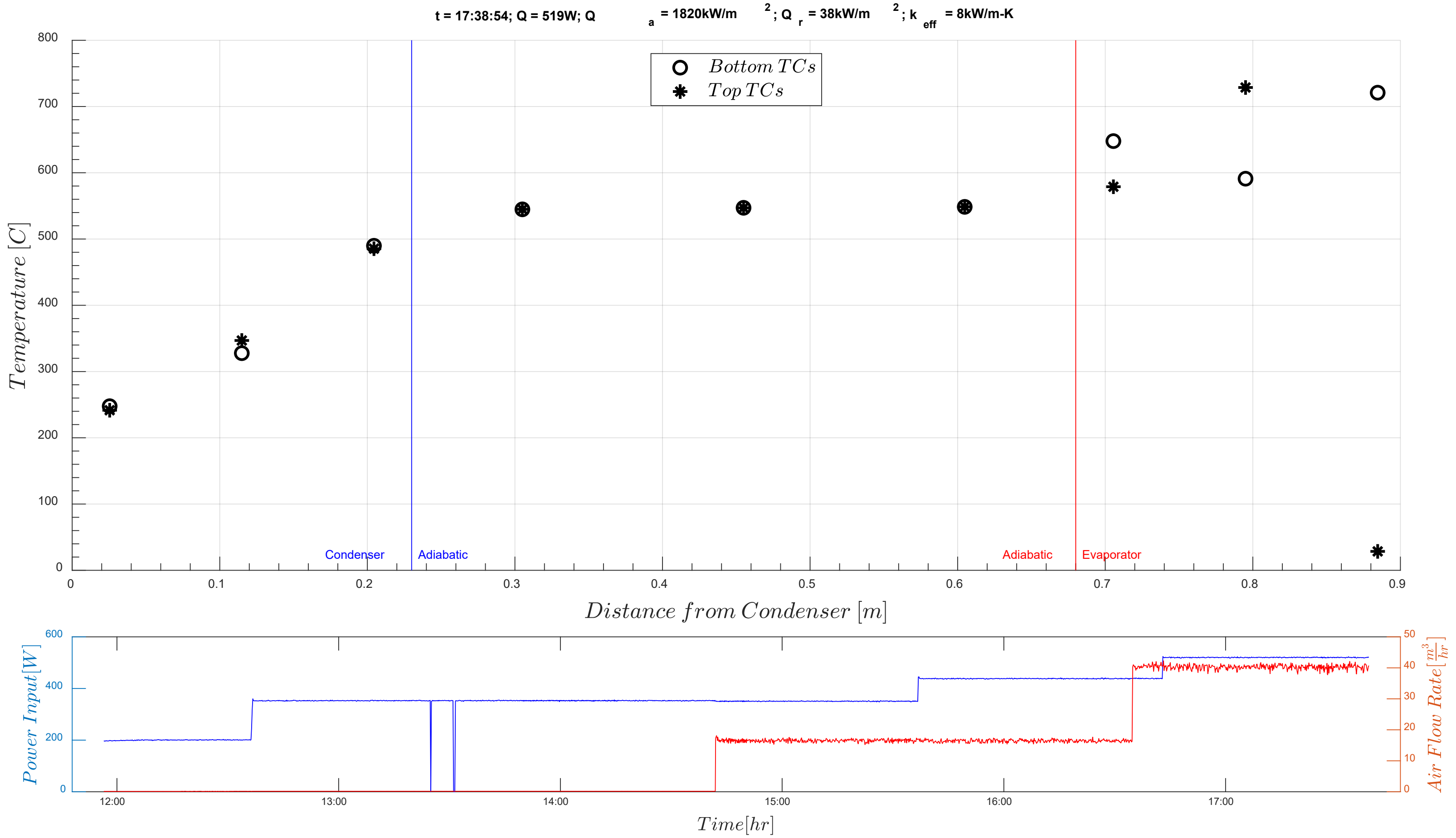
Mesh 1: 350W; No Blower; Steady State



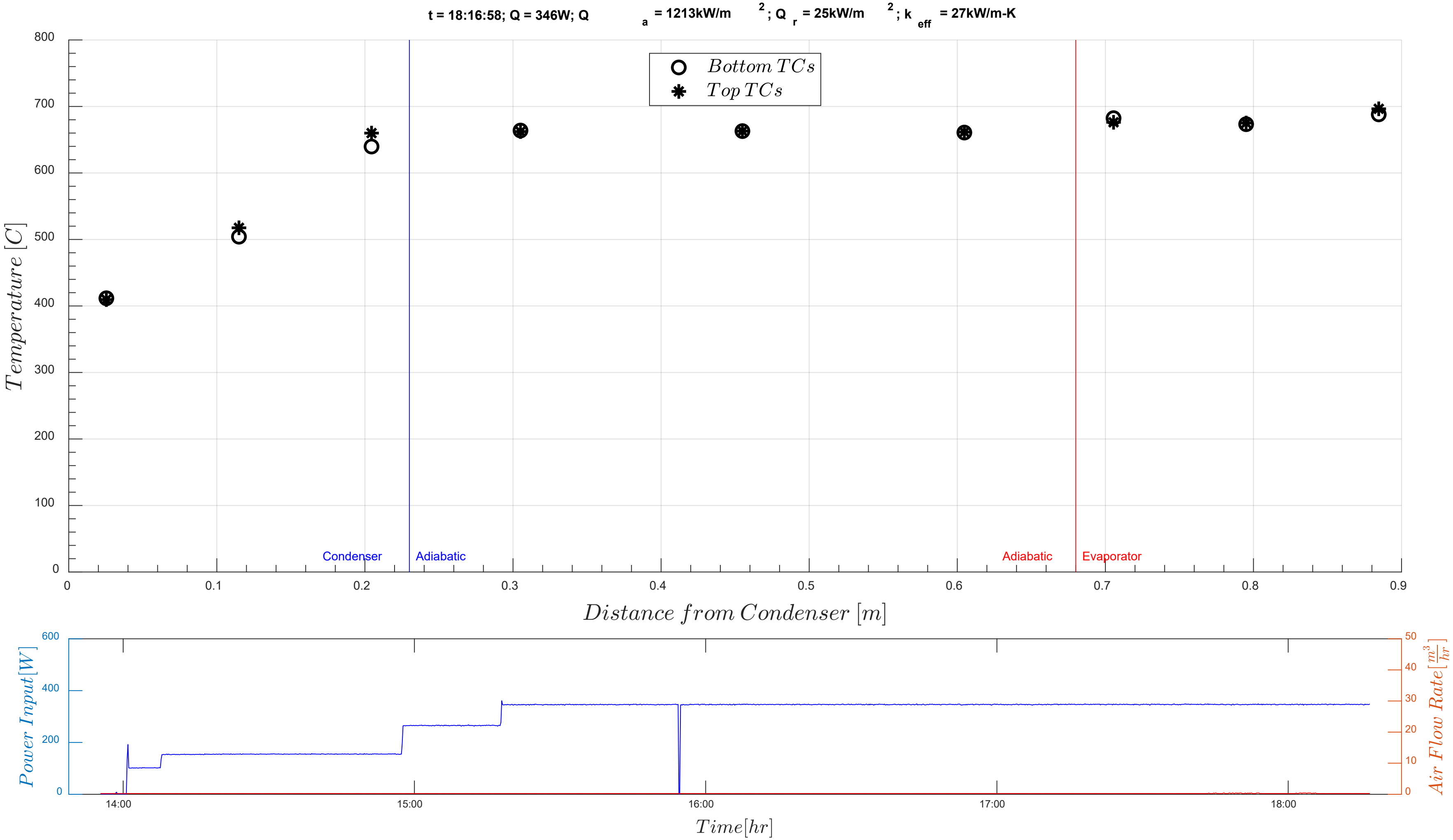
Mesh 1:440W; 15% Blower; Steady State



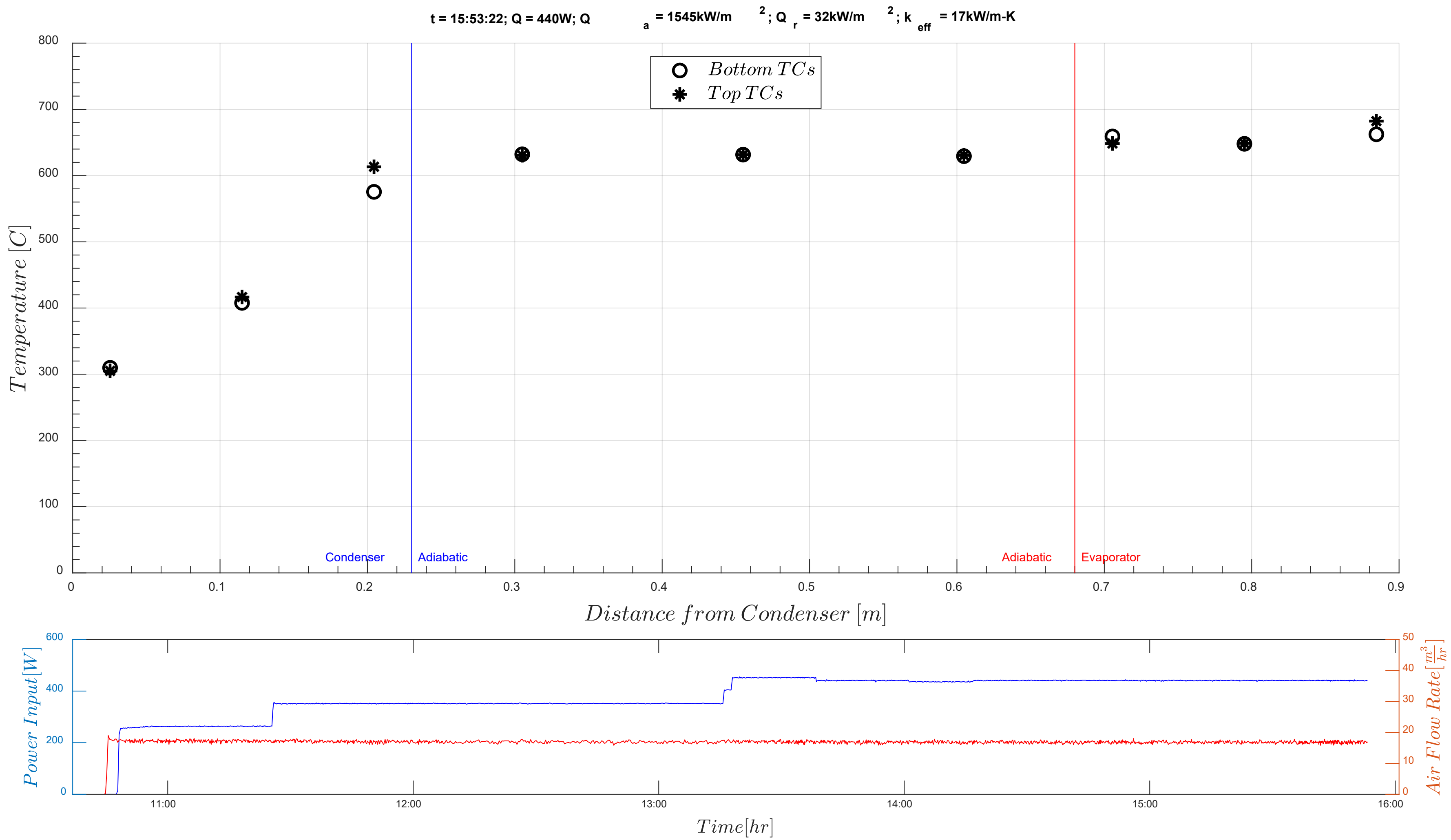
Mesh 1: 520W; 30% Blower; Steady State



Porous 3: 350W; No Blower; Steady State



Porous 3:440W; 15% Blower; Steady State



Porous 3: 520W; 30% Blower; Steady State