NEUP Program

Experiments for Modeling and Validation of Liquid-Metal Heat Pipe Simulation Tools for Micro-Reactors

March 04, 2022

Yassin. A. Hassan | Texas A&M University

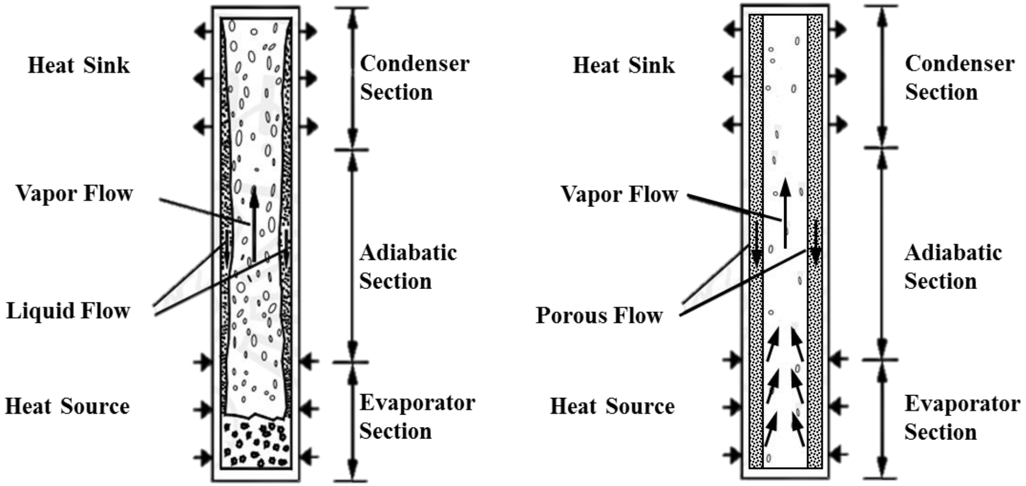
Joseph Seo | Texas A&M University

Daeguen Kim | Texas A&M University

Hansol Kim | Texas A&M University

Rodolfo Vaghetto | Texas A&M University

Overview of the Project



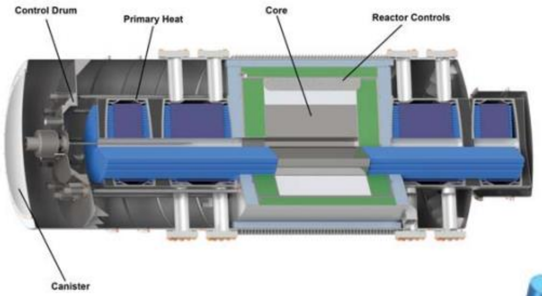
- The heat pipe is a device of very high conductance
- It works passively on the principle of evaporation and condensation of a working fluid so that it can transfer large amount of heat.
- Intensive studies to apply the heat pipe as a primary heat transfer system of the micro-reactor have been pursued.

Spacecraft

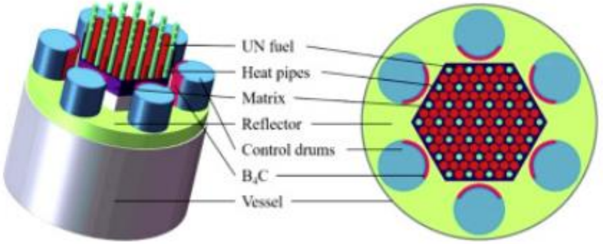
Computer

Pipeline

Spacecraft, heat pipes in computer, Alaska pipeline support legs cooled by heat pipe thermosyphons to keep permafrost frozen.
From: Heat pipe – Wikipedia and wall.alphacoders.com



Design of e-Vinci from Westinghouse



Wang et al., Thermal-hydraulic analysis of a new conceptual heat pipe cooled small nuclear reactor system (2018)

Single heat pipe test in MAGNET experimental station in INL.

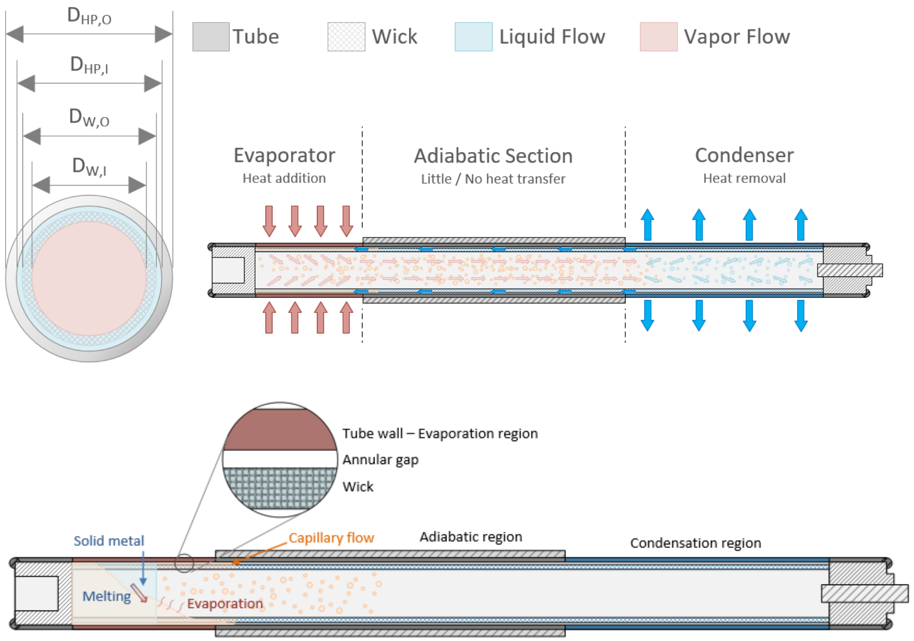
MRP Microreactor Program

Overview of the Project

Purpose: The proposed work aims to produce high-fidelity liquid-metal heat-pipe experimental data for the validation of the simulation tool, Sockeye, through both single heat-pipe and integrated heat-pipe experiments.

Objectives:

- **Single Heat-Pipe Hydraulic Experiment**
  Measurements of the hydraulic resistance for validation / development of wall friction, wick friction/form loss models.
- **Single Liquid-Metal Heat-Pipe Experiment**
  Measurements of internal temperature, pressure, and phase distribution for validation/development of heat transfer and flow models in Sockeye.
- **Multiple Liquid-Metal Heat-Pipes Experiment in Hexagonal Arrangement**
  Investigate the integrated system performance under various operational scenarios such as partial failure of constituent heat pipes and non-uniform cooling/heating.



Sodium heat pipe with targeted design

MRP Microreactor Program

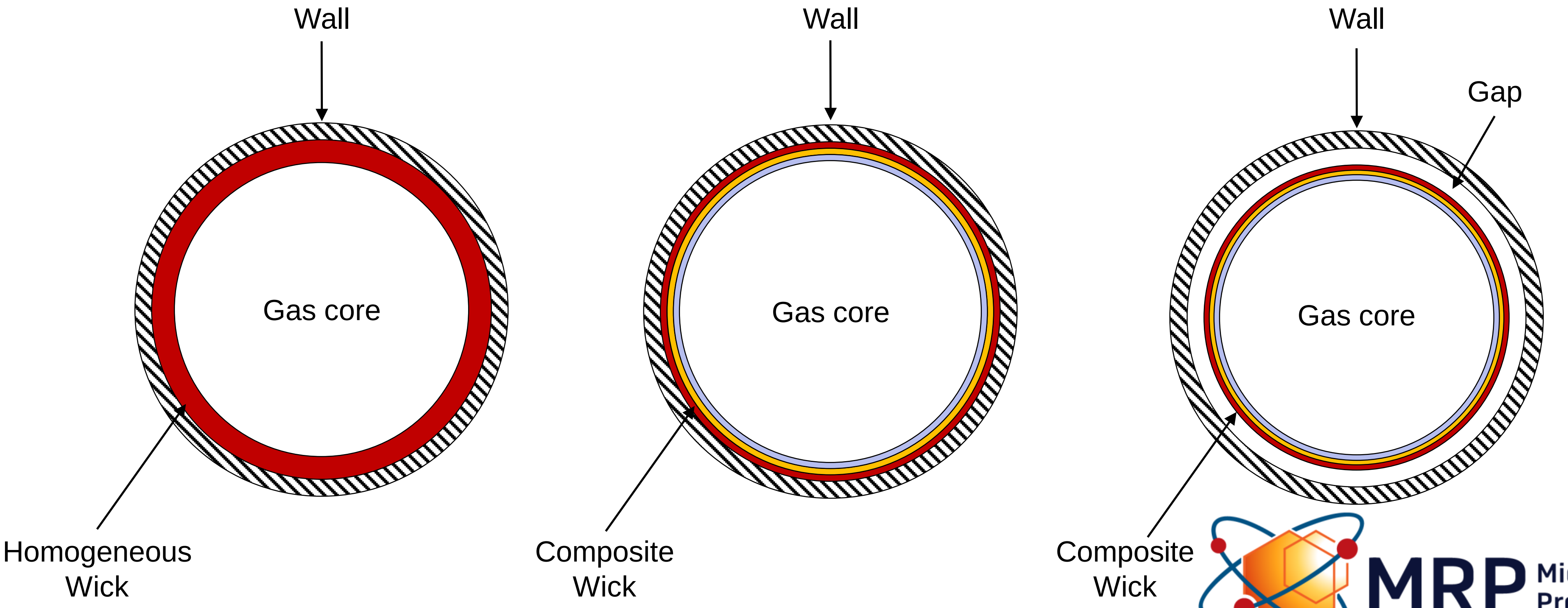
➢ Experiments at TAMU

- **Wick Characteristics Experiment**
- Gap Effect Experiment
- Capillary Rising Modeling
- Heat Pipe Fabrication and Experiment
- Heat Pipe Measurement
- Heat Pipe Visualization

MRP Microreactor Program

Introduction

- Pore radius, or pore size, is an average size of voids inside the porous media. This parameter should be small to acquire a large capillary pressure difference between the evaporator and condenser region.
- For a heat pipe, the permeability is a parameter of the wick resistance to the liquid flow along the pipe axial direction. Large permeability is needed for achieving a small liquid pressure drop along the wick structure.
- Having a low pore radius and a high permeability is hard to achieve in most homogeneous wick designs (Optimization/Tradeoff problem).
- The composite wick structures provide high capillary pressure by having small pores, while gaining high permeability from large size pores.
- The other way to overcome the tradeoff problem is to introduce an extra flow path for liquids other than wick structures.

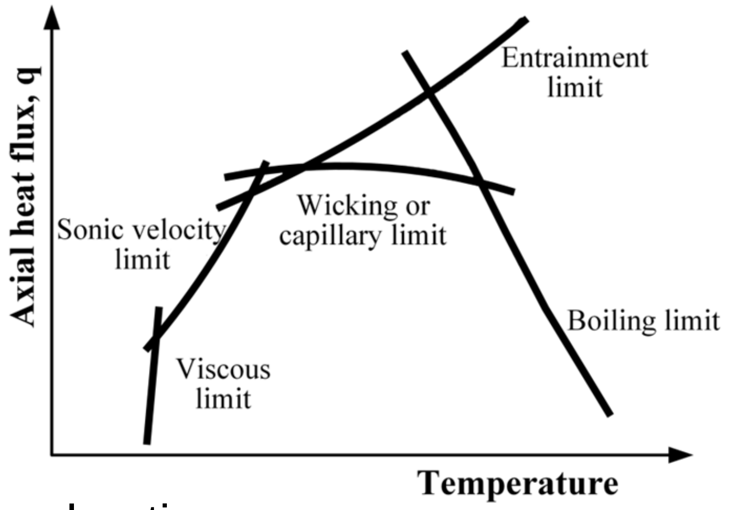


MRP Microreactor Program

Operating Limitation of the Interest

Capillary limitation

During heat pipe operation, the working fluid evaporates in the evaporator and condenses in the condenser, transporting the latent heat from one end of the heat pipe to the other.
The liquid condensate is passively returned to the evaporator by capillary forces in the wick.
The maximum power that the heat pipe can transport and still return the condensate by capillary forces is the capillary limit.



$\Delta P_c > \Delta P_g + \Delta P_v + \Delta P_l$

ΔP_c: Capillary force generated in the wick

ΔP_g: Pressure drop due to gravitation and acceleration

ΔP_l: Liquid pressure drop in the wick

ΔP_v: Fractional pressure drop in the vapor

MRP Microreactor Program

Operating Limitation of the Interest

Capillary limitation

ΔP_c: Capillary force generated in the wick

$$\Delta P_C = \frac{2\sigma}{r_{eff}}$$

ΔP_g: Pressure drop due to gravitational acceleration

$$\Delta P_g = (\rho_l - \rho_v) gh$$

ΔP_l: Liquid pressure drop in the wick (Darcy's law)

$$\Delta P_l = \frac{\dot{m}\mu L}{\rho_l K A_{wick}} = \frac{q}{h_{lv}} \frac{\mu L}{\rho_l K A_{wick}}$$

K: Permeability

A_{wick} : Wick cross-sectional area

ΔP_v: Fractional pressure drop in the vapor

$$\Delta P_v = \frac{f \rho_v u_v^2 L}{D_v}$$

f : Fanning friction factor

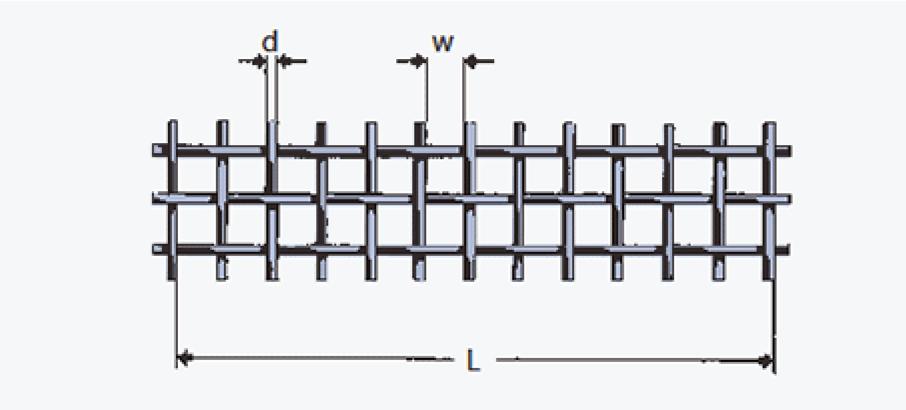
$$\Delta P_C > (\rho_l - \rho_v) gh + \frac{q}{h_{lv}} \frac{\mu L}{\rho_l K A_{wick}} + \frac{f \rho_v u_v L}{D_v}$$

$$q_C < \frac{h_{lv} \rho_l K A_{wick}}{\mu L} \left[(\rho_l - \rho_v) gh + + \frac{f \rho_v u_v L}{D_v} - \Delta P_C \right]$$

MRP Microreactor Program

Wick characteristics – Single Layer

Metal screen mesh wicks



Wick type	Wire diameter, d [mm]	Opening size, W [mm]	Opening area	r_{eff} $[mm]$ (W+d)/2	Mesh number, N=1/(W+d)	Porosity φ[-]	Permeability K[m^2]
60 x 60	0.1905	0.1397	12%	0.1651	3.028468	0.524	1.89E-10
100 x 100	0.1143	0.1524	30%	0.13335	3.749531	0.647	2.32E-10
200 x 200	0.04064	0.08636	46%	0.0635	7.874016	0.736	7.76E-11
200 x 200	0.05334	0.07366	34%	0.0635	7.874016	0.654	5.44E-11
400 x 400	0.0254	0.0381	38%	0.03175	15.74803	0.670	1.46E-11
500 x 500	0.02032	0.03048	36%	0.0254	19.68504	0.670	9.38E-12

MRP Microreactor Program

Test Matrix

The wick combining coarse and fine wick have superior performance since heat pipe performance requires high capillary pressure, and yet still offer low resistance to fluid flow*

Case	Type	Pore radius, d (um)	Porosity, ε	Permeability, K (m2)	Capillary Pressure (Pa)	Maximum Heat input (W)
1	100-mesh (6 wraps)					
2	400-mesh (6 wraps)					
3	60-mesh (6 wraps)					
4	100-mesh (2 wraps), 400-mesh (2 wraps), 60-mesh (2 wraps)					
5	100-mesh (1 wraps), 400-mesh (3 wraps), 60-mesh (2 wraps)					
6	100-mesh (2 wraps), 400-mesh (3 wraps), 60-mesh (1 wraps)					
7	100-mesh (2 wraps), 400-mesh (1 wraps), 60-mesh (3 wraps)					
8	100-mesh (3 wraps), 400-mesh (2 wraps), 60-mesh (1 wraps)					
9	100-mesh (3 wraps), 400-mesh (1 wraps), 60-mesh (2 wraps)					

Measured by EXP.

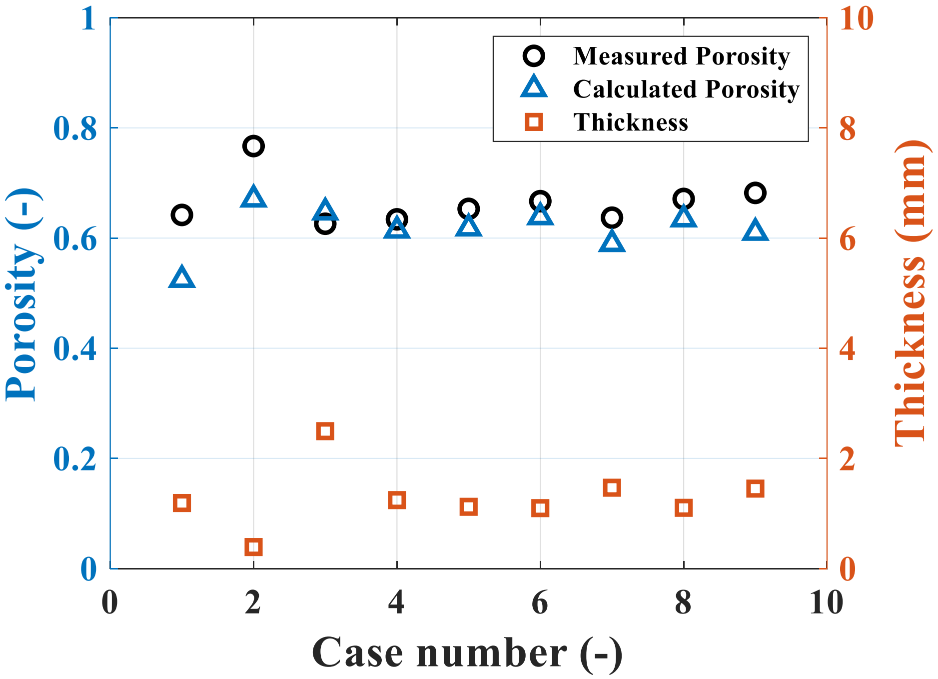
Calculated from theoretical models

- Mwaba et al., "Influence of wick characteristics on heat pipe performance", 2006, Carleton University

Porosity Measurement

m_{wick}

$m_{wick} + m_l$



Porosity of the mesh: $\frac{1}{\varepsilon} = 1 + \frac{m_{wick}\rho_l}{m_l\rho_{wick}}$

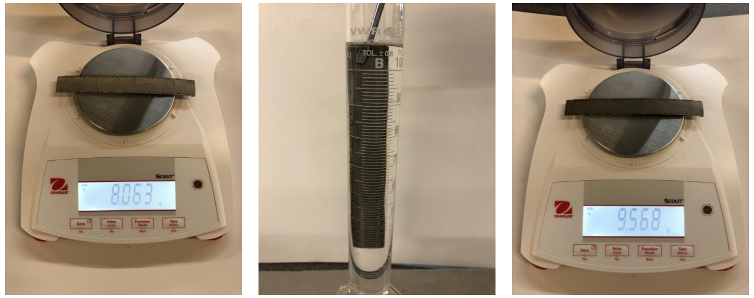
Wick Characteristics Experiment

The wick with the best performance

composite wick structures were characterized

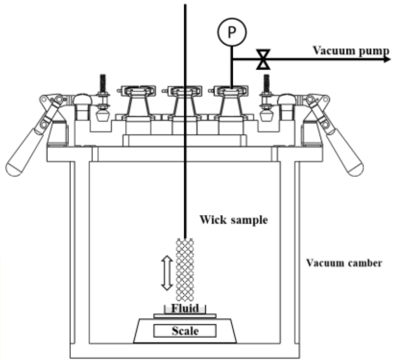
Case #	Total number of layers	Mesh composition			Measurement result			
		100-mesh (inside layer)	400-mesh (middle layer)	60-mesh (outside layer)	Porosity (ε [−])	Permeability (K [μm^2])	Effective Pore Radius (r_{eff}[mm])	$\frac{K}{r_{eff}}$ [μm]
1		6	0	0	0.642	0.815× 10^3	0.266	3.064× 10^3
2		0	6	0	0.767	0.825× 10^3	0.232	3.556× 10^3
3		0	0	6	0.626	0.745× 10^3	0.419	1.778× 10^3
4		2	2	2	0.634	0.985× 10^3	0.252	3.909× 10^3
5	6	1	3	2	0.653	1.435× 10^3	0.213	6.737× 10^3
6		2	3	1	0.667	1.205× 10^3	0.264	4.564× 10^3
7		2	1	3	0.637	0.300× 10^3	0.188	1.596× 10^3
8		3	2	1	0.671	0.635× 10^3	0.169	3.757× 10^3
9		3	1	2	0.682	1.080× 10^3	0.284	3.803× 10^3

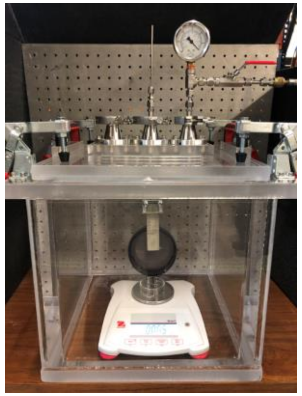
Porosity measurement

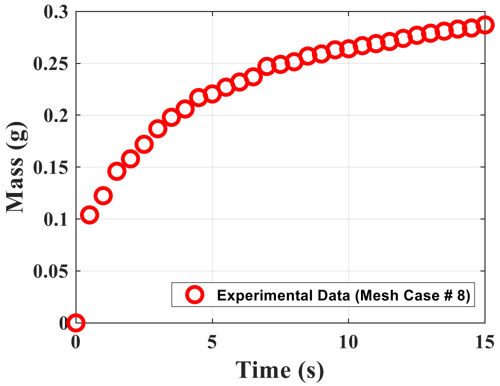


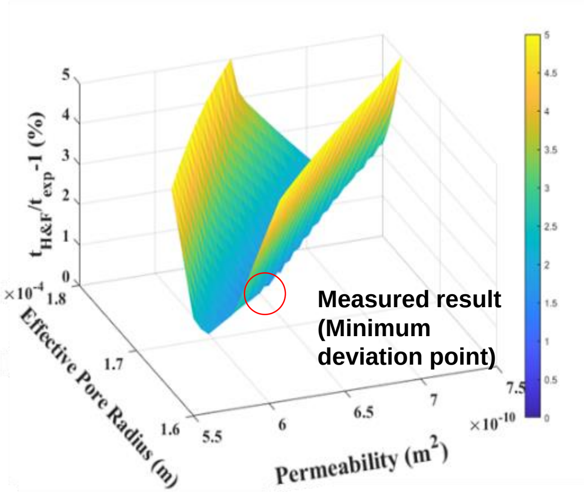
Porosity is calculated from the mass and density of the liquid filling void space of the mesh.

Permeability and effective pore radius measurement









The method by Holley and Faghri (2005) is used.

MRP Microreactor Program

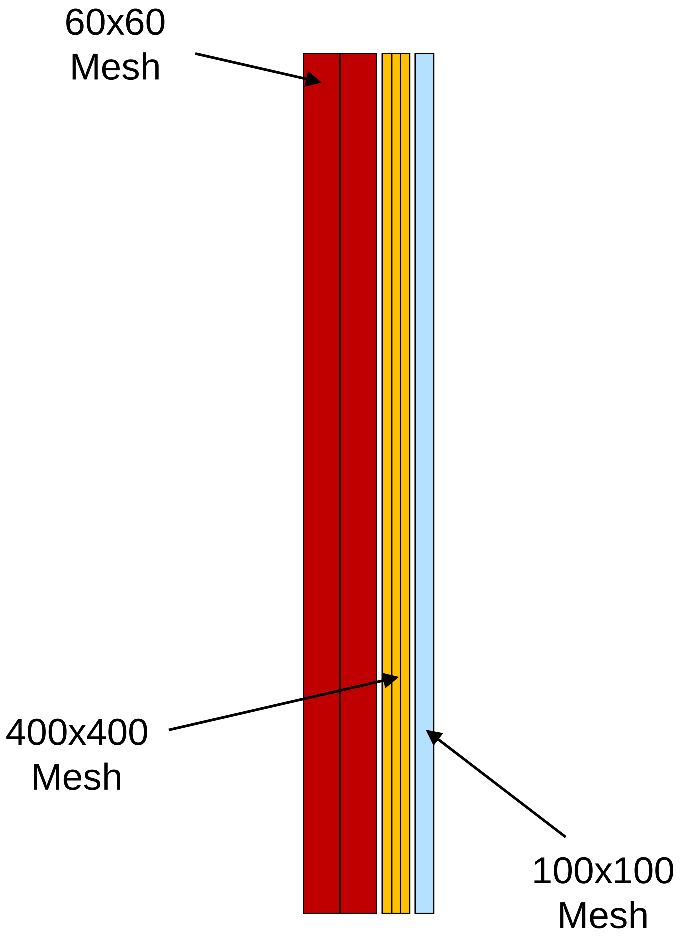
➢ Experiments at TAMU

- Wick Characteristics Experiment
- **Gap Effect Experiment**
- Capillary Rising Modeling
- Heat Pipe Fabrication and Experiment
- Heat Pipe Measurement
- Heat Pipe Visualization

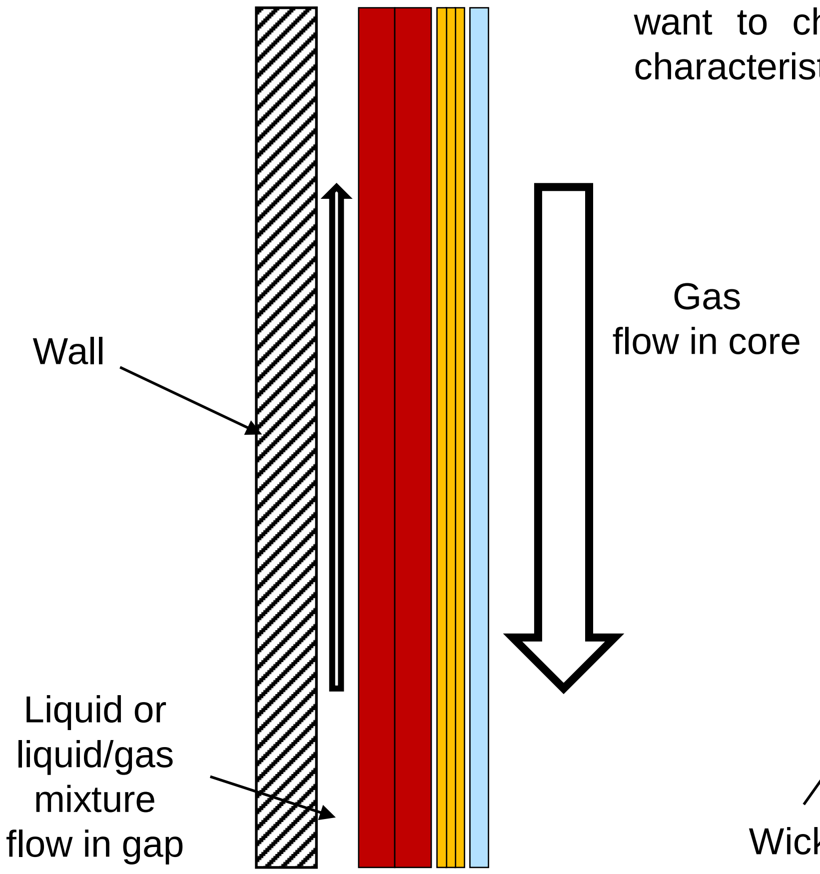
MRP Microreactor Program

Wall Effect Investigation

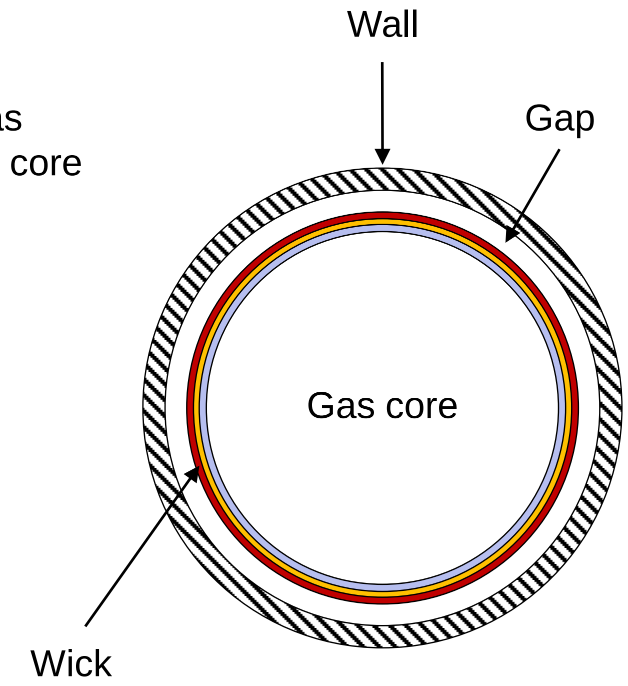
Tested case



Actual case inside heat pipe



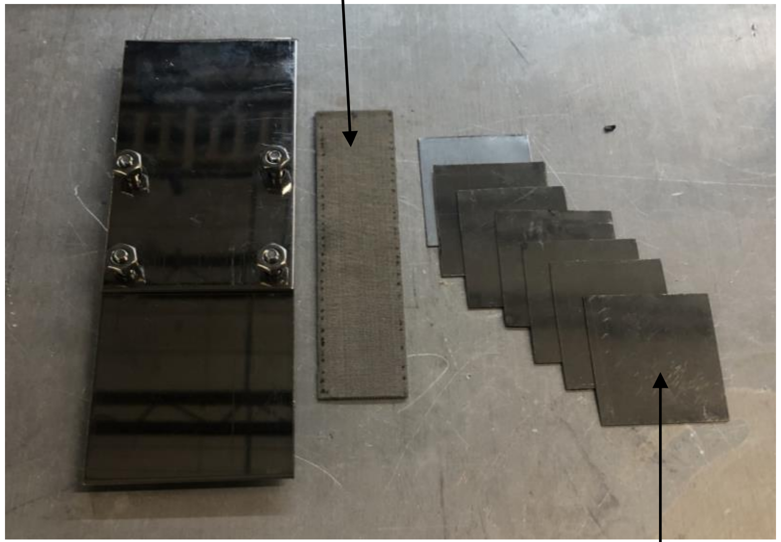
In SAFE-30 report, the gap of the heat pipe manufactured by LANL appeared as 0.7 mm. We want to check the effect of the gap to the wick characteristics.

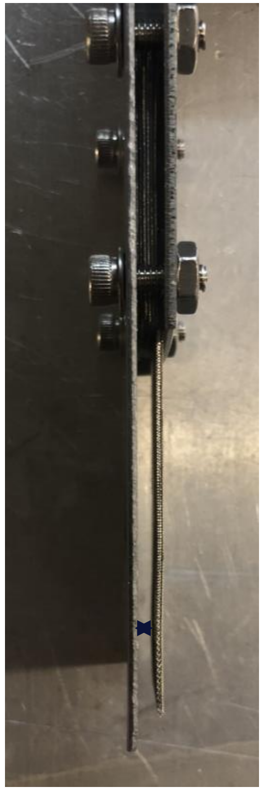


MRP Microreactor Program

Wall Effect Experimental Setup

Wick type #5
6-layered composite screen mesh





Shim structures with varying thickness
to control the size of the gap

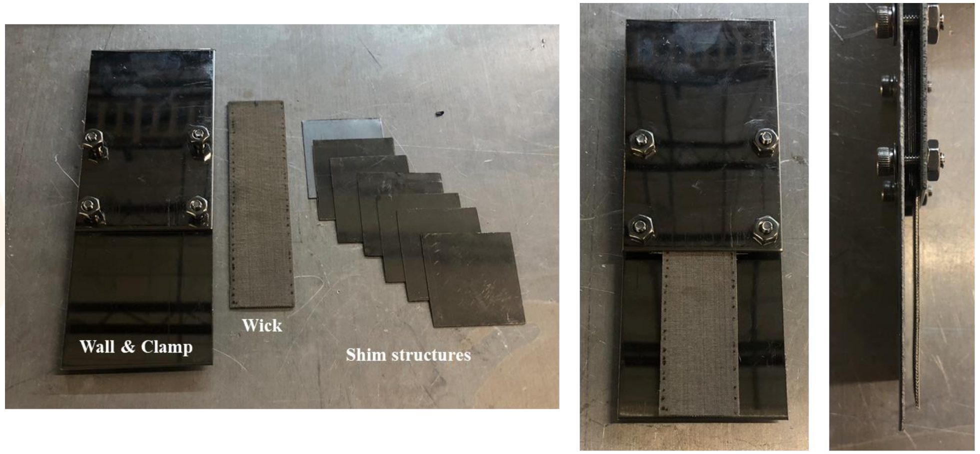
A Simple setup was prepared to measure permeabilities of a wick structure with different sizes of gap (0.0 mm ~ 30.0 mm) between stainless steel wall and the screen mesh.

The same method with previous study was utilized.

MRP Microreactor Program

Gap Effect Experiment

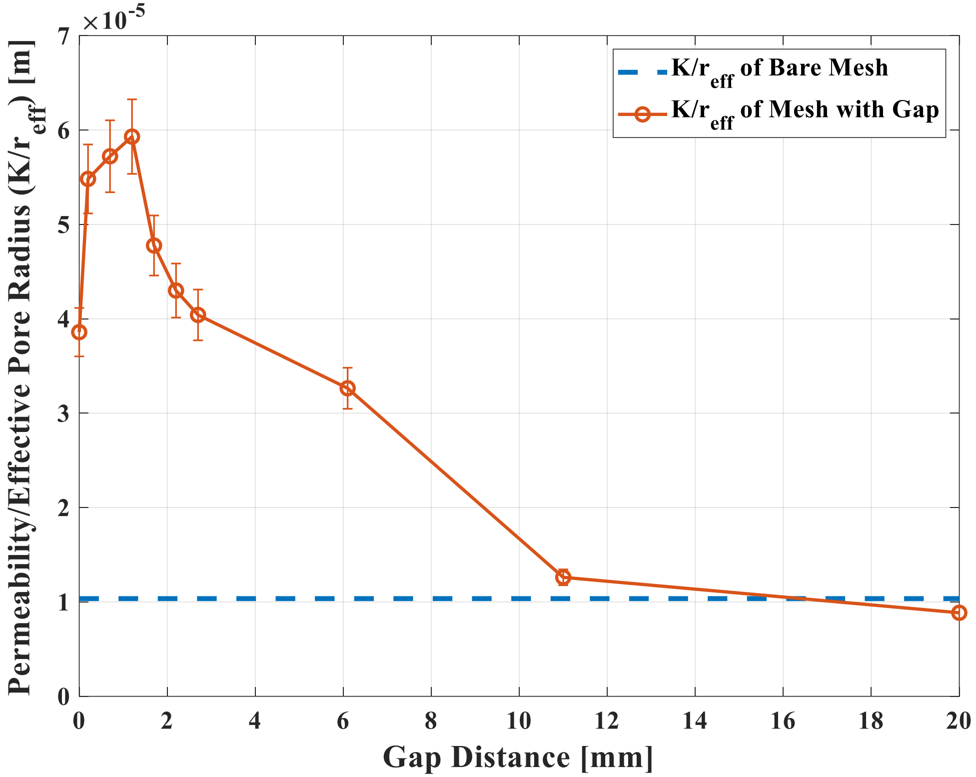
Wick assembly with adjustable gap between the wall

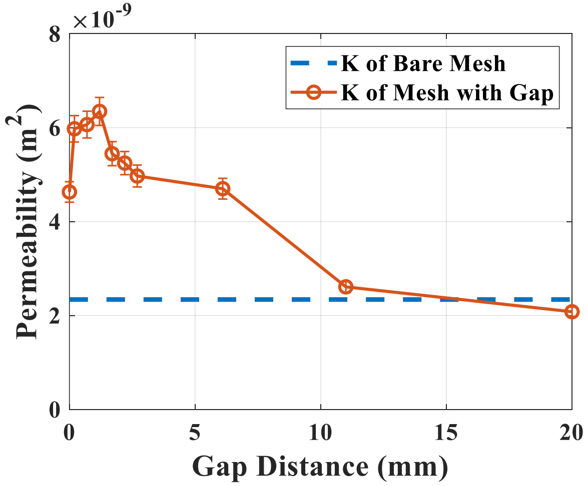


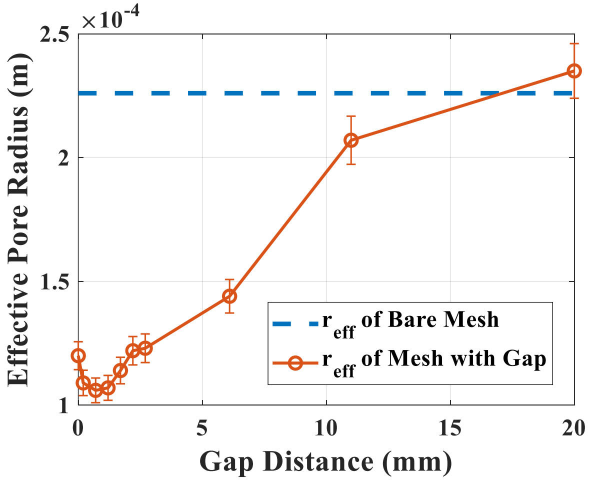
Front view

Side view

Wick samples were prepared to measure permeabilities and effective pore radius with different sizes of gap (0.0 mm ~ 20.0 mm) between stainless steel wall and the screen mesh.







Optimal distance of the gap for the annular type heat pipe was found

The result of the measurement is plotted vs. the gap distance.
An interesting trend can be found from the result. The $^{K}/_{R_{eff}}$ increases as the gap increase, a peak at 0.7 to 1.2 mm is observed. As the gap continues to increase, the permeability falls the bare mesh case.

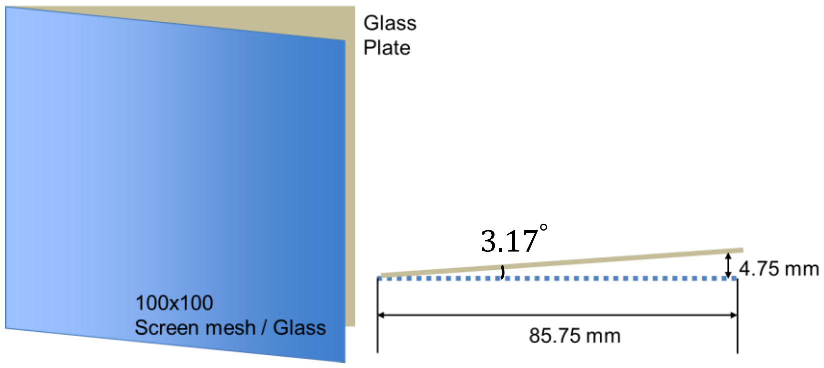
MRP Microreactor Program

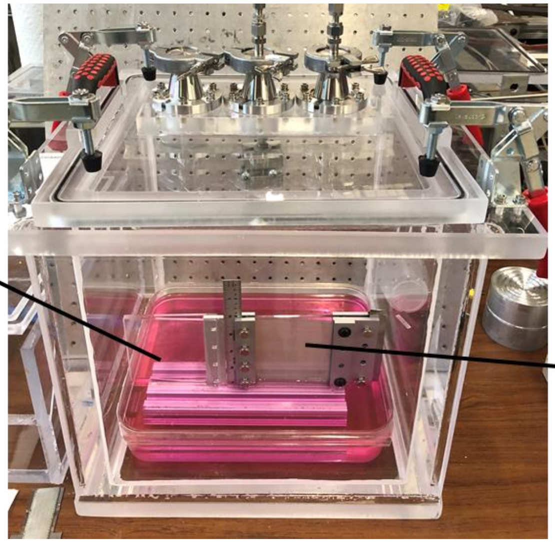
➢ Experiments at TAMU

- Wick Characteristics Experiment
- Gap Effect Experiment
- **Capillary Rising Modeling**
- Heat Pipe Fabrication and Experiment
- Heat Pipe Measurement
- Heat Pipe Visualization

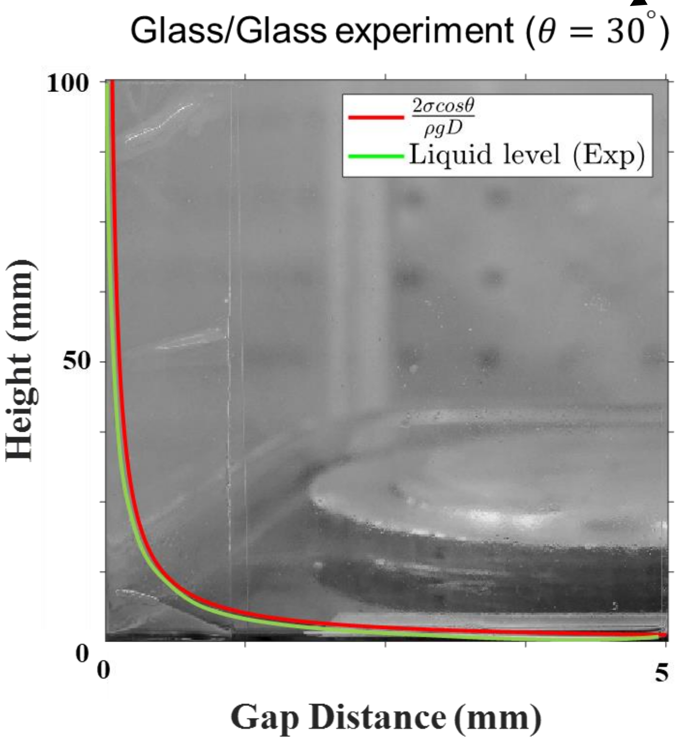
Capillary Rising Modeling

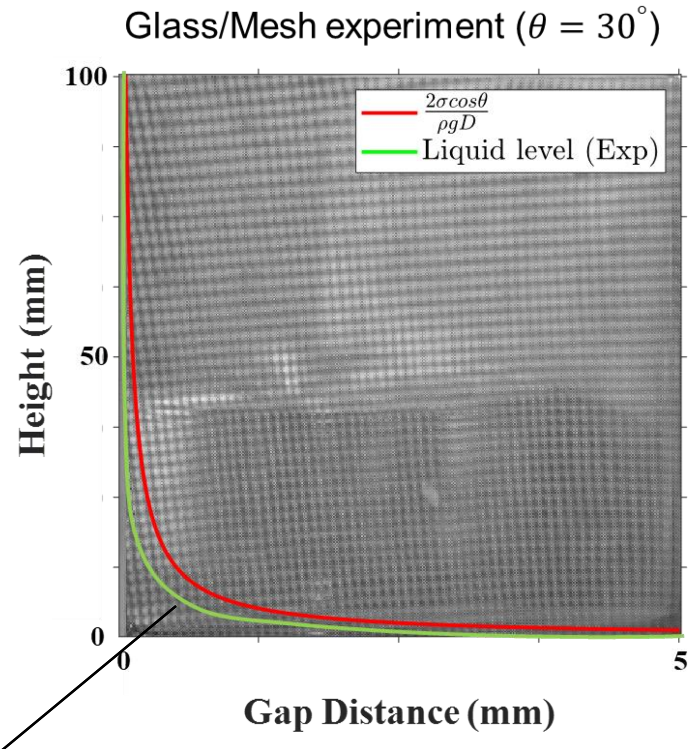
Experimental setup of angled mesh-plate experiment





Contact angle of ethanol on a glass surface



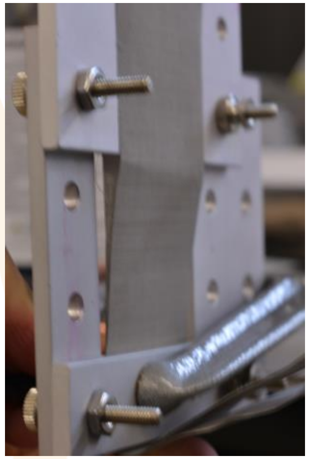


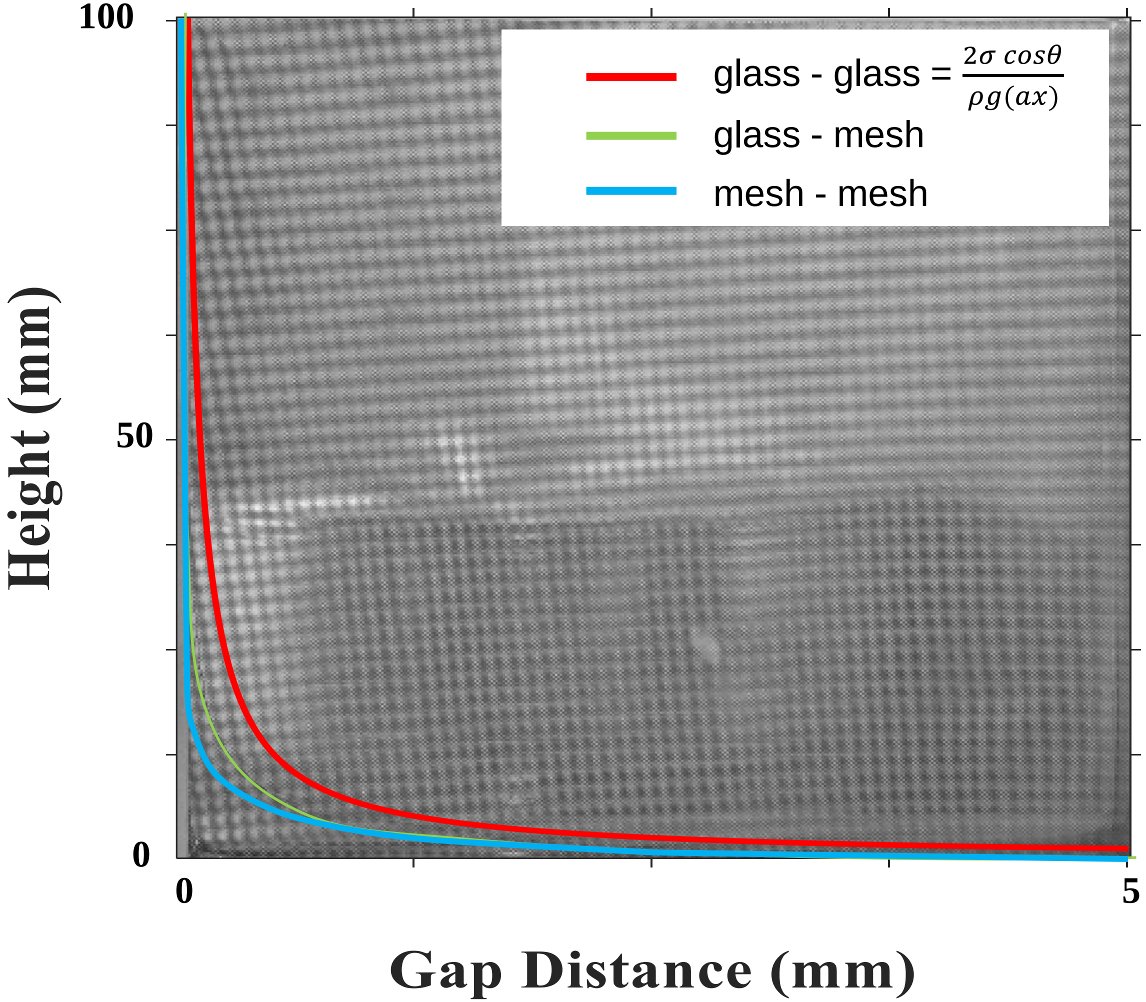
The rising height of the liquid in a gap between solid/mesh differs from solid/solid case. There is no study on the capillary pressure acting on solid surface/mesh surface. The result might be useful to model the gap effect.

MRP Microreactor Program

Capillary Rising Modeling

Mesh-mesh Exp.





Mesh-mesh graph is smaller than glass-mesh.
According to the formula, height is $h = \frac{\sigma\,(\cos\theta_0+\cos\theta_1)}{\rho g(w)}$
(where θ_0 = glass contact angle and θ_1 = mesh contact angle),
Therefore,

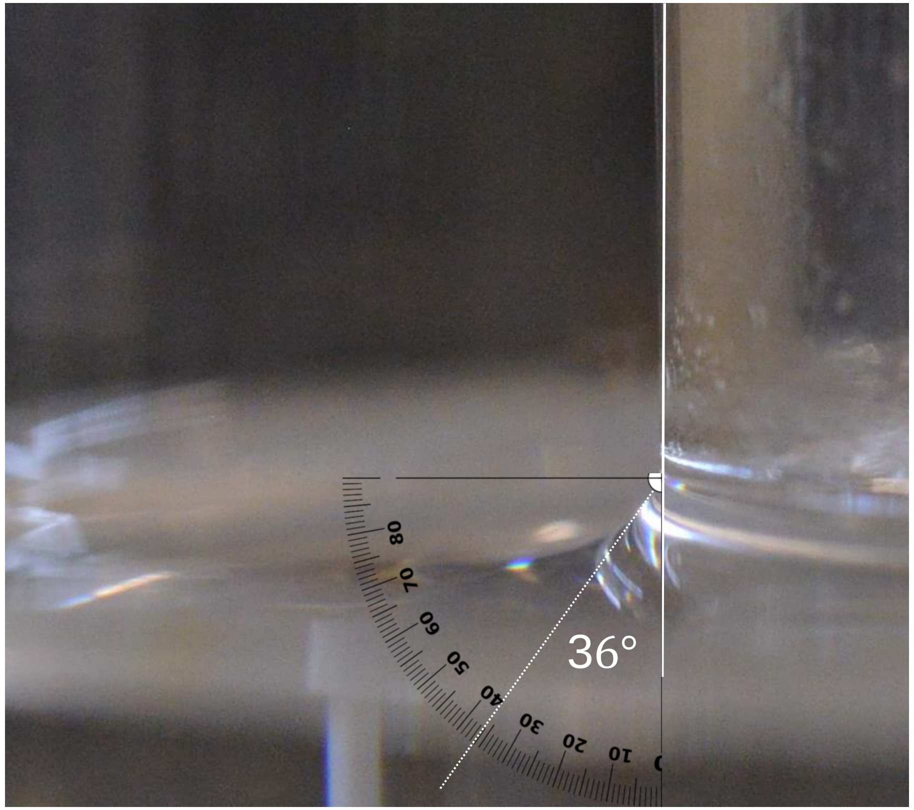
$\cos\theta_1 < \cos\theta_0\,,\ \theta_0 < \theta_1$

Glass contact angle with ethanol θ_0 is about 30°($\pi/6$), then Mesh contact angle with ethanol would be larger than 30°

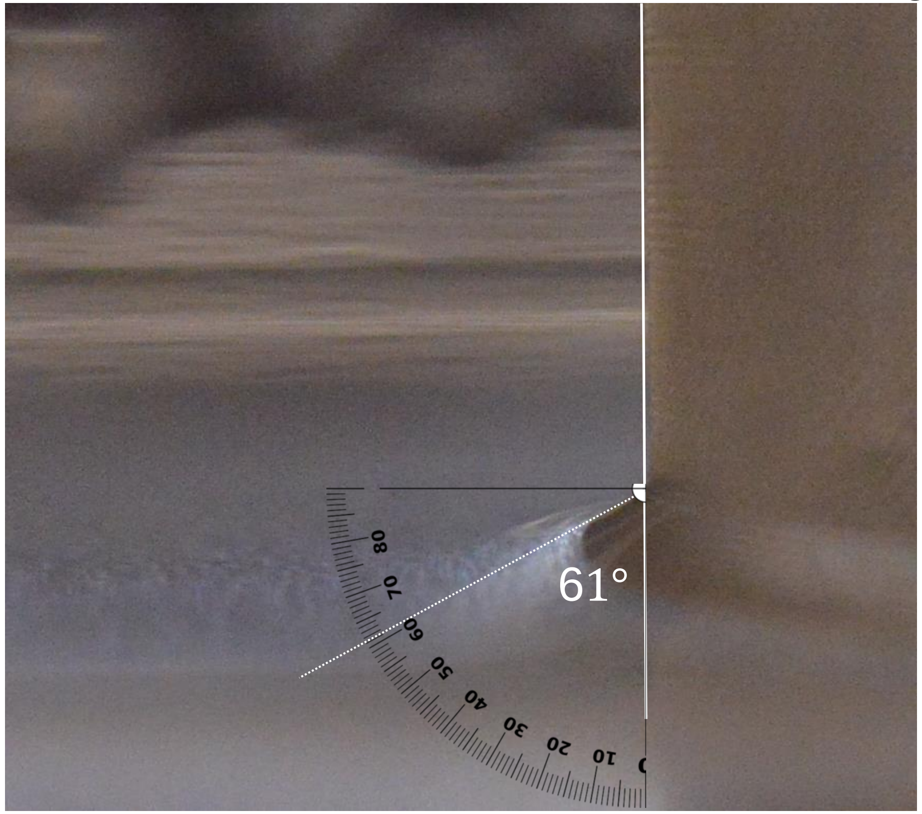
MRP Microreactor Program

Contact Angle Measurement

Glass – Ethanol contact angle

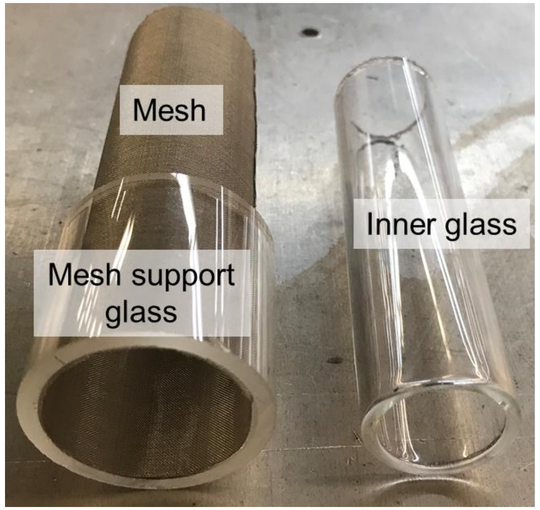


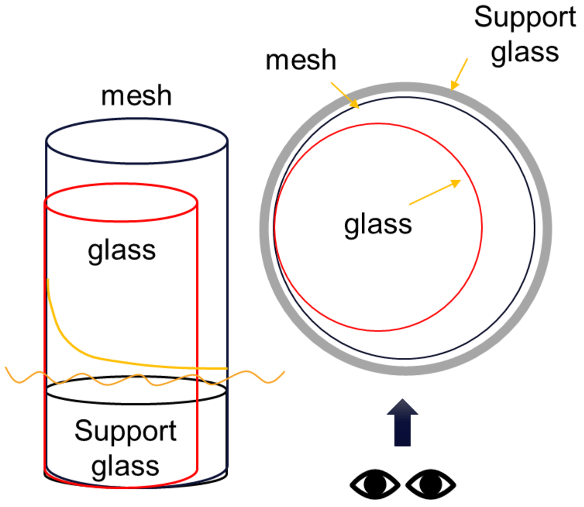
Stainless steel mesh – Ethanol contact angle

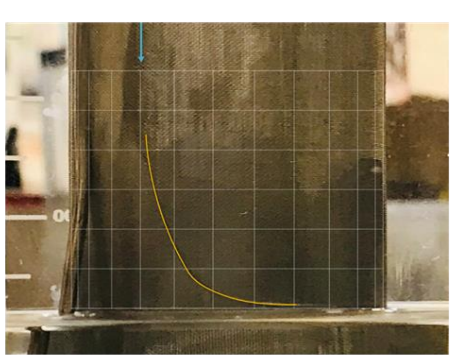


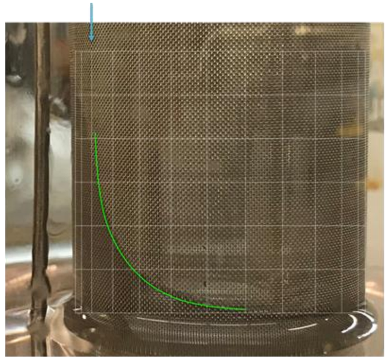
MRP Microreactor Program

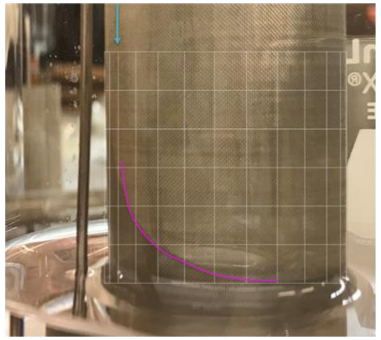
Curvature Effect

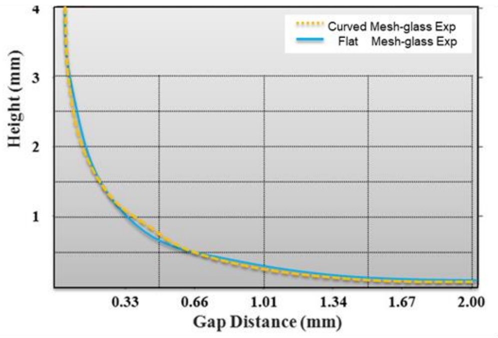


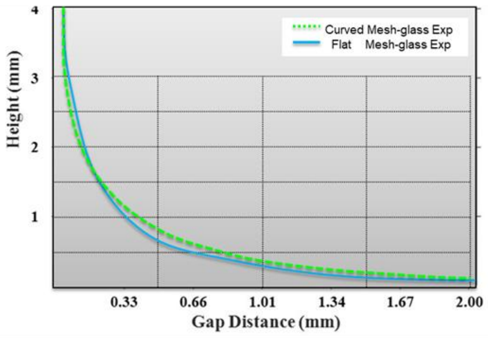


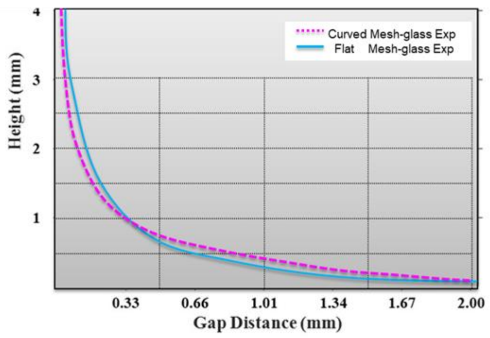












MRP Microreactor Program

➢ Experiments at TAMU

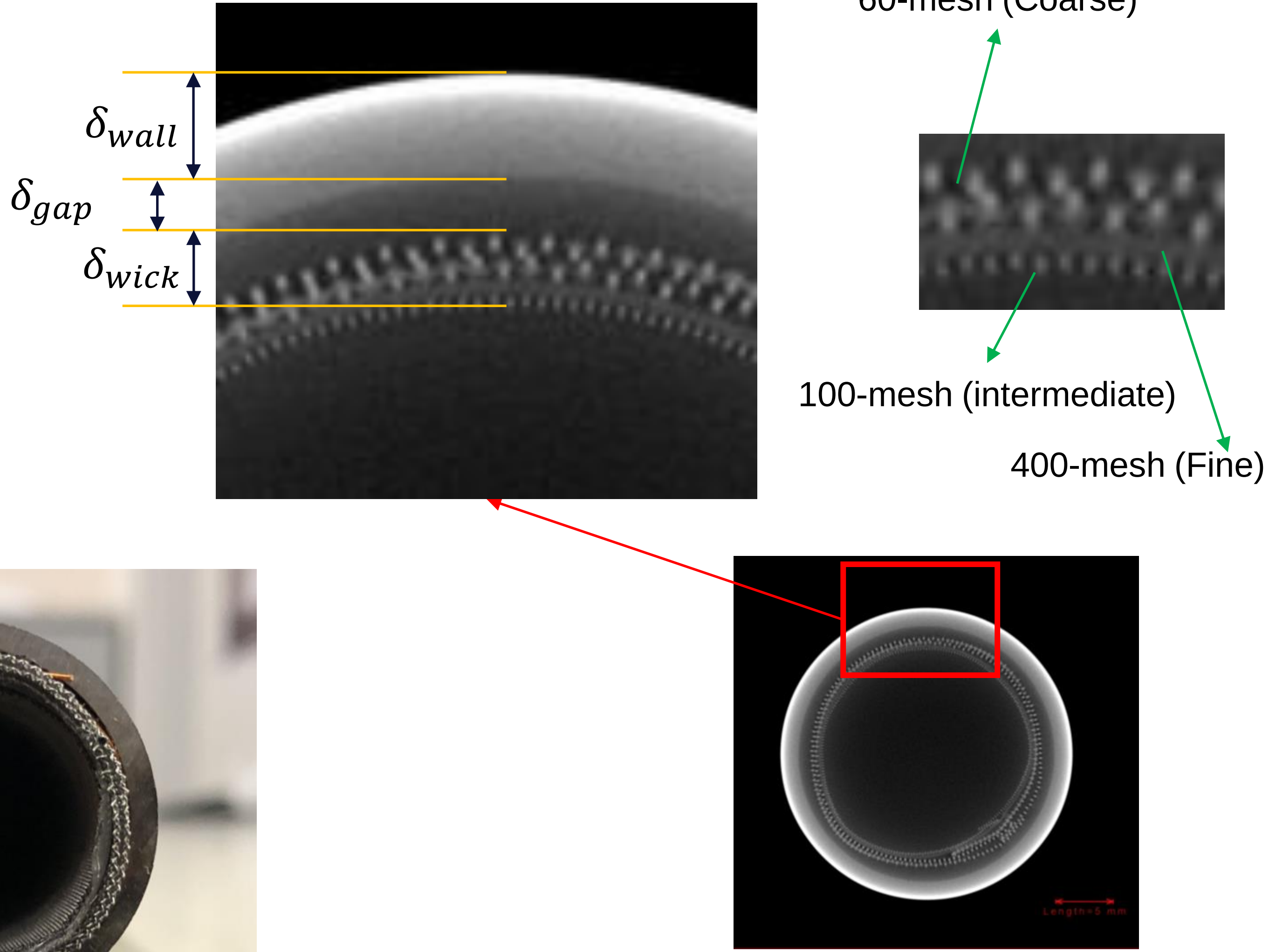
- Wick Characteristics Experiment
- Gap Effect Experiment
- Capillary Rising Modeling
- **Heat Pipe Fabrication and Experiment**
- Heat Pipe Measurement
- Heat Pipe Visualization

MRP Microreactor Program

Stainless Steel Heat Pipe

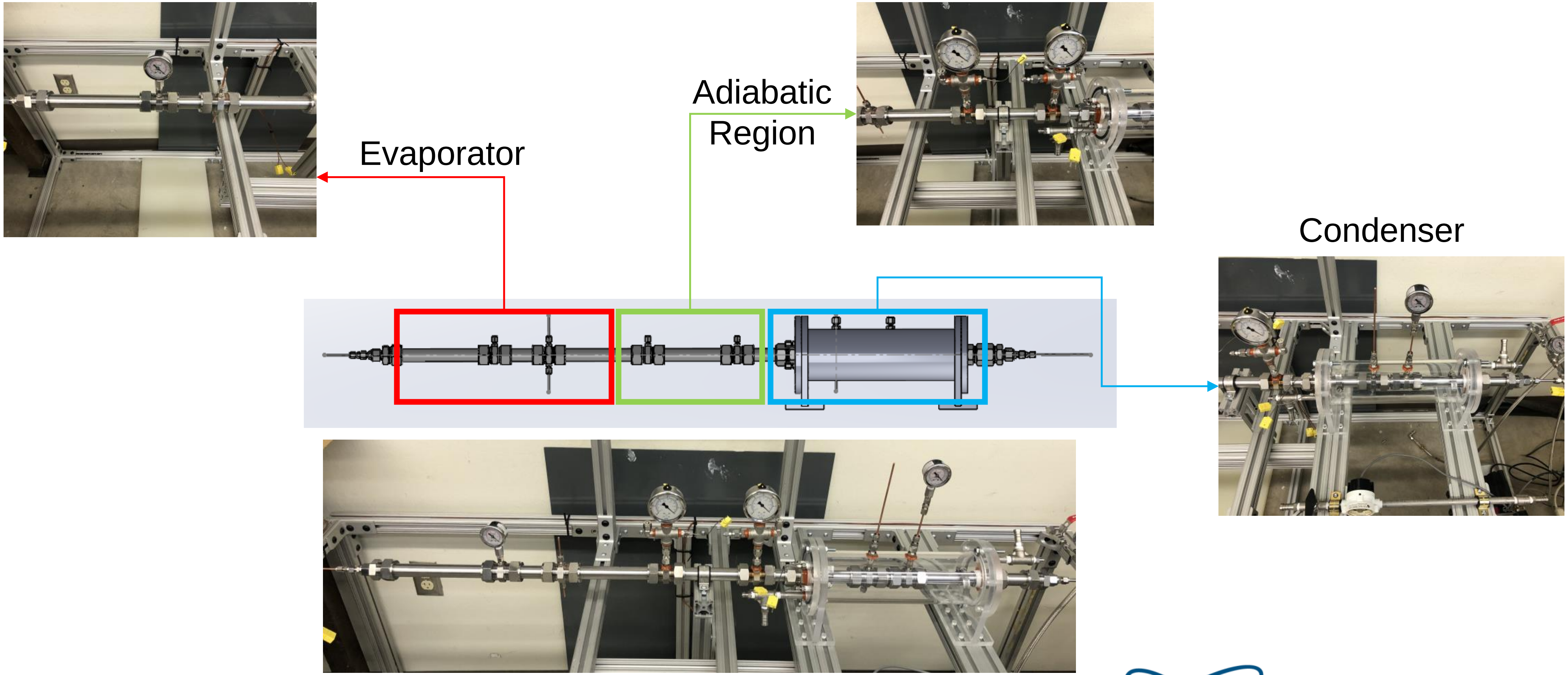
Multi-layered composite screen wick mesh was fabricated.

Micro CT scanning of the heat pipe cross-section

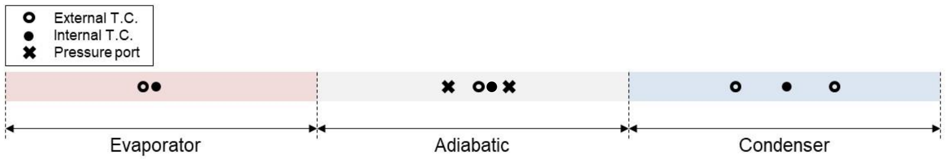


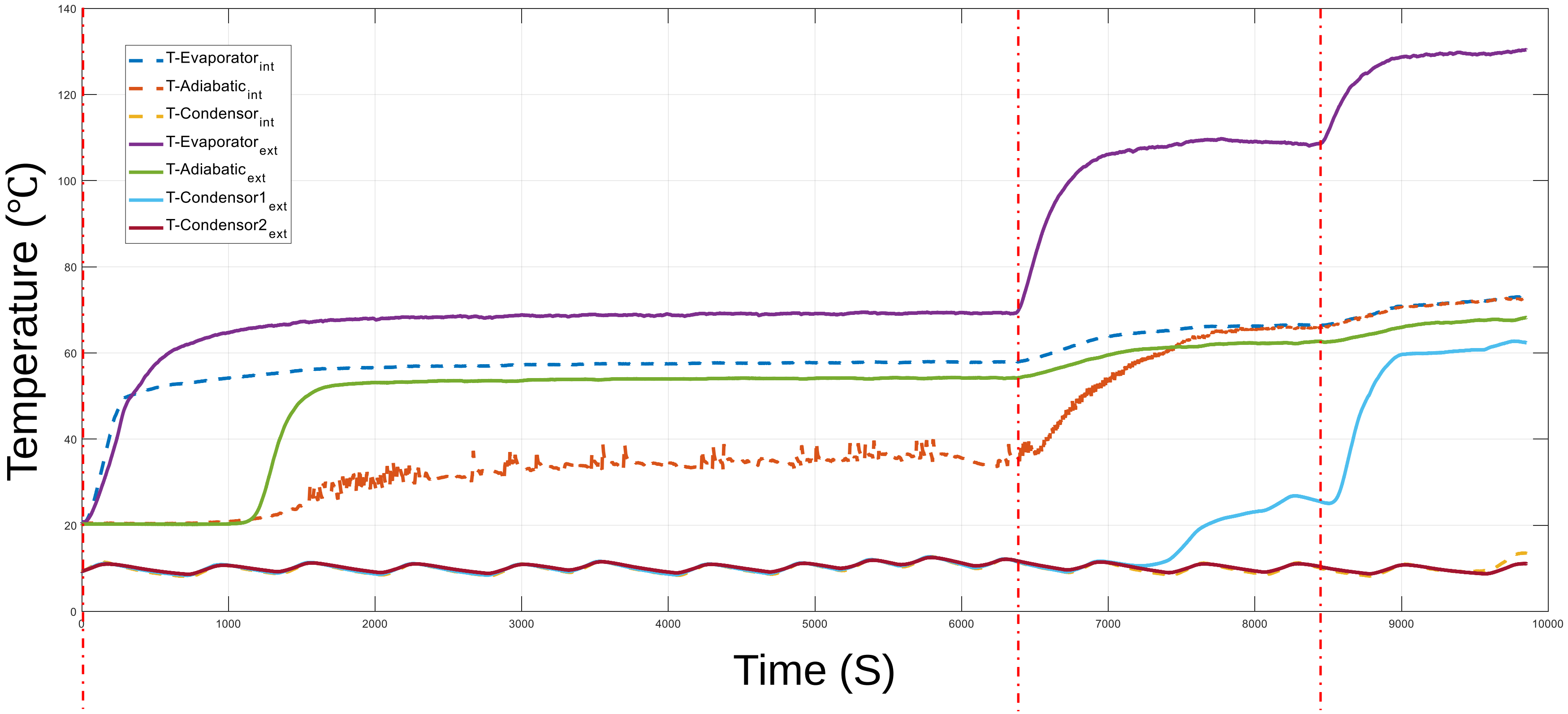
MRP Microreactor Program

Heat Pipe Experimental Facility



Shakedown Test



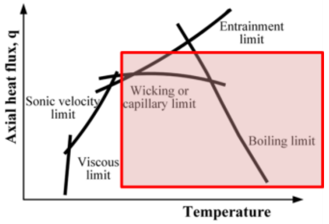


Initiate, P = 140.4 W

P = 234.0 W

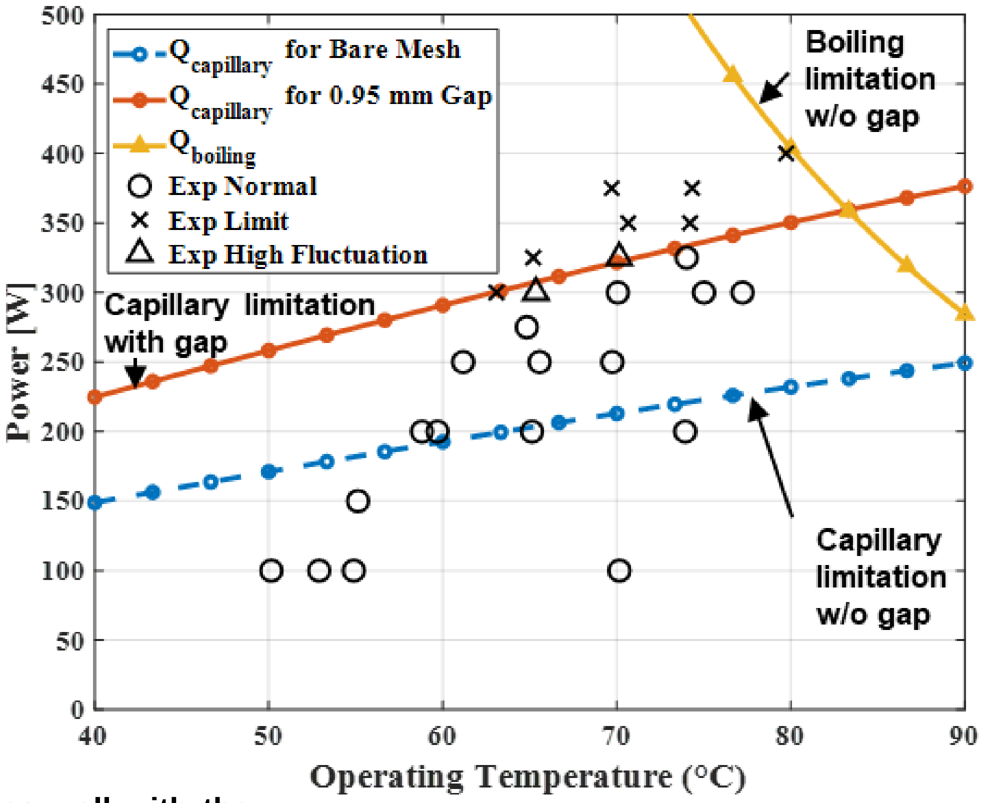
P = 280.8 W

Heat Pipe Fabrication and Experiment



$$Q_{capillary.gap} = G \cdot Q_{capillary} = G \frac{2\sigma}{r_{eff}} \frac{KA_{wick} h_{lv} \rho_l}{\mu_l L_{eff}}$$

Gap Distance [mm]	G [-]
0	1.00
0.2	1.42
0.7	1.48
1.2	1.54
1.7	1.24
2.2	1.11
2.7	1.05



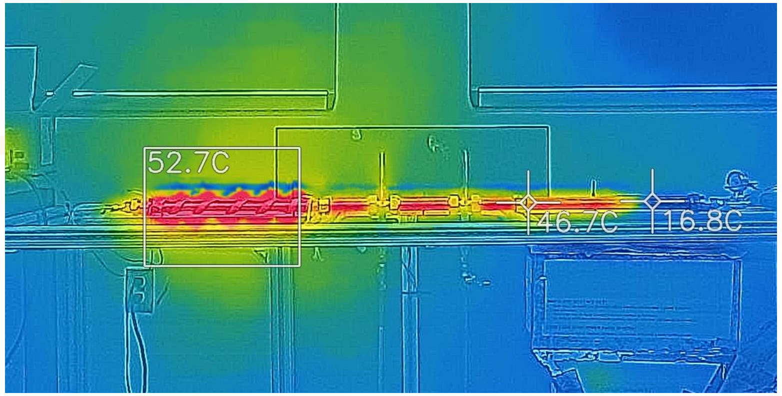
The operating limitation of the heat pipe matches well with the prediction from the result of the wick characterization and gap effect experiment.

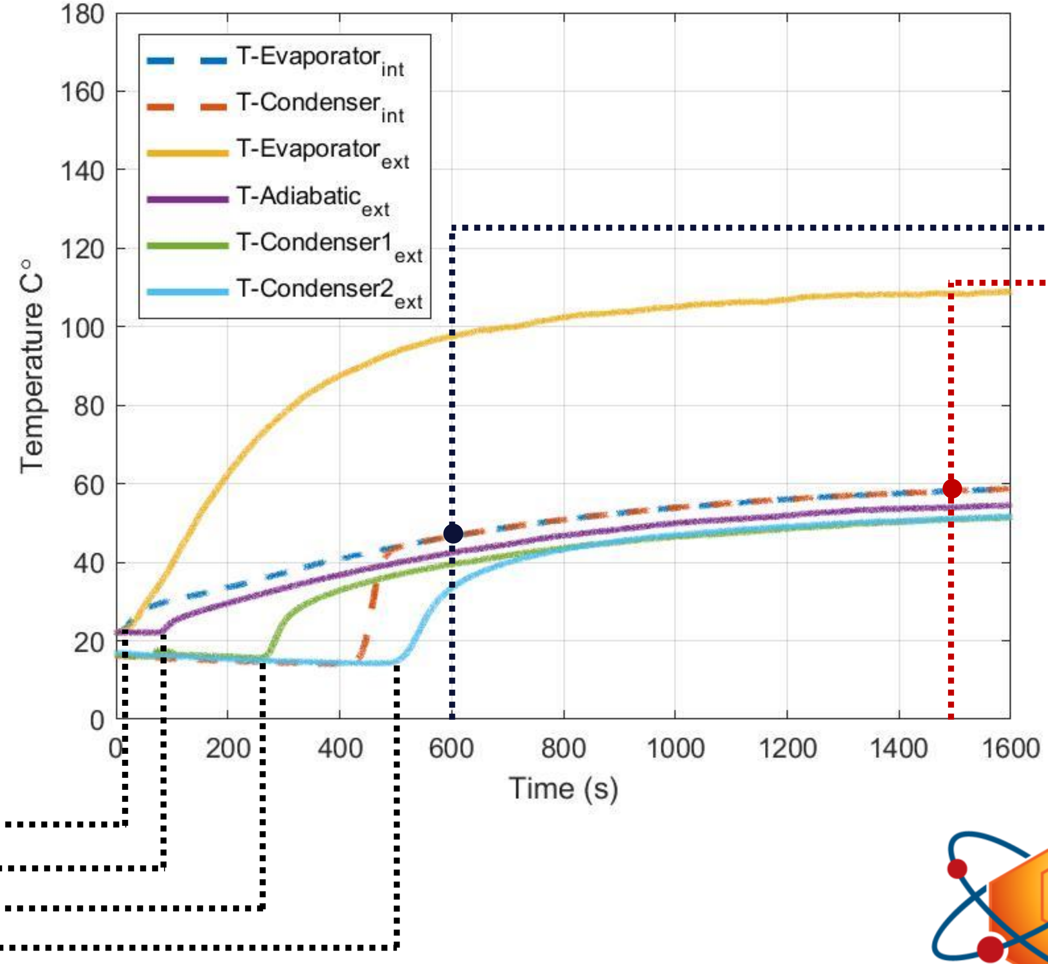
➢ Experiments at TAMU

- Wick Characteristics Experiment
- Gap Effect Experiment
- Capillary Rising Modeling
- Heat Pipe Fabrication and Experiment
- **Heat Pipe Measurement**
- Heat Pipe Visualization

MRP Microreactor Program

Temperature Measurement System

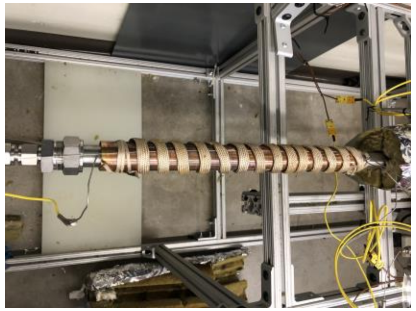


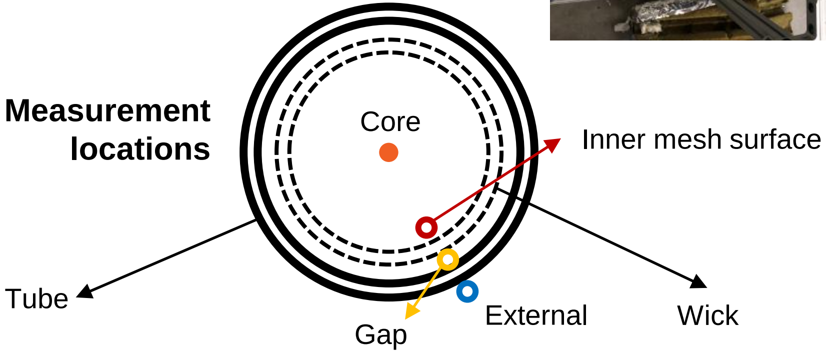


Temperature (C)	Pressure (MPa)	Density (kg/m3)
0.028556	0.00061248	999.79
46.974	0.010612	989.33
60.711	0.020612	982.79
69.560	0.030612	977.98
76.223	0.040612	974.08
81.620	0.050612	970.75
86.187	0.060612	967.82
90.161	0.070612	965.19
93.691	0.080612	962.79
96.873	0.090612	960.57
99.777	0.10061	958.51

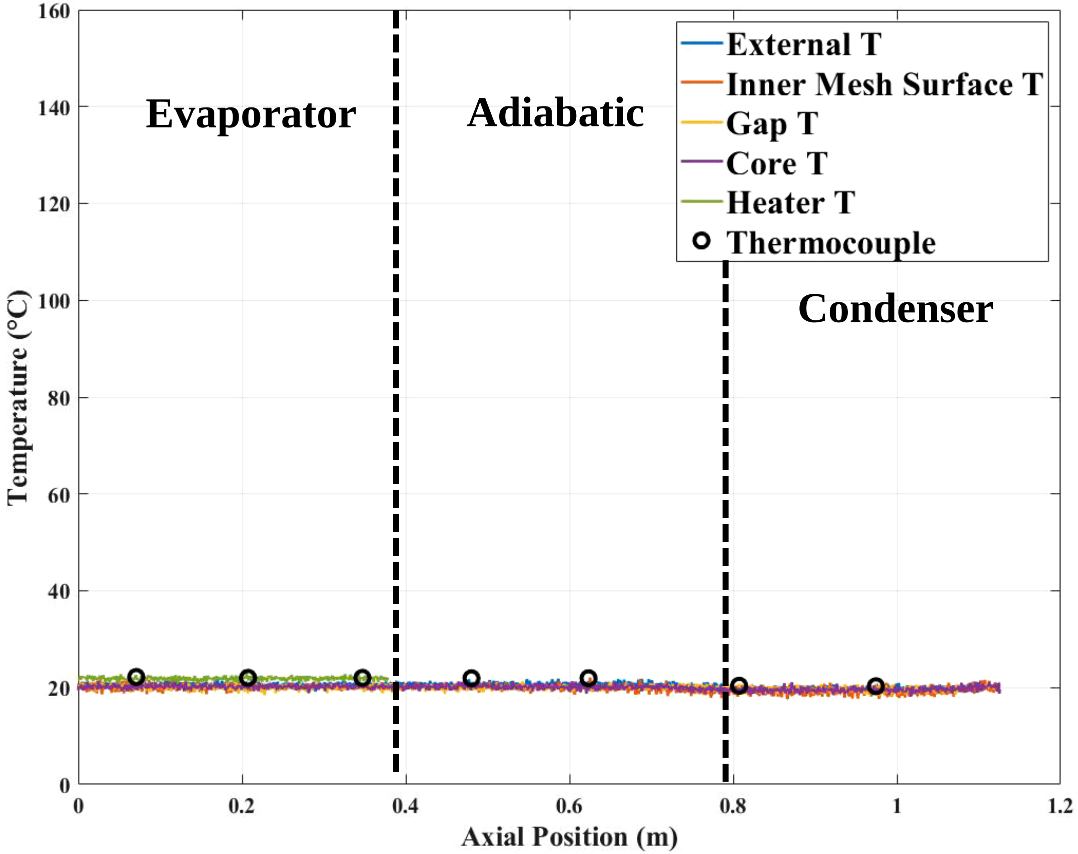
Distributed Temperature Sensing (DTS)

Heater was wrapped on the copper tube for uniform heat transfer to the heat pipe.

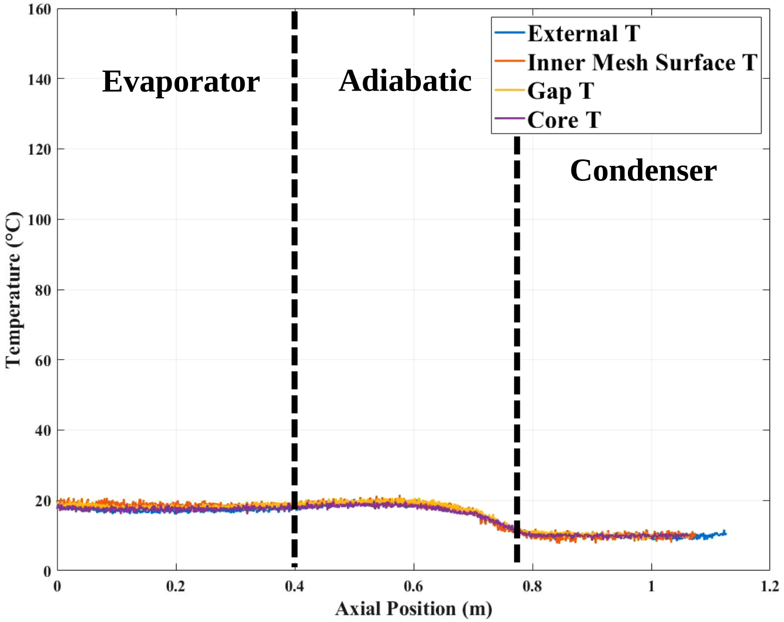




Slow start (30W, ~60 mins) of the heat pipe



Rapid start (75W, ~60 mins) of the heat pipe



➢ Experiments at TAMU

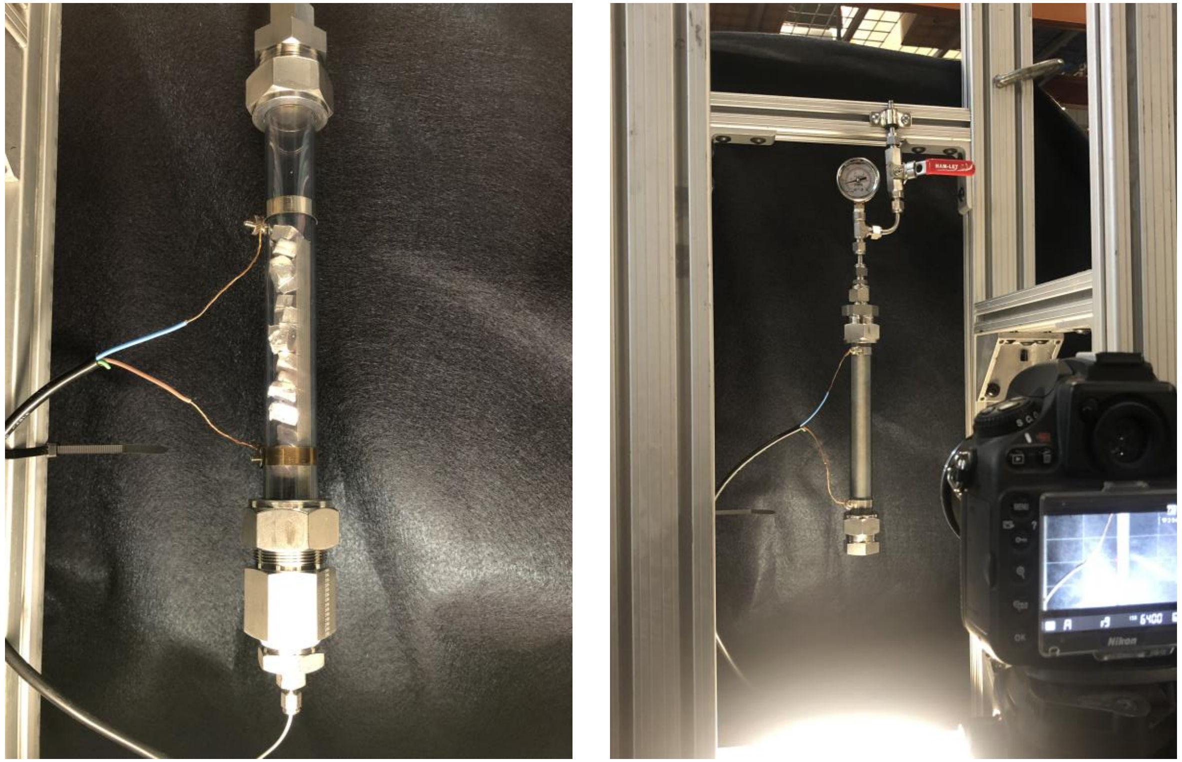
- Wick Characteristics Experiment
- Gap Effect Experiment
- Capillary Rising Modeling
- Heat Pipe Fabrication and Experiment
- Heat Pipe Measurement
- **Heat Pipe Visualization**

MRP Microreactor Program

Flow Visualization of Liquid Metal

TAMU has a capability of transparent heating up to 700 ℃ and ~101 kW/m^2 of heat flux.

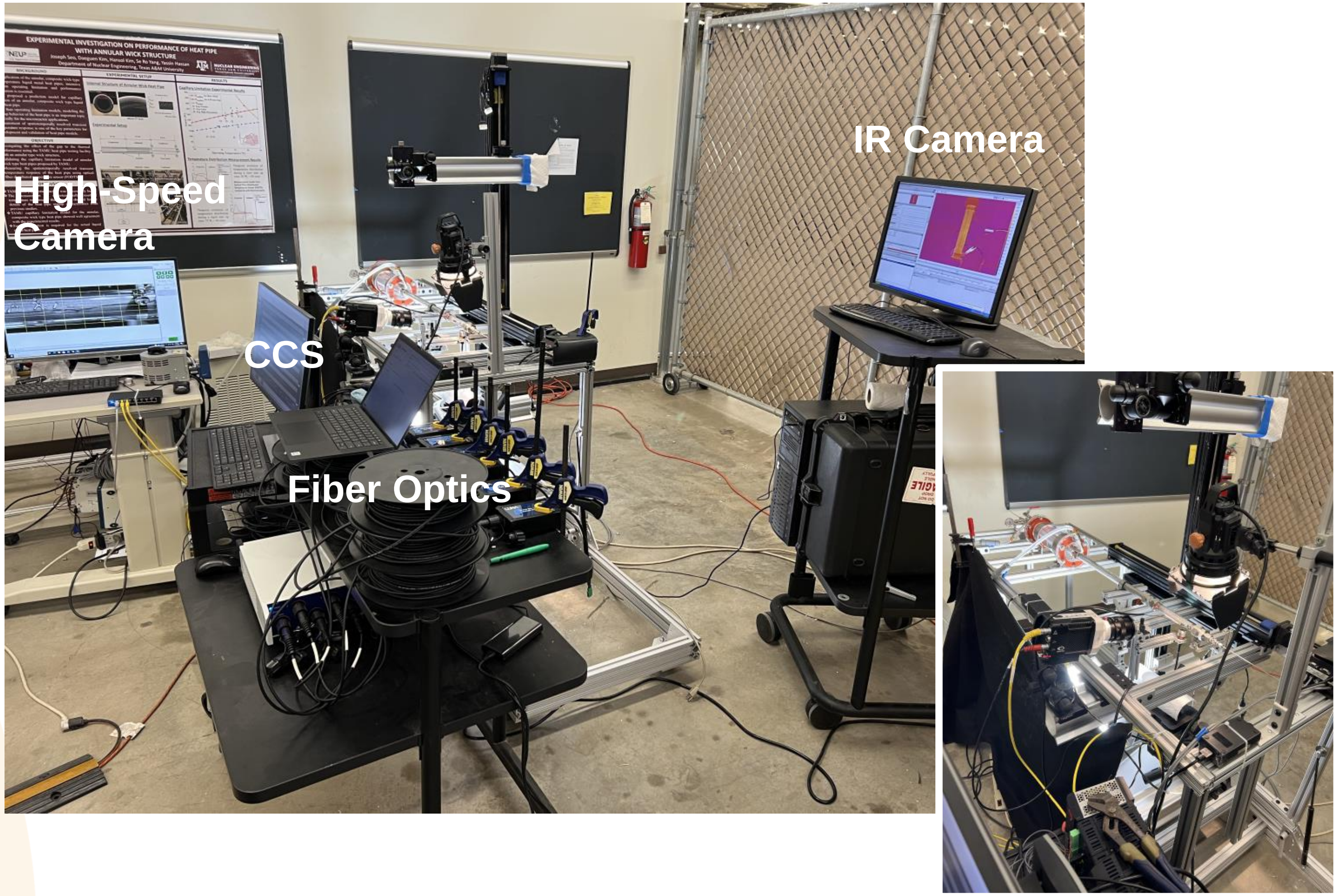
Water boiling experiment using transparent heater.



TAMU is being conducted to perform melting/boiling experiment using the transparent heater.
The experiment will allow to obtain information about flow behavior of liquid metal at different operating status of the heat pipe.

MRP Microreactor Program

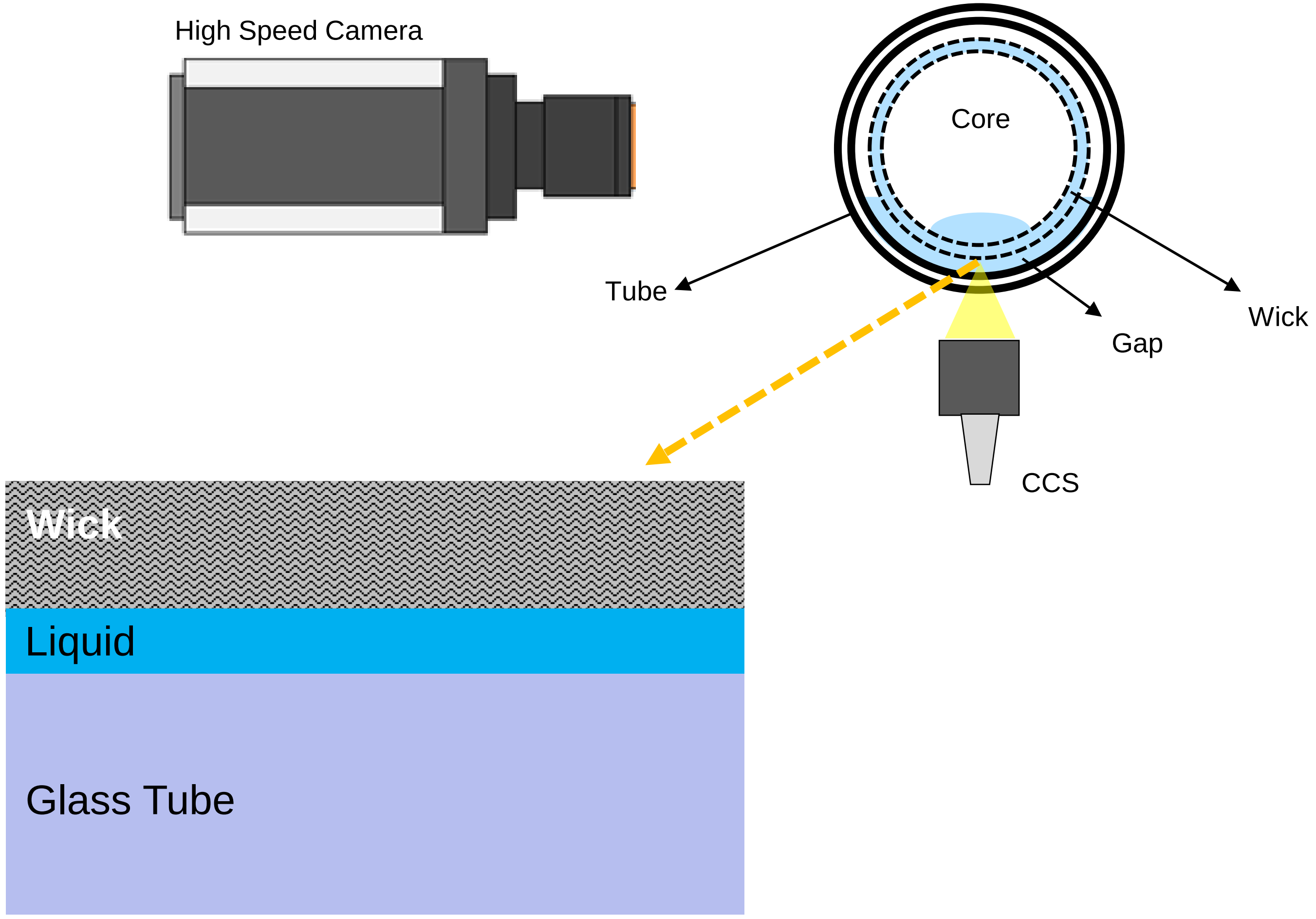
Heat Pipe Visualization Experimental Setup

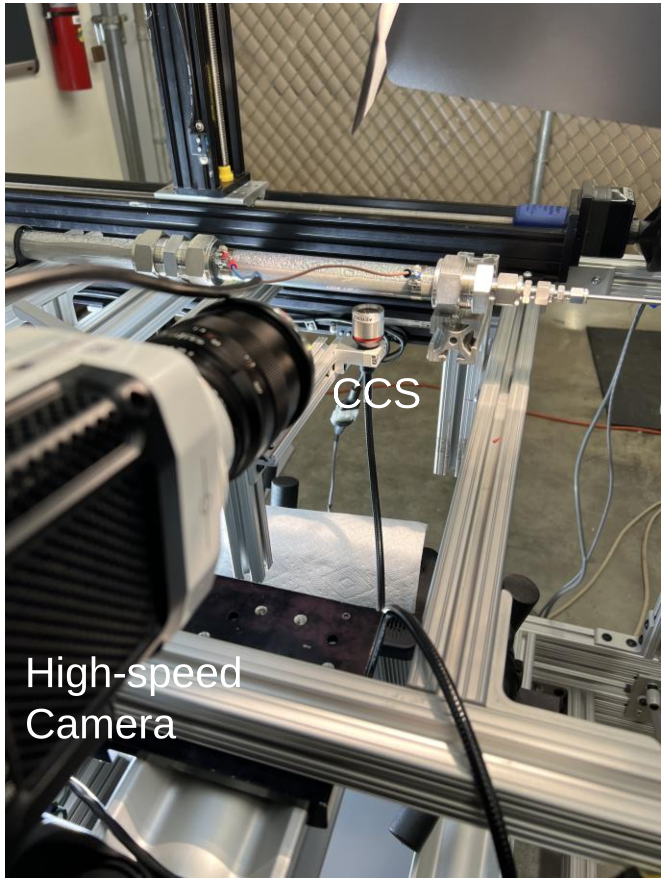


- Visualization using high speed camera and IR camera is conducted.
- Temperature measurement using fiber optical sensor and IR camera is implemented.
- Confocal Chromatic Sensor (CCS) is applied to measure the liquid film behavior.
- 4 gas cylinders were added to adjust inclination angle.

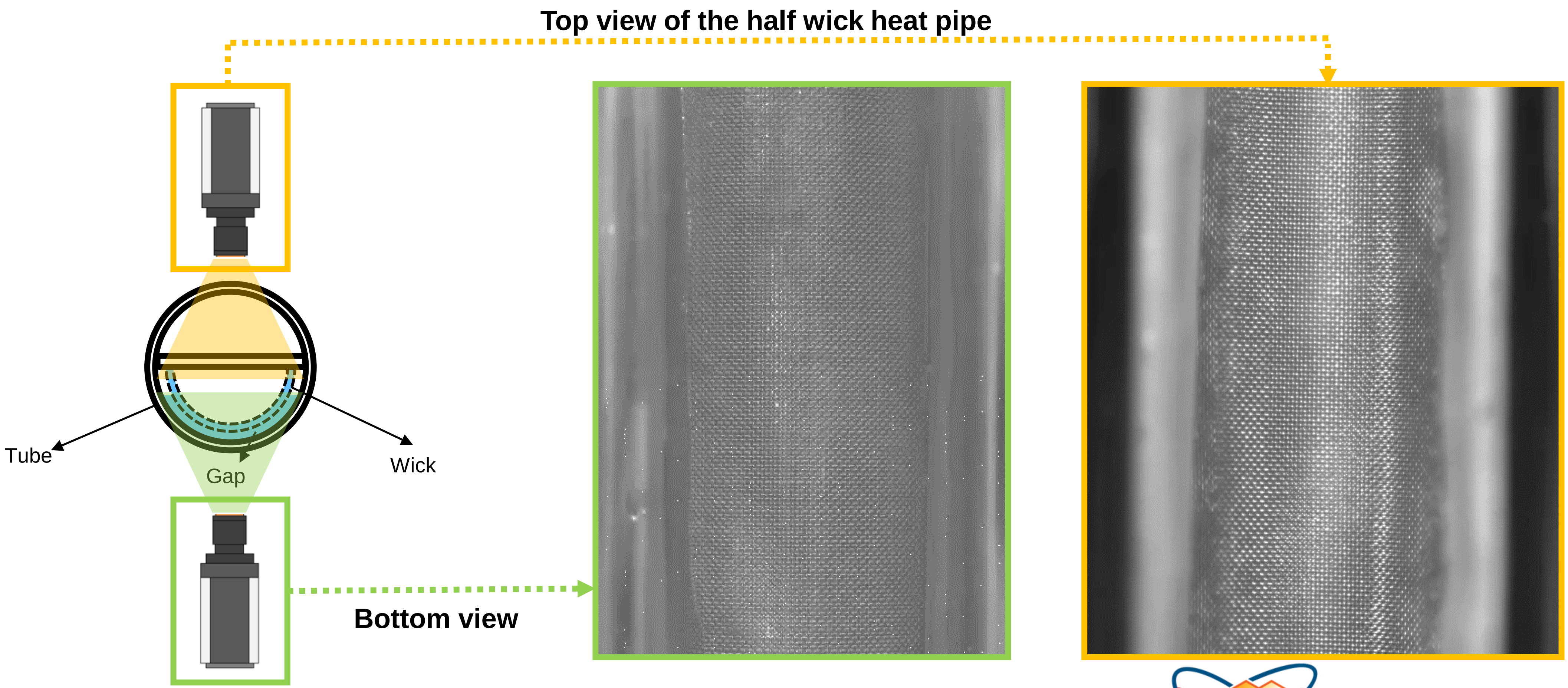
MRP Microreactor Program

CCS Measurement & High-Speed Images



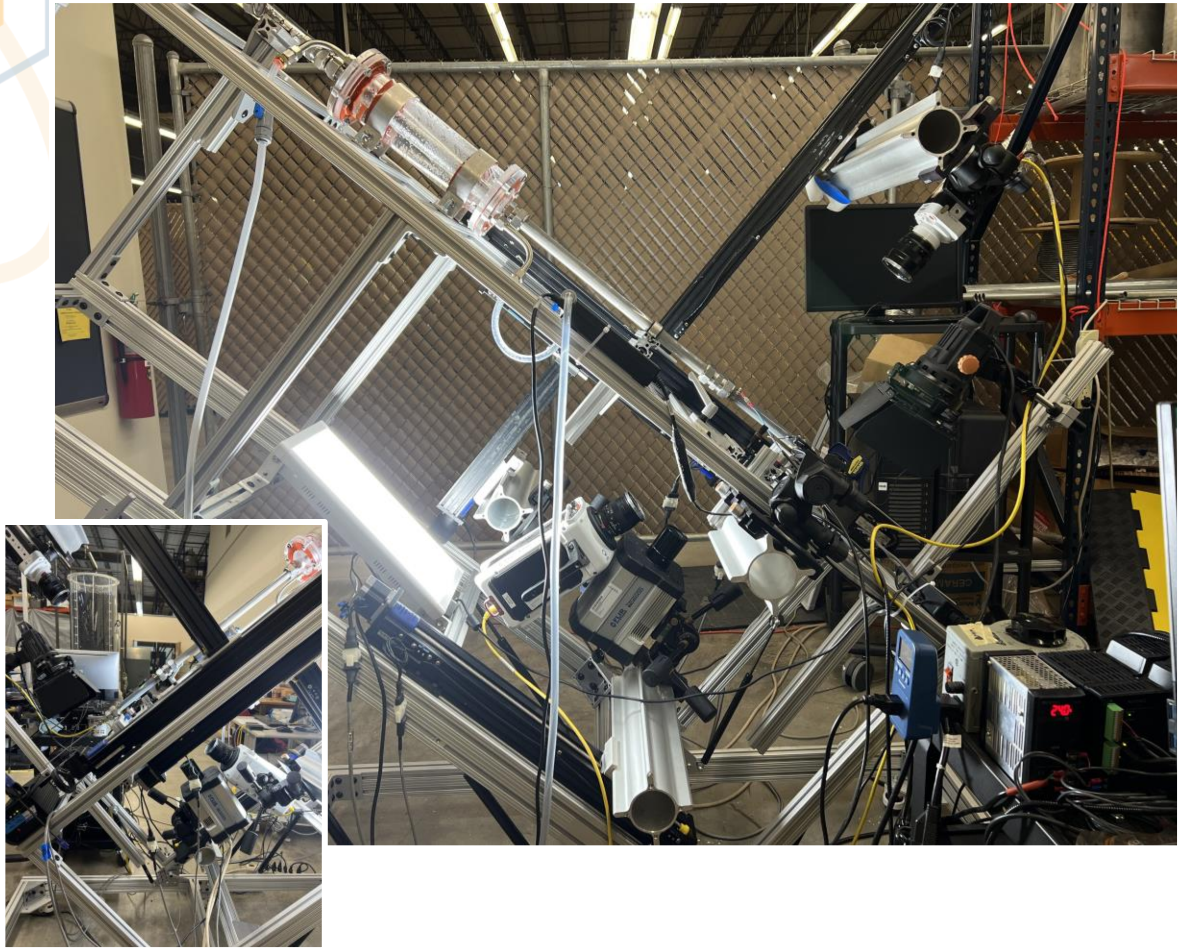


Boiling Pattern Inside Heat Pipe – Half Wick Exp

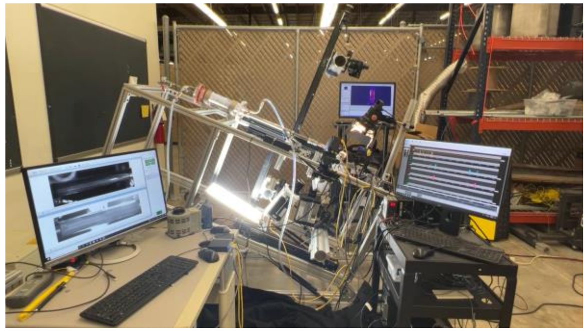


MRP Microreactor Program

Heat Pipe Visualization with Inclination Angle



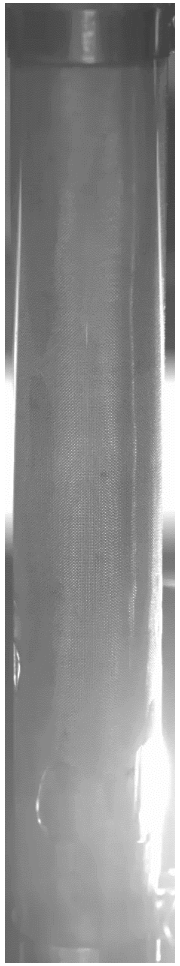
- Visualization of the heat pipe with different inclination angle.
- Temperature measurement using fiber optical sensor and IR camera is implemented.
- Two high-speed camera was set (bottom side and top side)



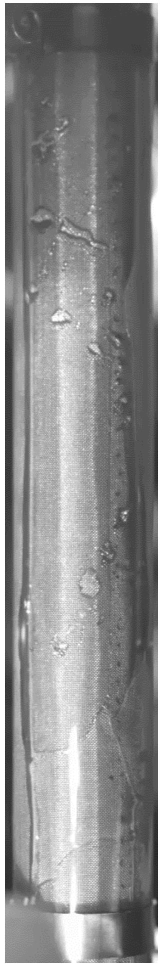
MRP Microreactor Program

Heat Pipe Visualization Results

Horizontal
0-degree
100W

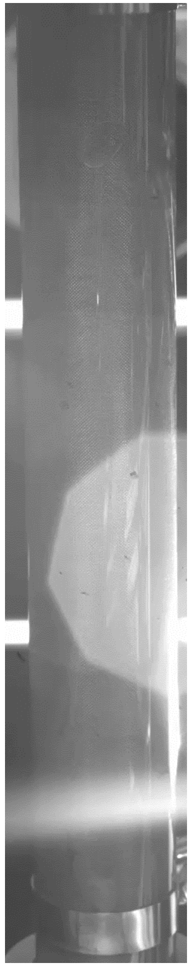


Bottom

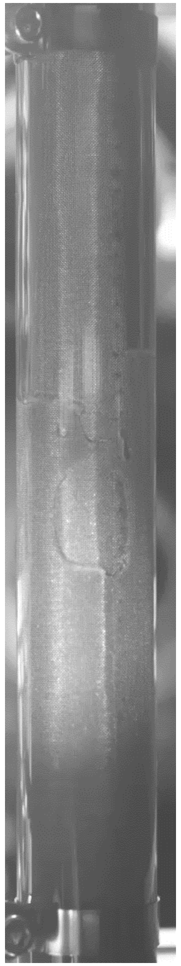


Top

45-degree
200W

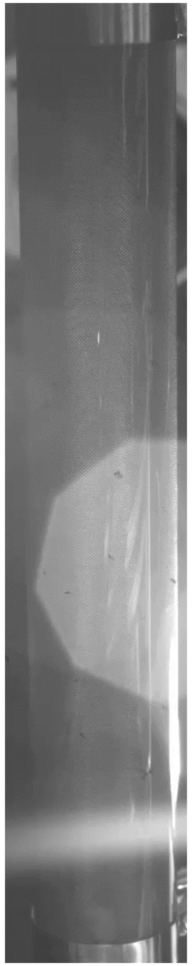


Bottom

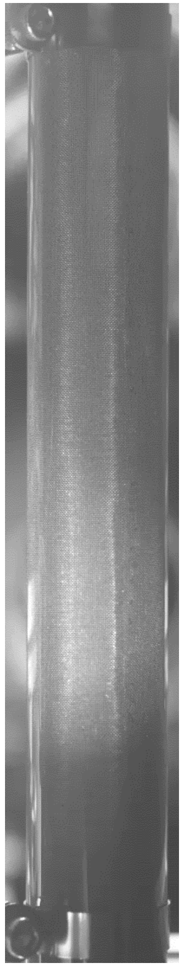


Top

Vertical
90-degree
200W



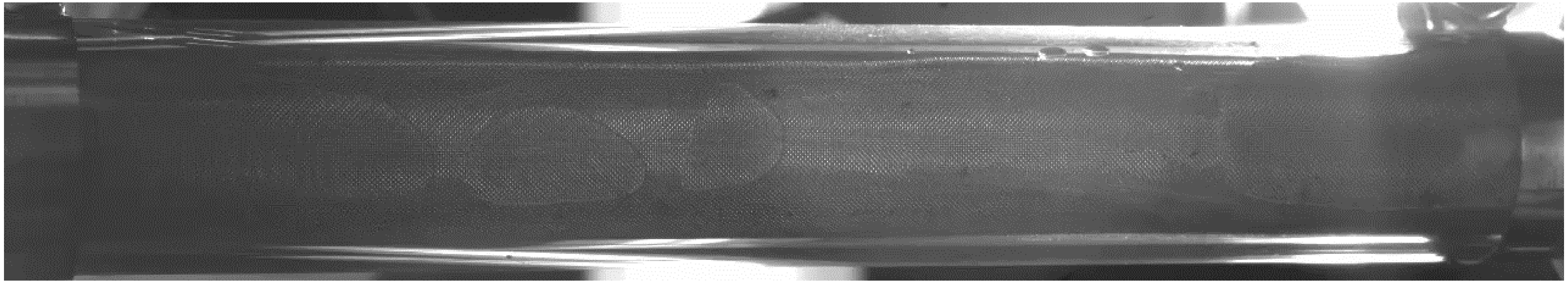
Bottom



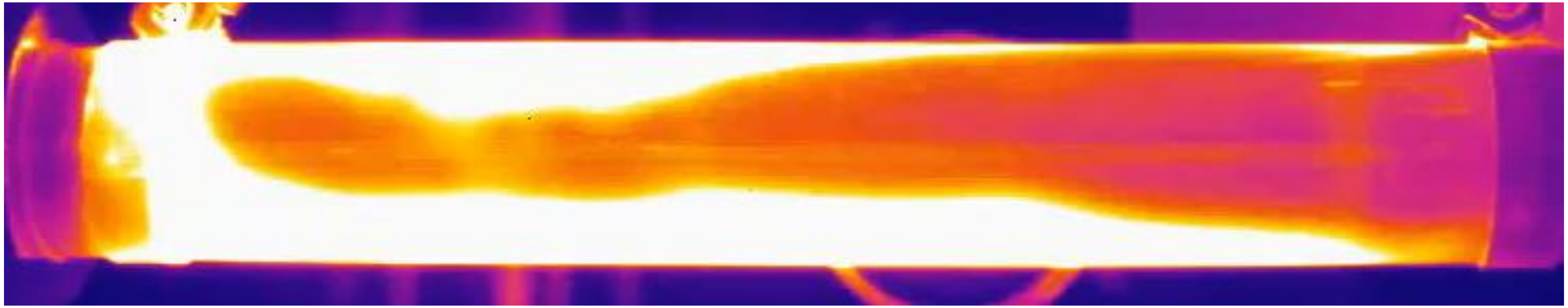
Top

MRP Microreactor Program

Heat Pipe Visualization Results - Limitation



High-speed camera

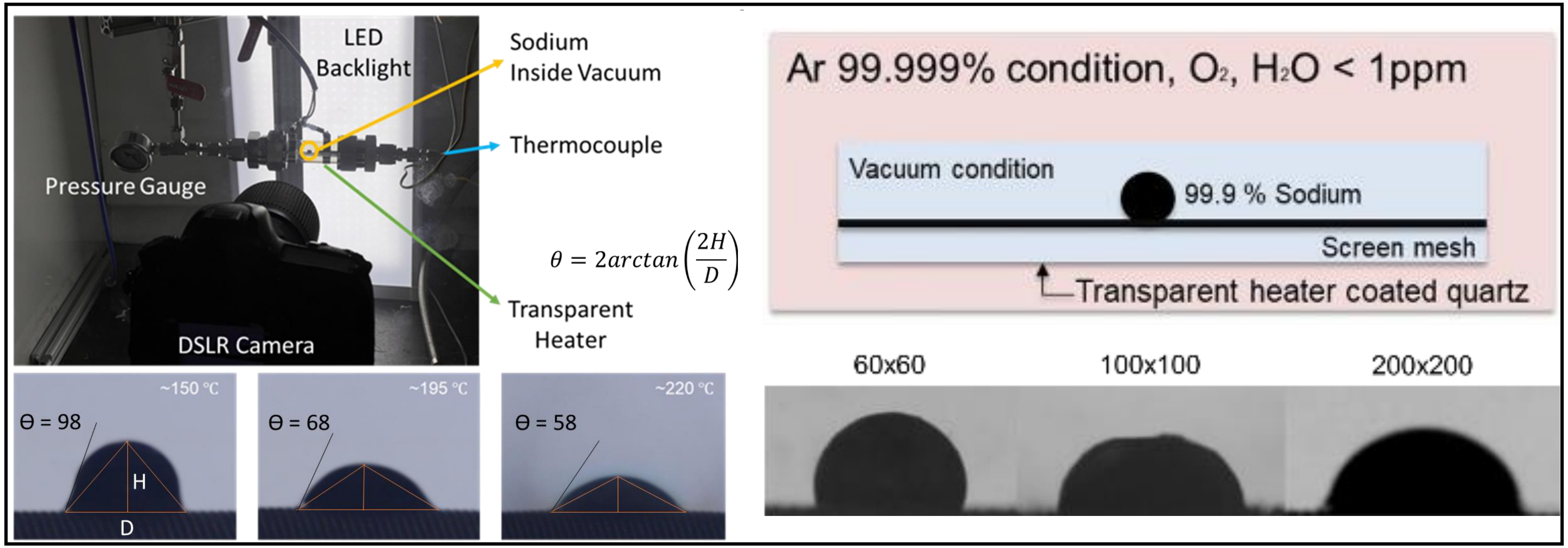


IR camera

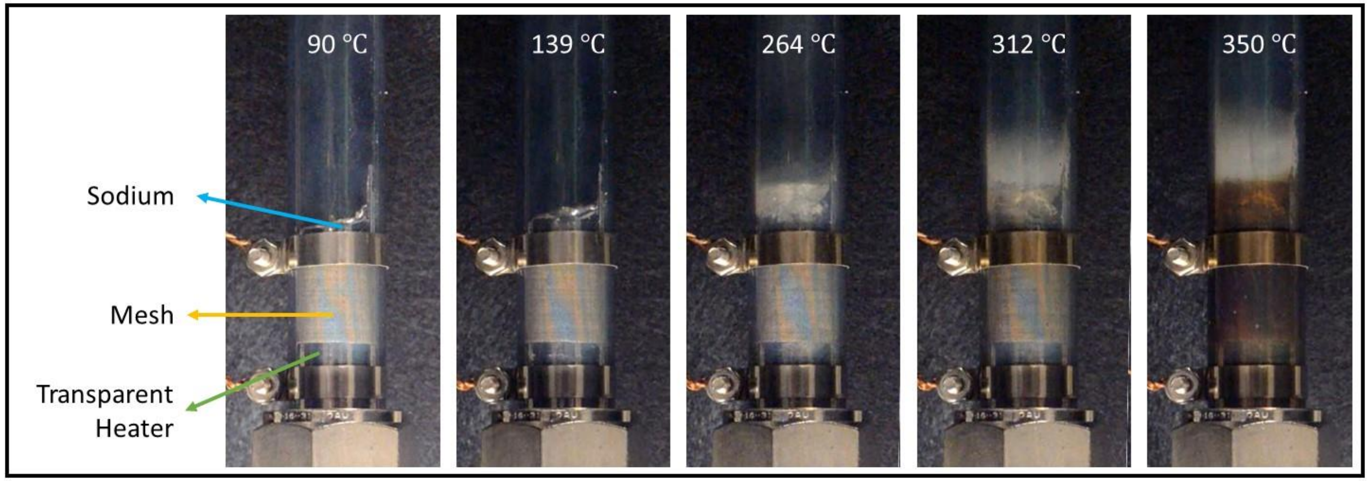
200W, 0-degree inclination, rapid start-up

Microreactor Program

In Progress – Moving on to the Liquid Metal



The contact angle measurement of the liquid sodium with different material (stainless steel plate and meshes) is being conducted in TAMU.



Visualization of melting/boiling of the sodium in a vacuum condition is under the progress.

MRP Microreactor Program

MRP Microreactor Program