Cryogenic Pulsating Heat Pipes Update and Direction

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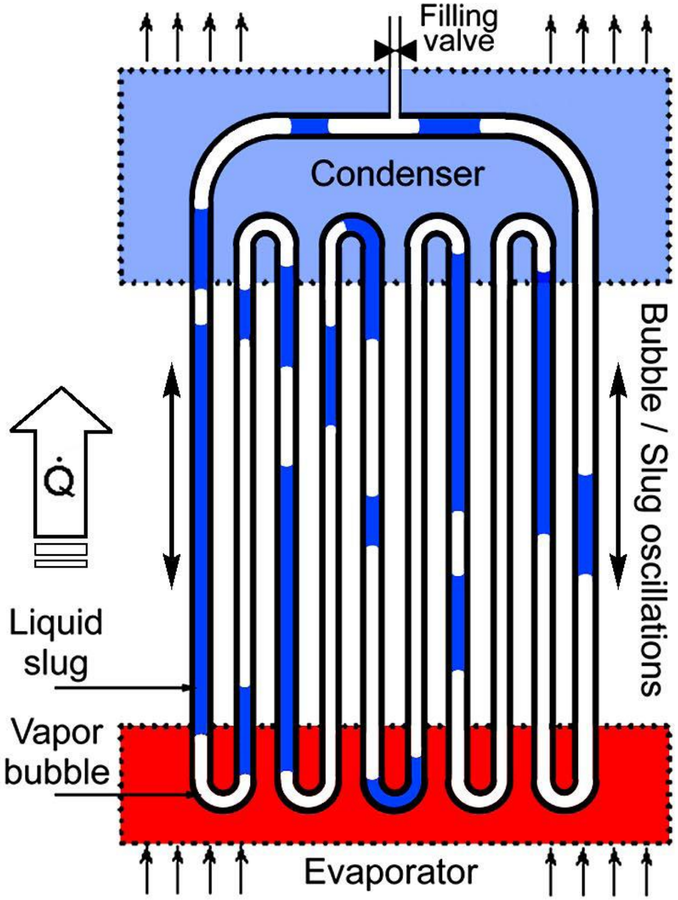
Structure

- Introduction to the topic
- Unique features of cryogenic PHPs - recent reports
- Modeling a helium PHP using Fluent CFD
  - Scope & specifications
  - Mass balance
    - Properties
    - Phase change
  - Model output
  - Influence of copper plate
  - On-going activities

Introduction

What is a Pulsating Heat Pipe (PHP)?

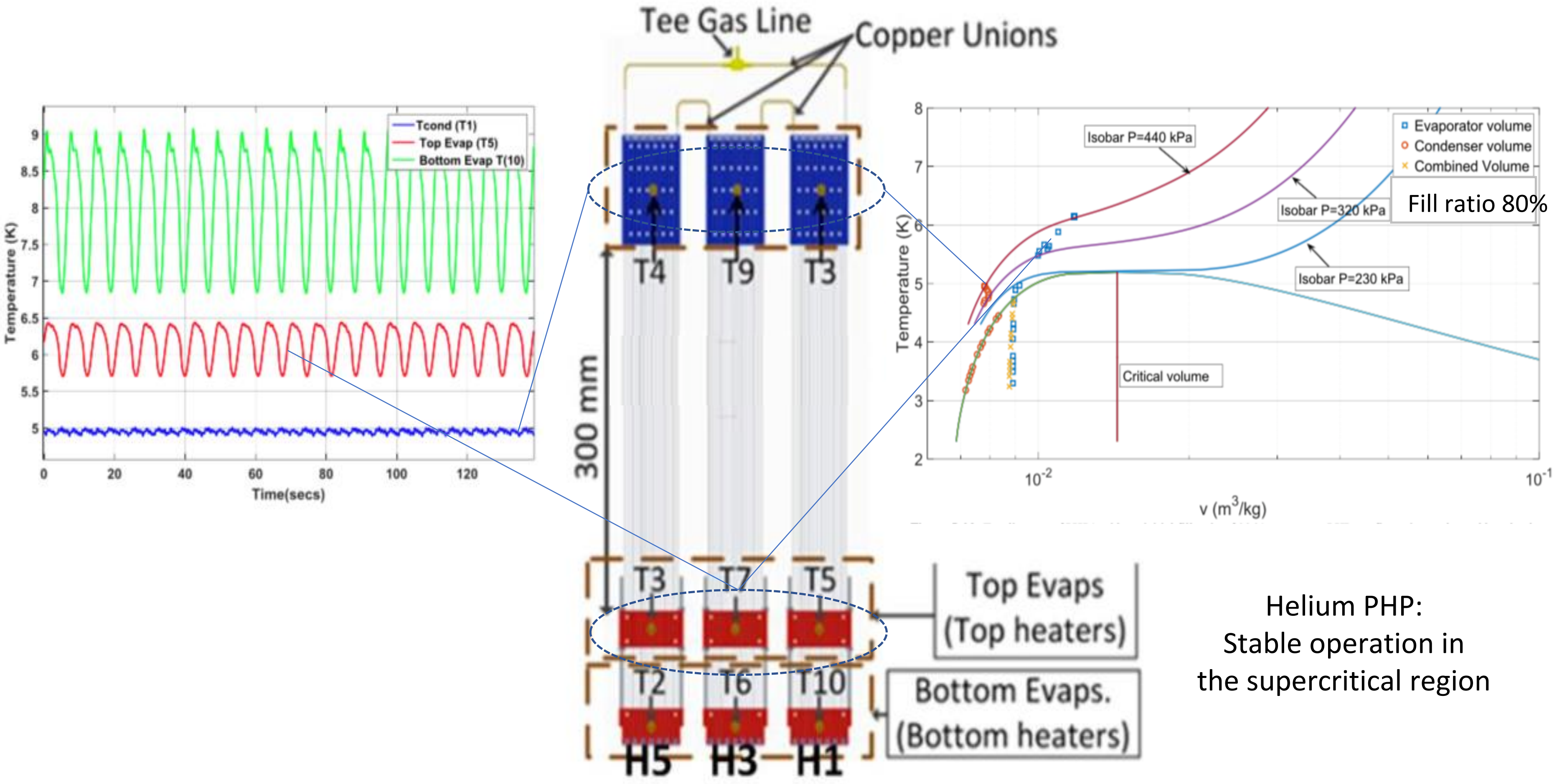


- First developed in 1990: Akachi, *5th Intl. Heat Pipe Symposium*
- Multiple loops of capillary tubing (no wicking structure)
- Partially filled with heat transfer fluid – alternating liquid slugs and vapor plugs
- Oscillatory and circulatory motions effectively transfer heat from evaporator (hot) end to condenser (cold) end
- World wide interest for room temperature applications
- Cryogenic attention since 2010

Khandekar, S., 2004, "Thermo-hydrodynamics of Closed Loop Pulsating Heat Pipes," *Institut fur Kernenergetik und Energiesysteme der Universitat Stuttgart*

Recent Findings with Cryogenic PHPs

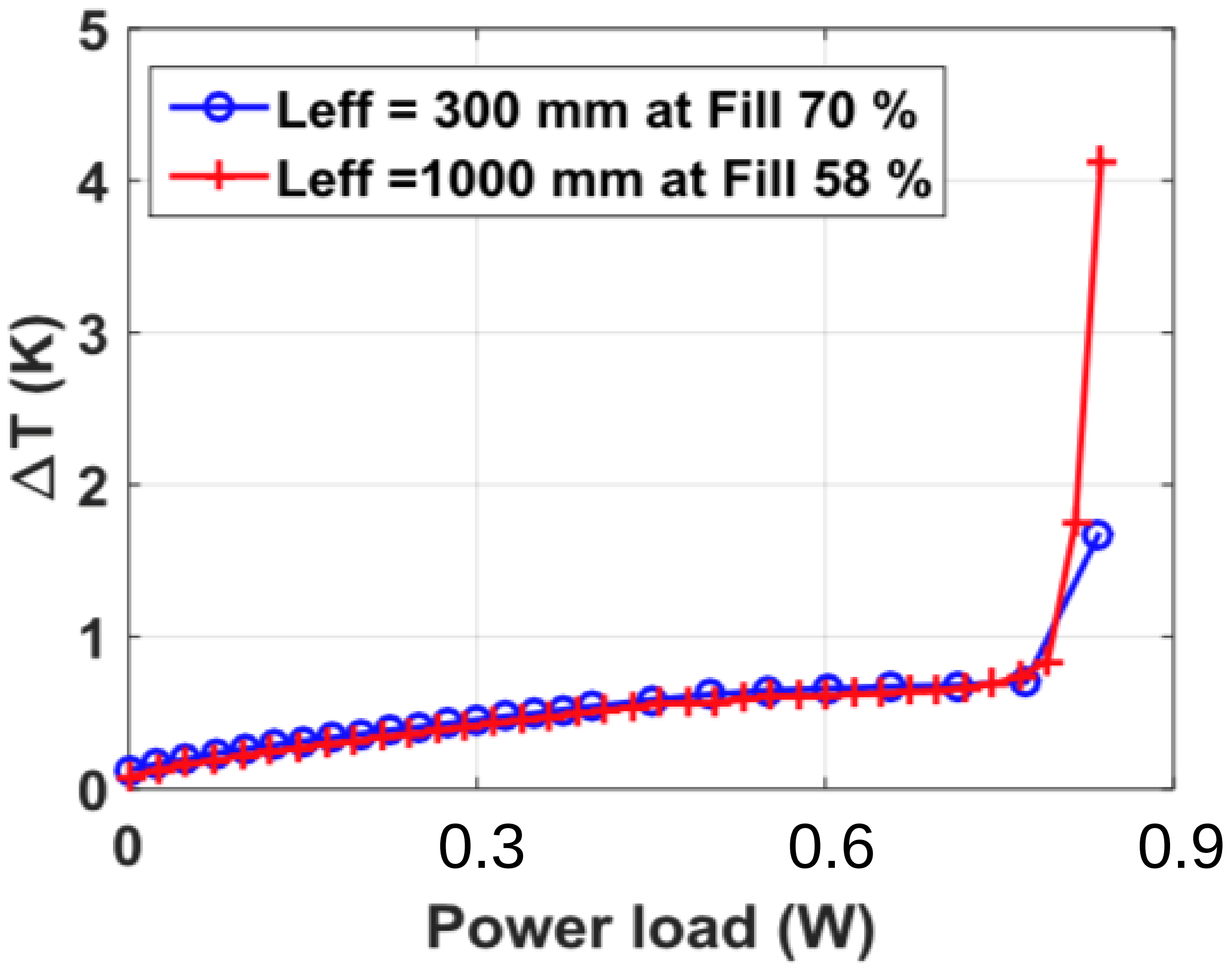
Continued Operation in Helium's Supercritical Region



Helium PHP:
Stable operation in
the supercritical region

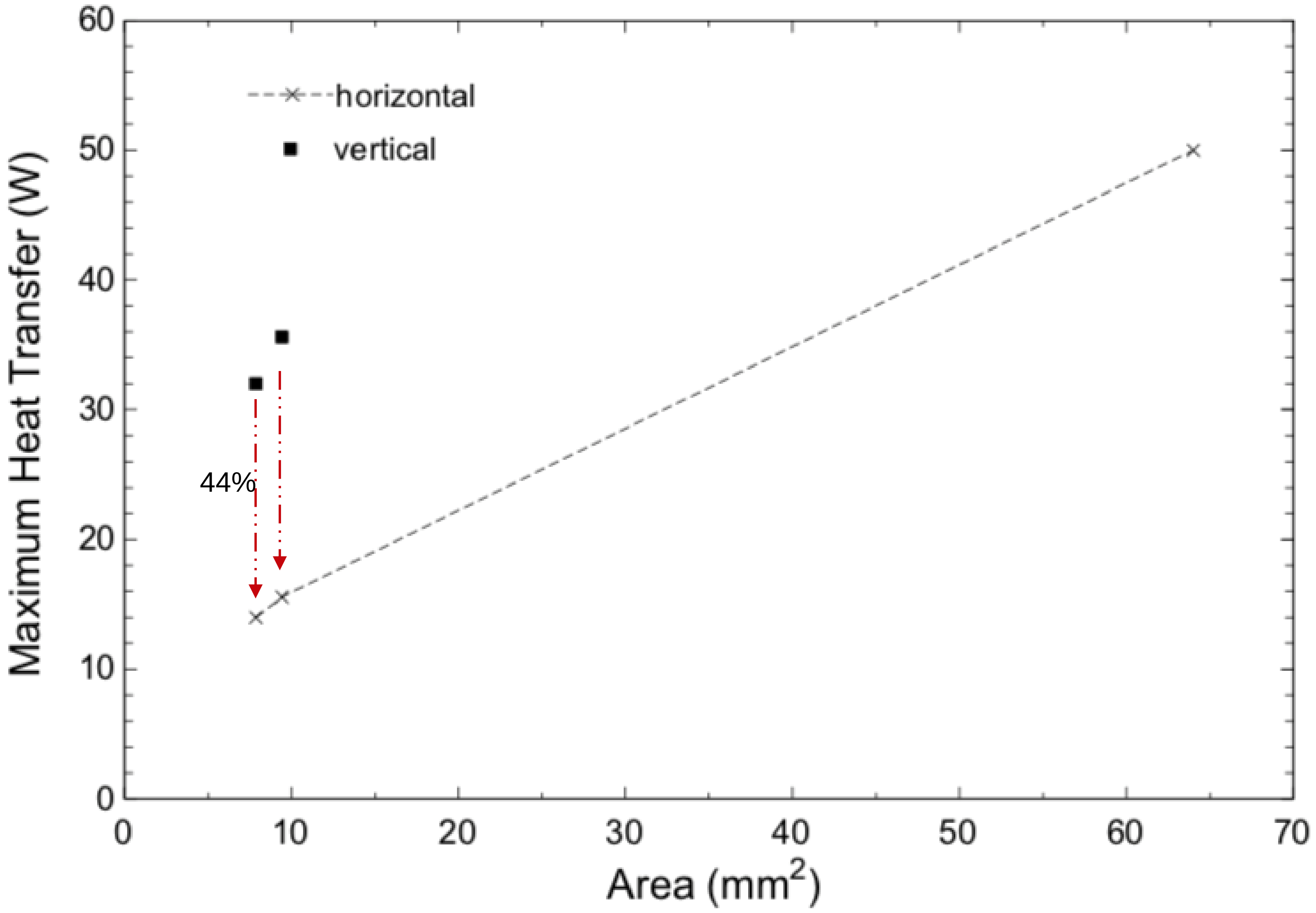
UW-Madison: 2017. Fonseca PhD Thesis
Similar behavior reported by: TIPC-CAS, 2018. Li, Li, Xu, *Cryogenics* ***96****, pp. 159-165*

Adiabatic-Length-Independent Conductance
(Helium)



Dependence of Maximum Heat Transfer on A_{flow} and Orientation

(Neon)



Modeling a Helium PHP via FLUENT

Objectives

- Match model results to experimental data
- Gain insight regarding the internal flow characteristics and associated thermal performance
- Challenges & Learning:
  - Number of nodes as size increases: match full scale results: UW-Madison 21 turns 500 mm, TIPC-CAS 8 turns 200 mm.
  - Mass balance
  - Properties – helium vapor is NOT an ideal gas (UDF)
  - Length independent conductance - unidirectional flow?
  - Include copper plate on evaporator / condenser
  - How much detail is needed: film layer?

Geometry of Modeled PHPs

- Tube diameter: 0.5 mm
- Number of turns: 2, 5,10, 21, and 24 turns
- Length: 50 mm, 200 mm, and 500 mm
- Bend diameter: 10 mm
- Evaporation length: 30 mm, and 50 mm
  - Uniform Heat Flux BC (remember this)
- Condenser length: 90 mm, and 50 mm
  - Uniform Temperature BC
- Typically model the condenser walls as fixed temperature and evaporator walls as fixed heat flux. Not exactly the same BC’s as experiments but we assumed this was a good starting point.

Ansys Fluent Model

Fluid Model

- Two phase: VOF method
- Viscous model: Laminar
- Mass Transfer Model: Lee Model

Numerical method:

- Pressure-velocity coupling: PISO
- Gradient: least square cell based
- Pressure: body forced weighted
- Density: second order upwind
- Momentum: Quick
- Volume fraction: geo-reconstruct
- Energy: first order upwind
- Transient: first order implicit

High Performance Computing(HPC) system

Setup:

- Using 128 CPUs in the HPC system
- RAM/core=4 GB
- vs: Desktop:4 CPU with RAM/core=4GB

Running time:

- Takes a day on HPC to run 12 second simulation time for 10 turns 500 mm (This simulation would take more than a month on a desktop machine)
- Running times linearly increasing with increasing mesh size(geometry size) in each dimension and in time step size.

Mesh number examples:

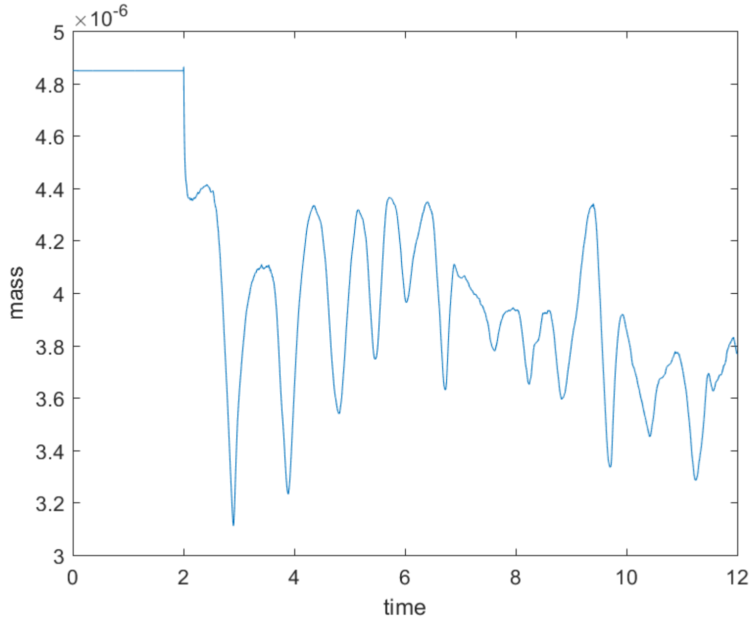
- 2turn 50mm: 24190
- 2turn 500mm:196762
- 24turn 200mm:479407

Mass Balance

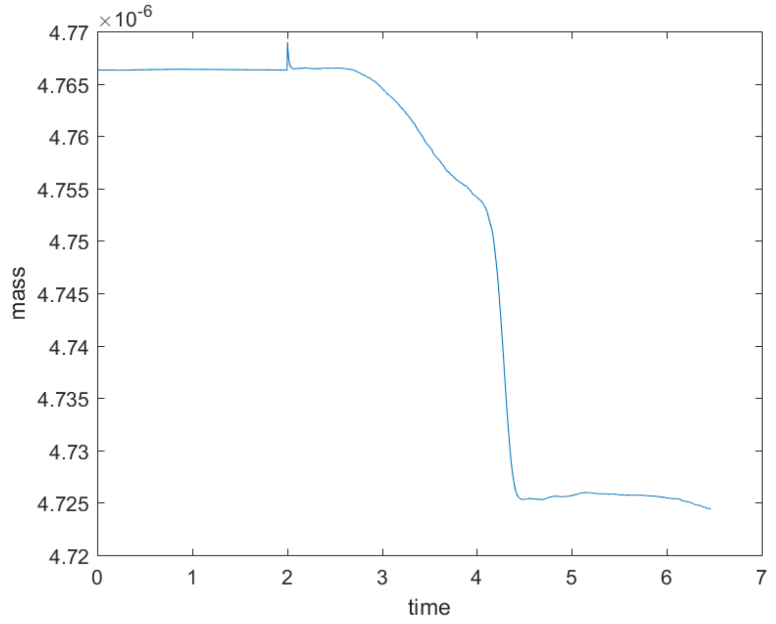
Influencing factors:

- Properties
- Lee model frequency
- Time step
- Iterations per time step
- Initial guess of T_{evap}

Ideal gas properties



Vapor properties = f(T,P)



Helium Fluid Properties

Properties defined in the range from 3 Kelvin up to 20 Kelvin

Vapor: Using user defined functions (UDF)

- conductivity and viscosity: piecewise polynomial
- Density, enthalpy, and heat capacity: functions of both temperature and pressure

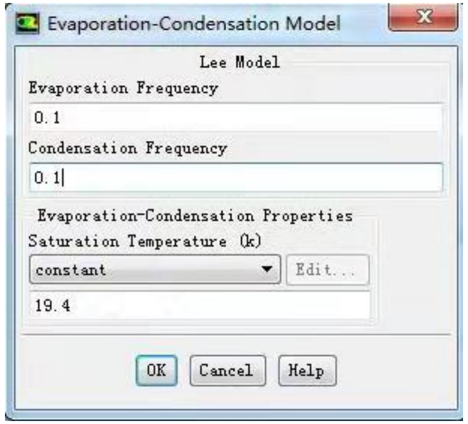
Liquid: all properties use piecewise polynomial function along the saturation line

Lee model

The liquid-vapor mass transfer (evaporation and condensation) is governed by the vapor transport equation.

$$\frac{1}{\rho_v}\left[\frac{\partial}{\partial t}(\alpha_v\rho_v)+\nabla\cdot(\alpha_v\rho_v\boldsymbol{v})=\cancel{S_{\alpha_v}}+\dot{m}_{lv}-\dot{m}_{vl}\right]$$

$$\begin{cases}\text{If } T_l > T_{sat} \text{ (evaporation)} \\ \dot{m}_{lv}=\text{coeff}_e\,\alpha_l\rho_l\dfrac{T_l-T_{sat}}{T_{sat}} \\ \text{If } T_v < T_{sat} \text{ (condensation)} \\ \dot{m}_{vl}=\text{coeff}_c\,\alpha_v\rho_v\dfrac{T_{sat}-T_v}{T_{sat}}\end{cases}$$

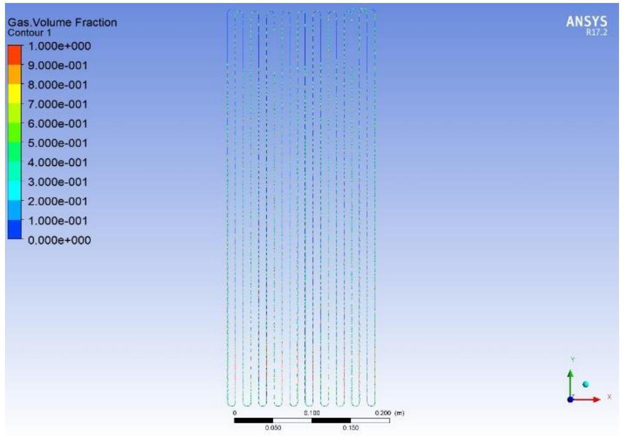


- Saturation temperature is set as a function of pressure

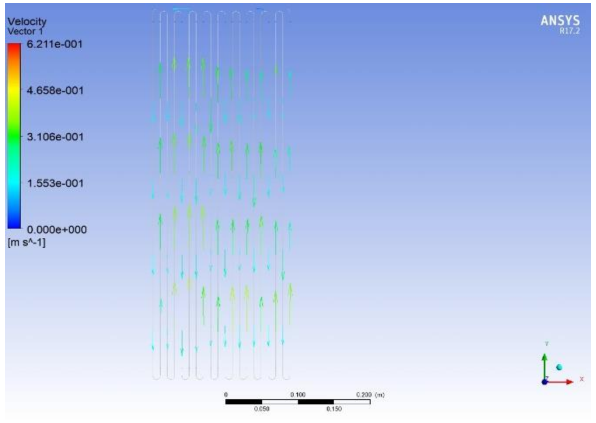
- Evaporation frequency :1
- Condensation frequency:50

- Frequency ratio:
  - Successful values: 1-50,1-150,10-10,10-50,10-500
  - Influenced by: heat flux, $T_{condenser}$, $A_{evaporator}$ / $A_{condenser}$

Visualization of inside of PHP

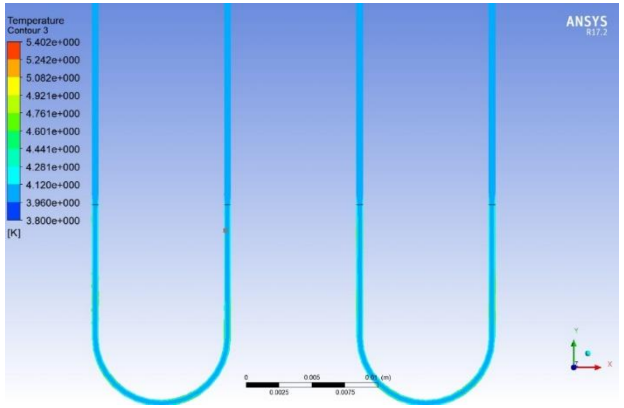


VOF plot

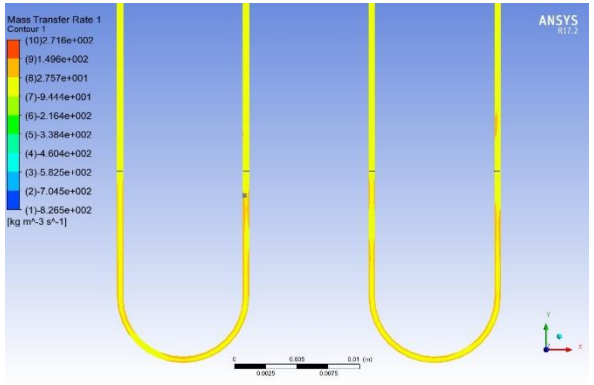


Velocity plot

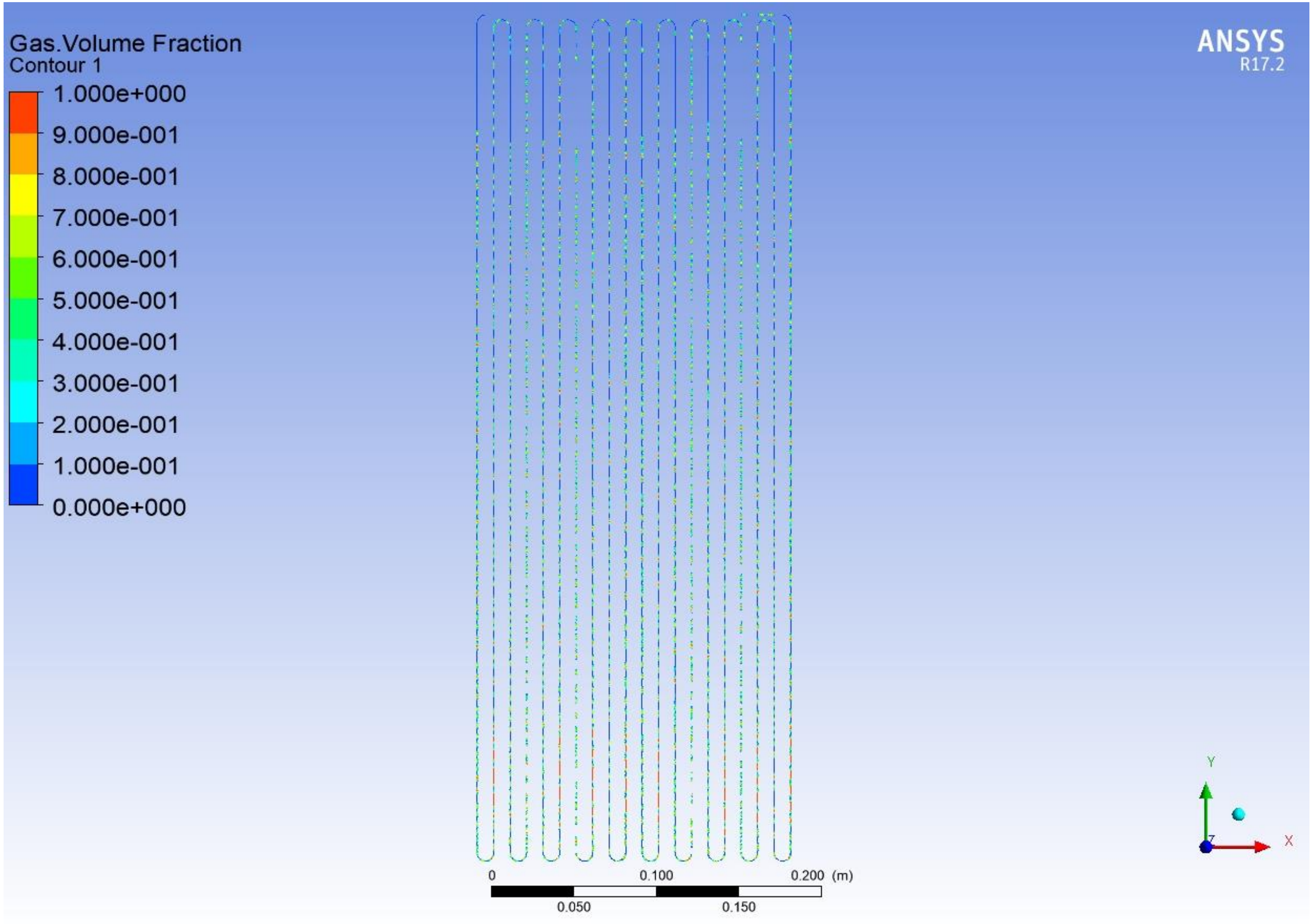
10 turn
500 mm



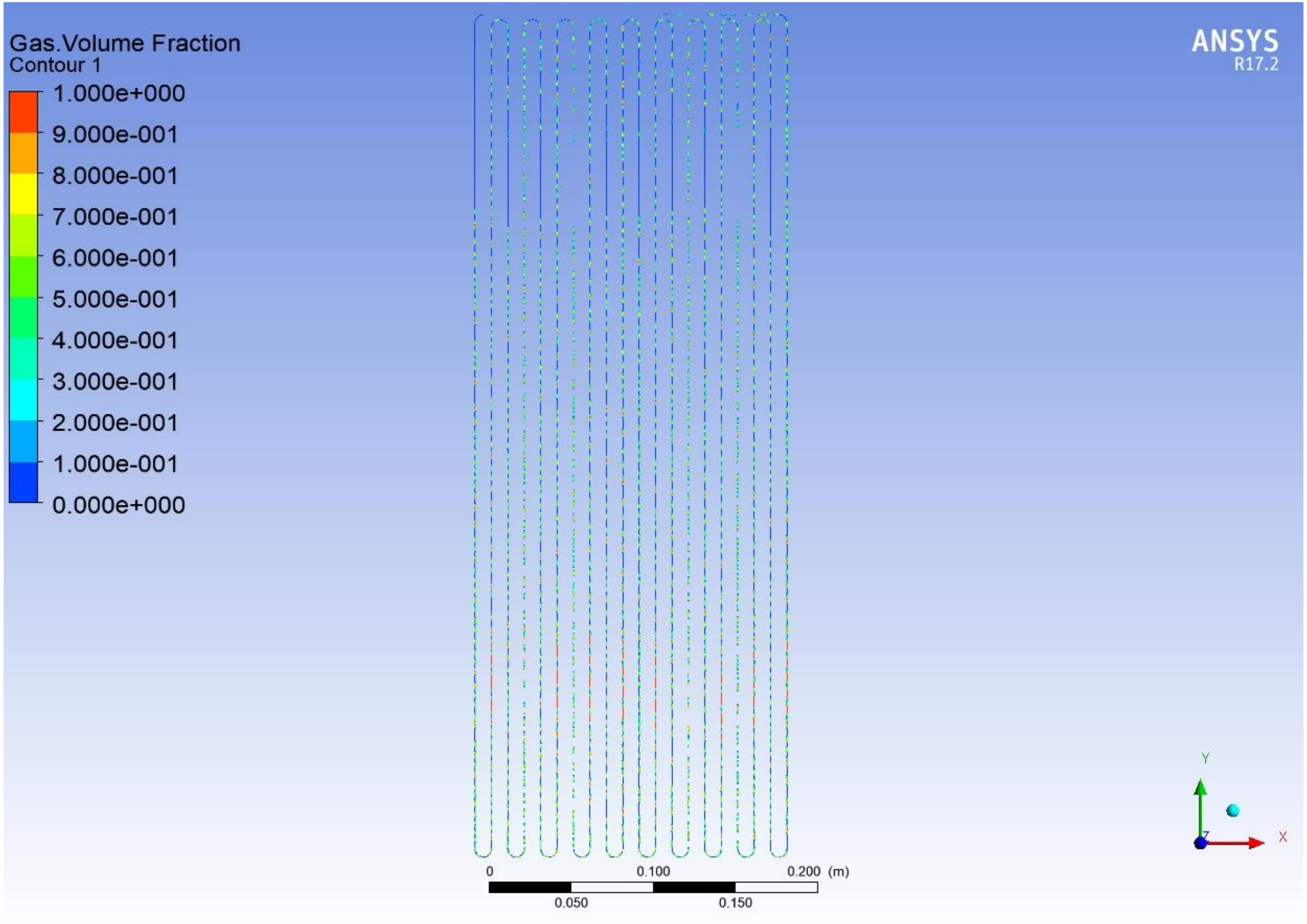
Temperature plot

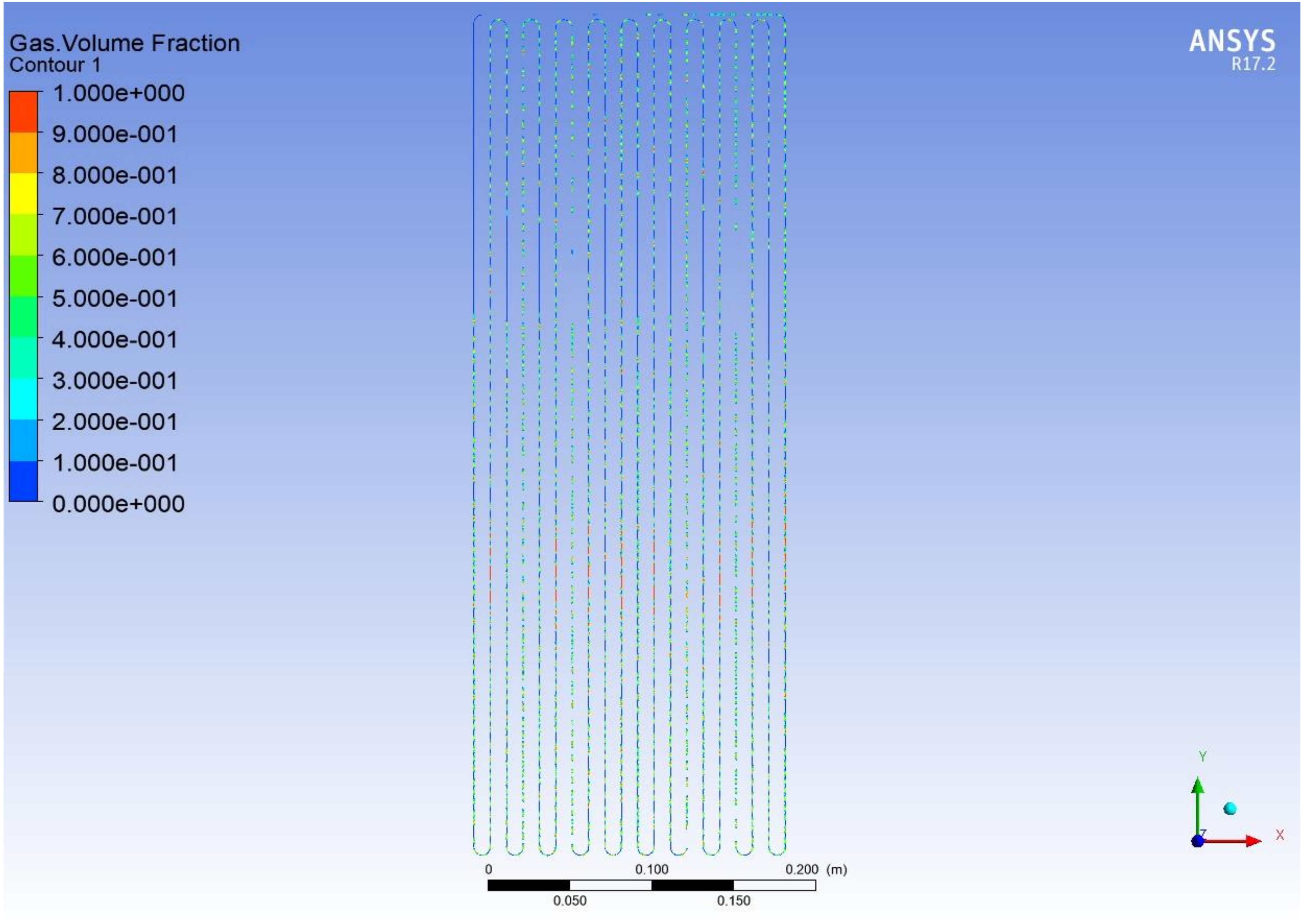


Mass transfer rate plot

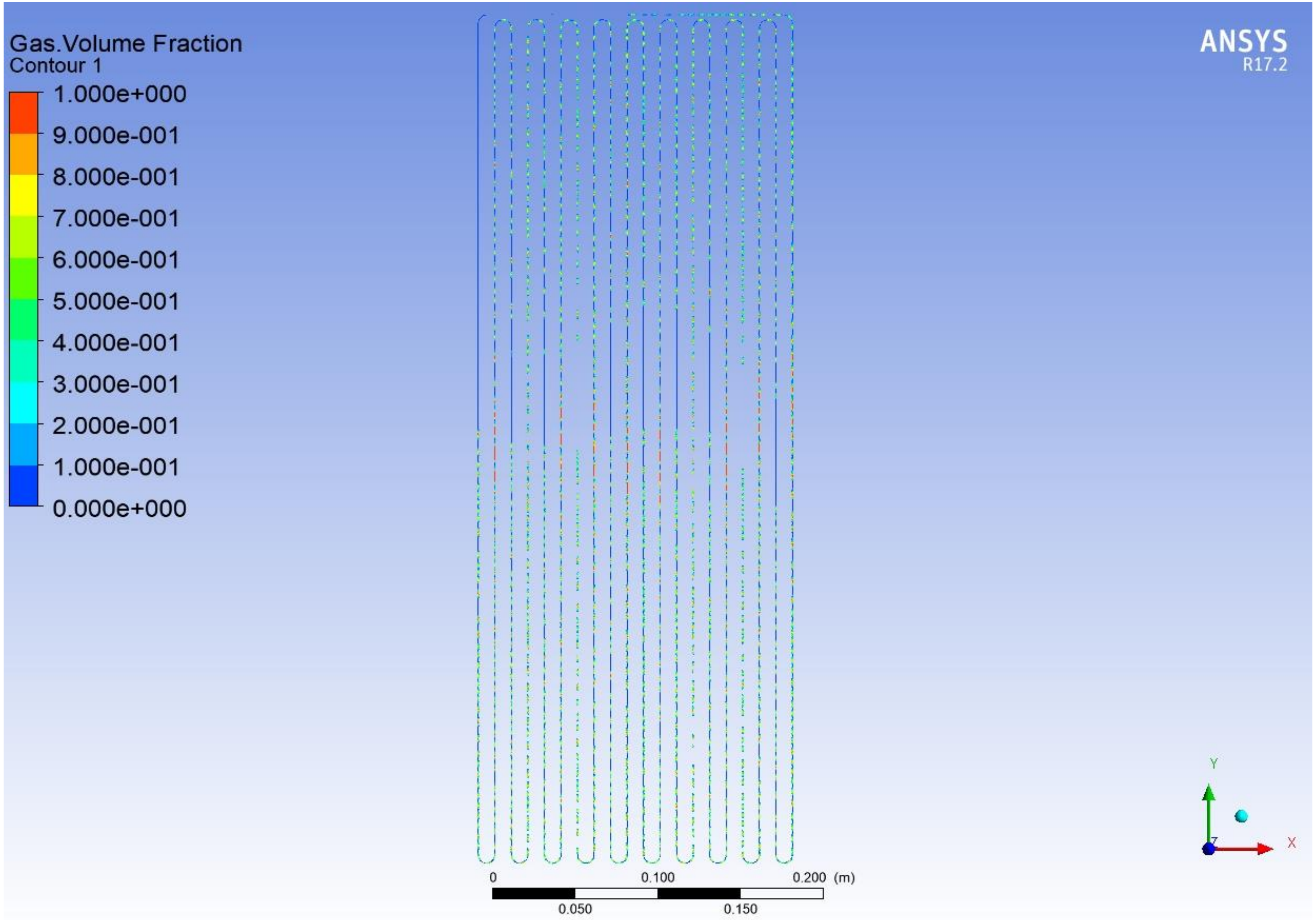


Gas.Volume Fraction
Contour 1
1.000e+000
9.000e-001
8.000e-001
7.000e-001
6.000e-001
5.000e-001
4.000e-001
3.000e-001
2.000e-001
1.000e-001
0.000e+000
ANSYS
R17.2
0
0.100
0.200 (m)
0.050
0.150
Y
X

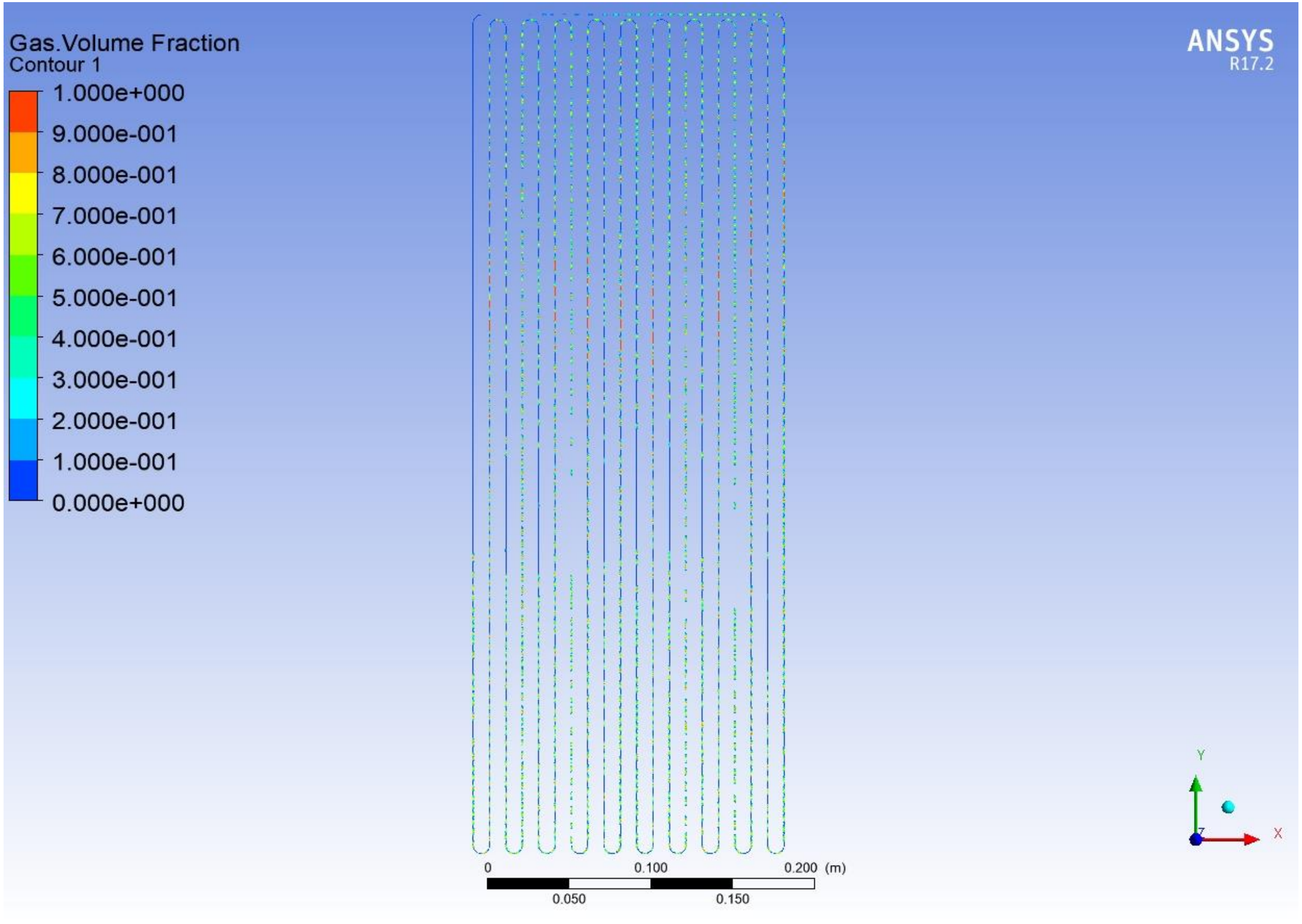

Gas.Volume Fraction
Contour 1
1.000e+000
9.000e-001
8.000e-001
7.000e-001
6.000e-001
5.000e-001
4.000e-001
3.000e-001
2.000e-001
1.000e-001
0.000e+000
ANSYS
R17.2
0
0.100
0.200 (m)
0.050
0.150
Y
X



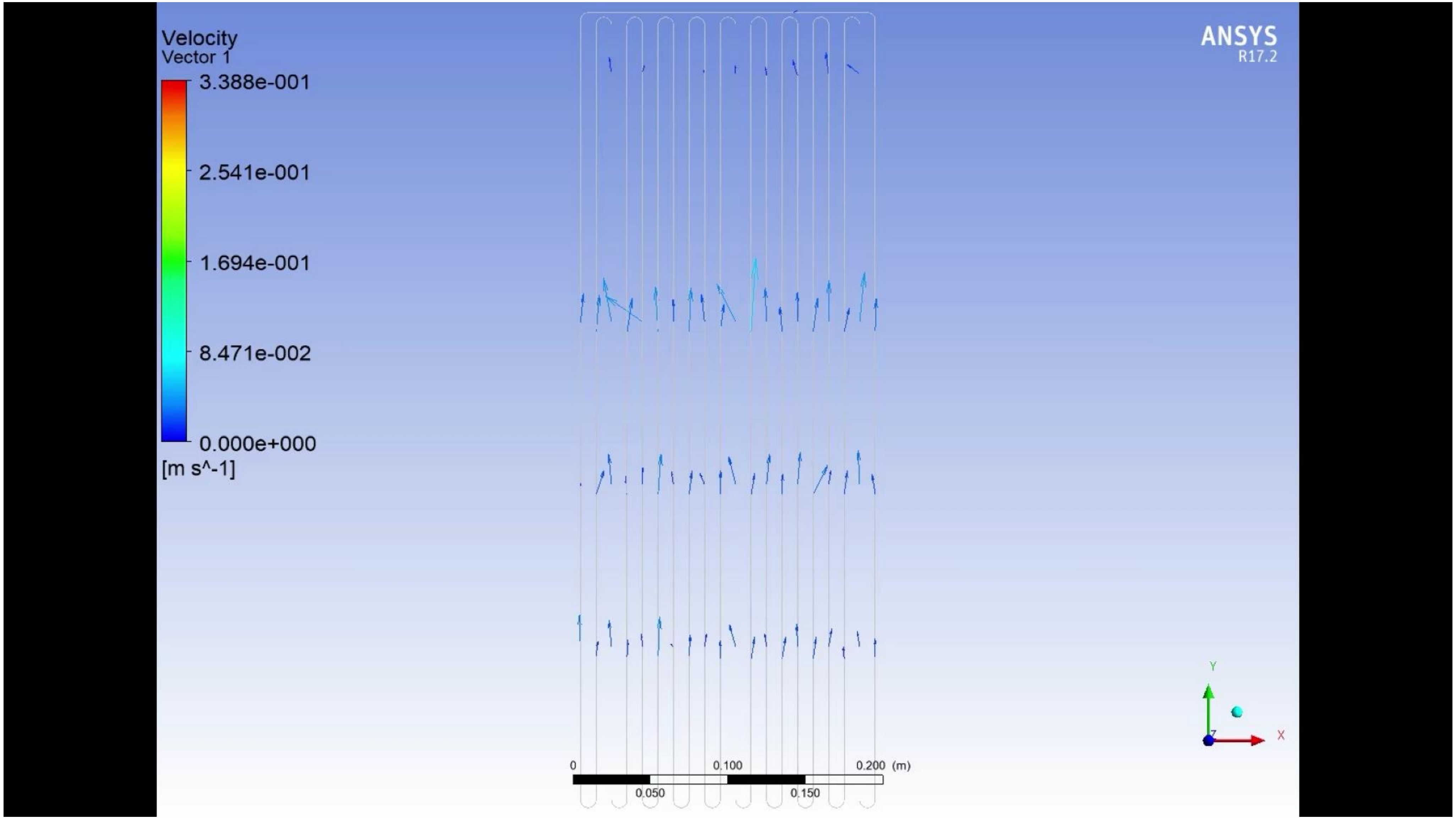
Gas.Volume Fraction
Contour 1
1.000e+000
9.000e-001
8.000e-001
7.000e-001
6.000e-001
5.000e-001
4.000e-001
3.000e-001
2.000e-001
1.000e-001
0.000e+000
ANSYS
R17.2
0
0.100
0.200 (m)
0.050
0.150
Y
X



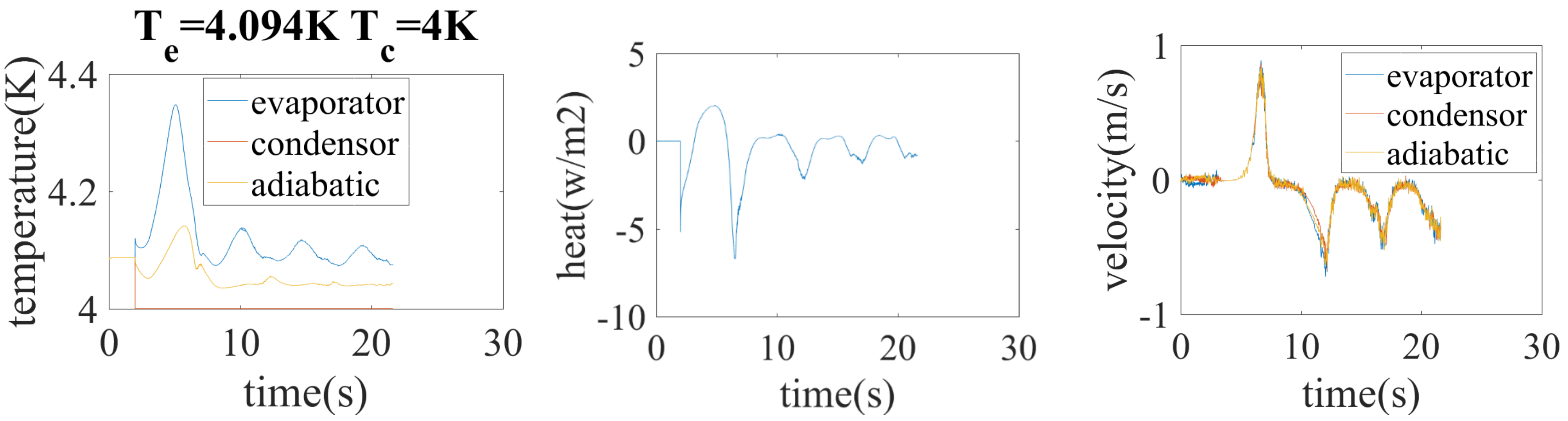
Gas.Volume Fraction
Contour 1
1.000e+000
9.000e-001
8.000e-001
7.000e-001
6.000e-001
5.000e-001
4.000e-001
3.000e-001
2.000e-001
1.000e-001
0.000e+000
ANSYS
R17.2
0
0.100
0.200 (m)
0.050
0.150
Y
X



Gas.Volume Fraction
Contour 1
1.000e+000
9.000e-001
8.000e-001
7.000e-001
6.000e-001
5.000e-001
4.000e-001
3.000e-001
2.000e-001
1.000e-001
0.000e+000
ANSYS
R17.2
0
0.100
0.200 (m)
0.050
0.150
Y
X


Velocity
Vector 1
3.388e-001
2.541e-001
1.694e-001
8.471e-002
0.000e+000
[m s^-1]
ANSYS
R17.2
0
0.100
0.200 (m)
0.050
0.150
Y
X

Time dependent plot



Oscillation of temperature, heat flux, velocity are observed

Observations

- We get oscillatory motion at low heat flux
- Circulation at high heat flux.
- Reversals of predominate flow direction
- Bubbles growing in the evaporator and shrinking in the condenser
- Changes in the number of bubbles in the PHP with time.
- However…

Experimental data

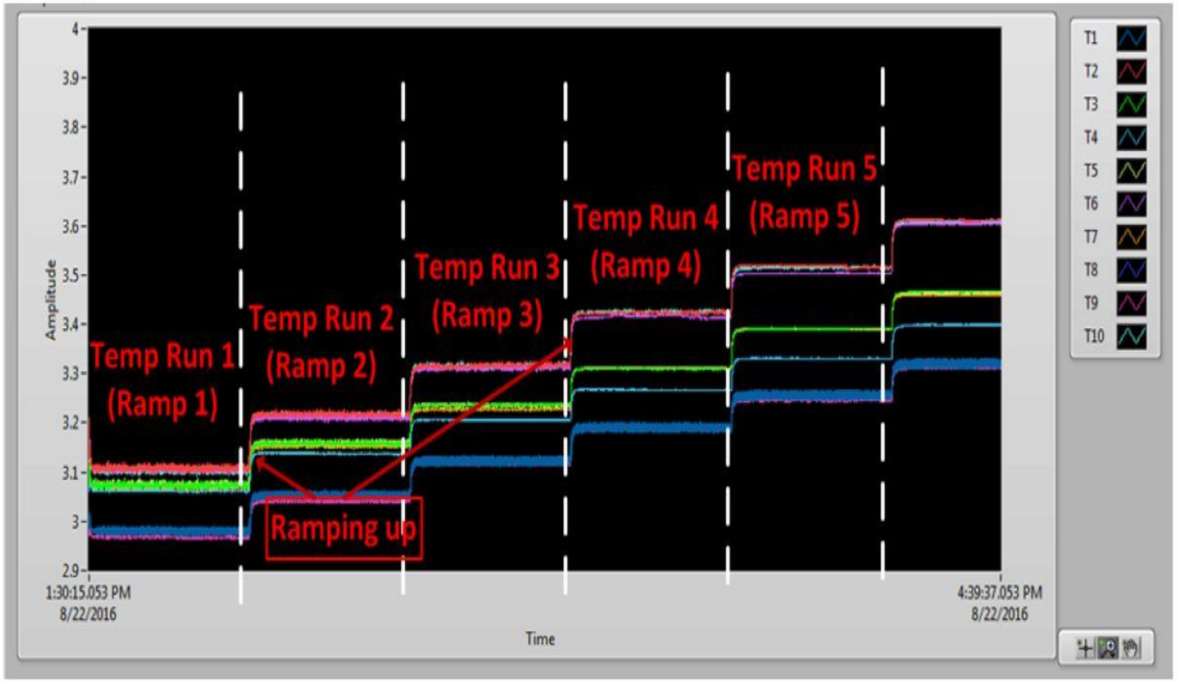


Figure 5-1: Ramping process, Labview snapshot

Data from our experiments at UW-Madison

Temperature profile slowly climbs up and then becomes steady

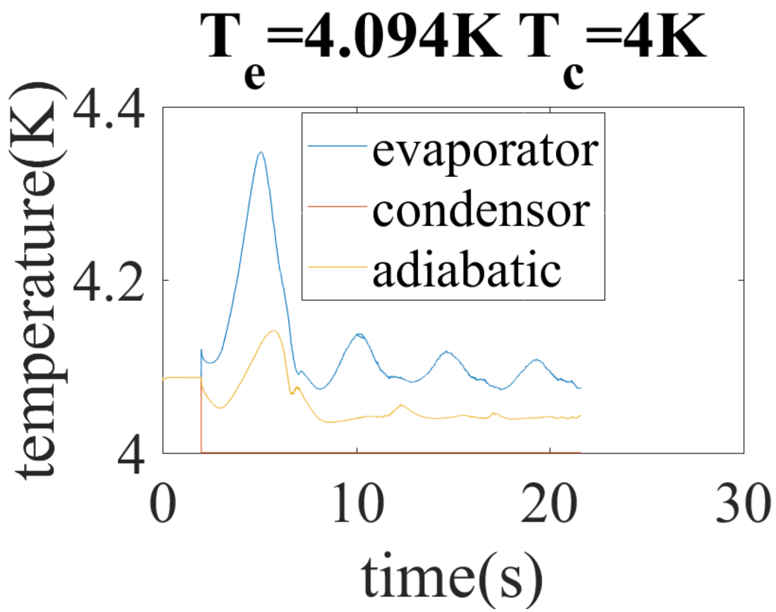
Very small temperature oscillation

30 minutes per run
Approximately 3-5 minutes for the transient.

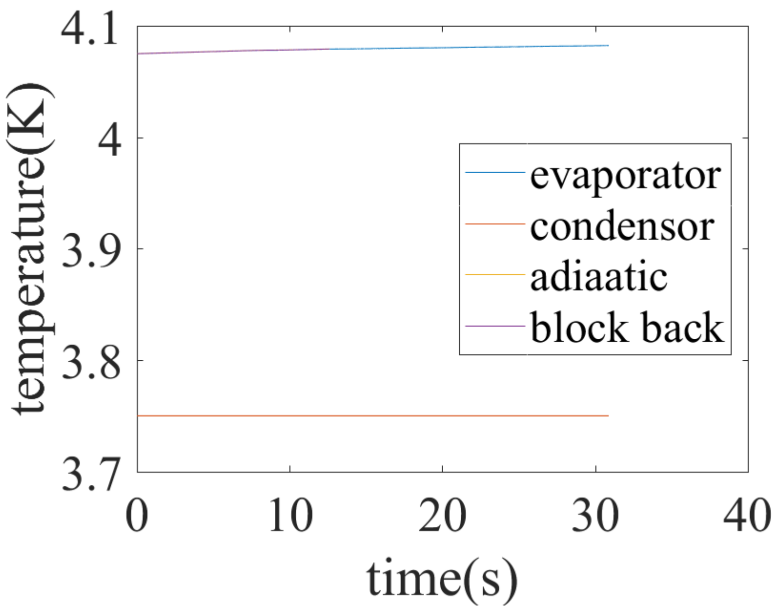
The average delta T between condenser and evaporator matches the simulation for the same heater input power.

With plate vs no plate

Adding heat flux on the back of the plate vs adding heat flux directly on evaporator wall



With no plate



With plate

Adding the plate ‘damped’ the temperature oscillations

Heat capacity of the plate?

- Specific heat of copper at room temperature is 389.4 J/kg-K
- Specific heat of copper at 4 K is 0.09 J/kg-K. (4300 x smaller)
- The heat capacity of the copper is small and is not damping the oscillations.

Heat capacity of the plate?

However:

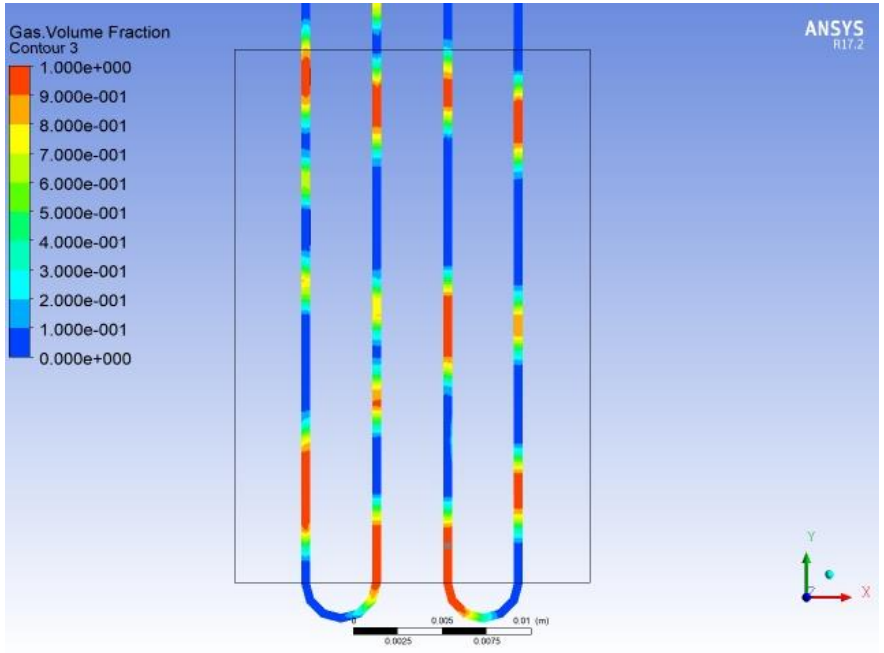
- Thermal diffusivity of RRR 100 copper at room temperature is 1.14 E-4 m^2/s.

This means the thermal wave propagation time for a 1 cm distance is 0.9 s. (90 s for 10 cm)

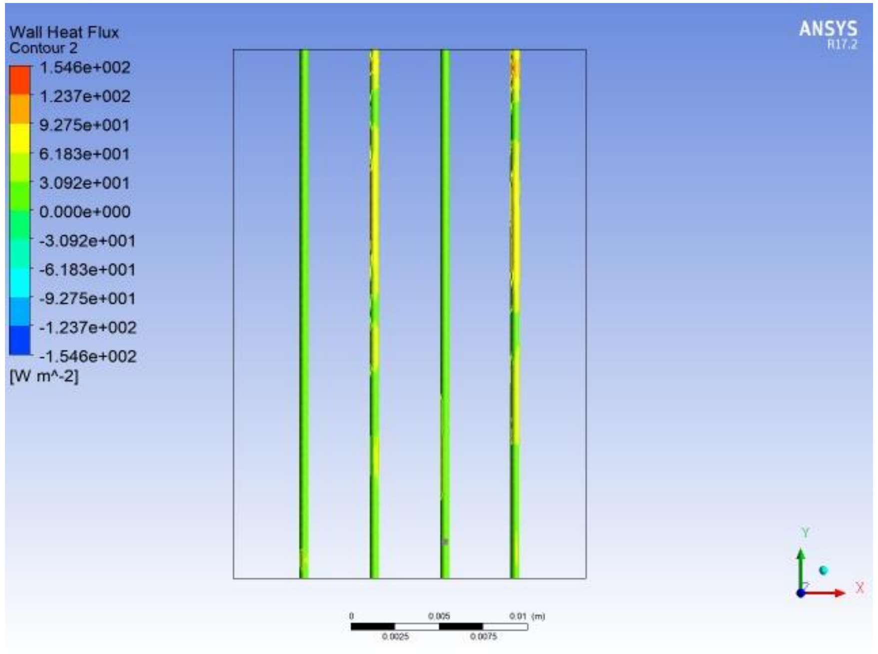
- Thermal diffusivity of RRR 100 copper at 4K is 0.71 m^2/s.

This means the thermal wave propagation time for a 1 cm distance is 0.14 ms. (0.014 s (14 ms) for 10 cm)

At 10 second



vof

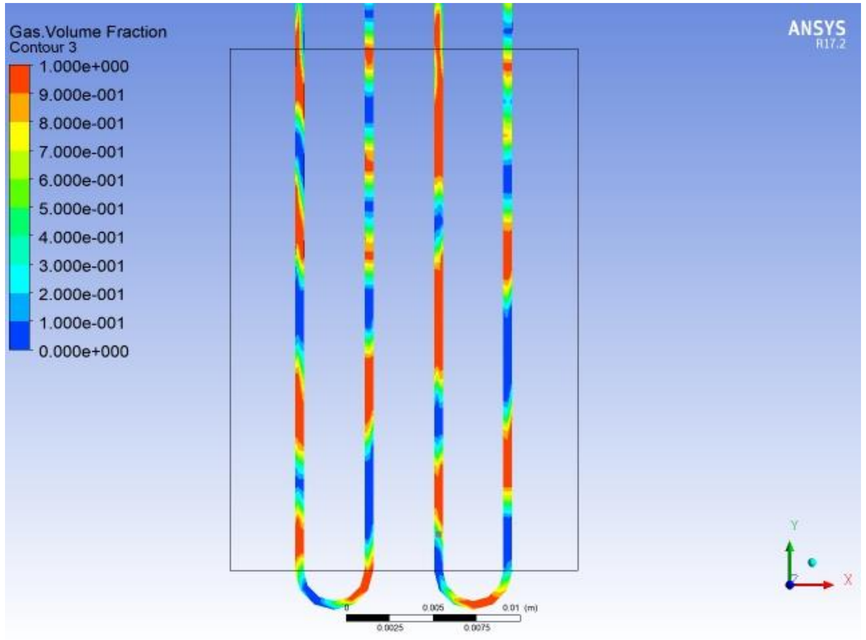


Wall heat flux

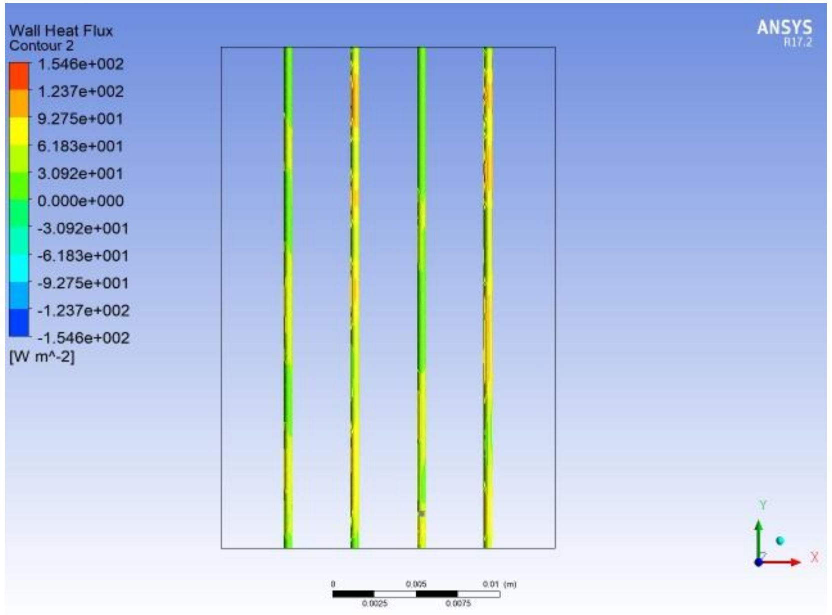
Wall heat flux is smaller when vapor is present
While wall heat flux is bigger when the liquid is present

Boundary condition on wall: neither constant temperature/heat flux
Changing heat flux on wall

11 second

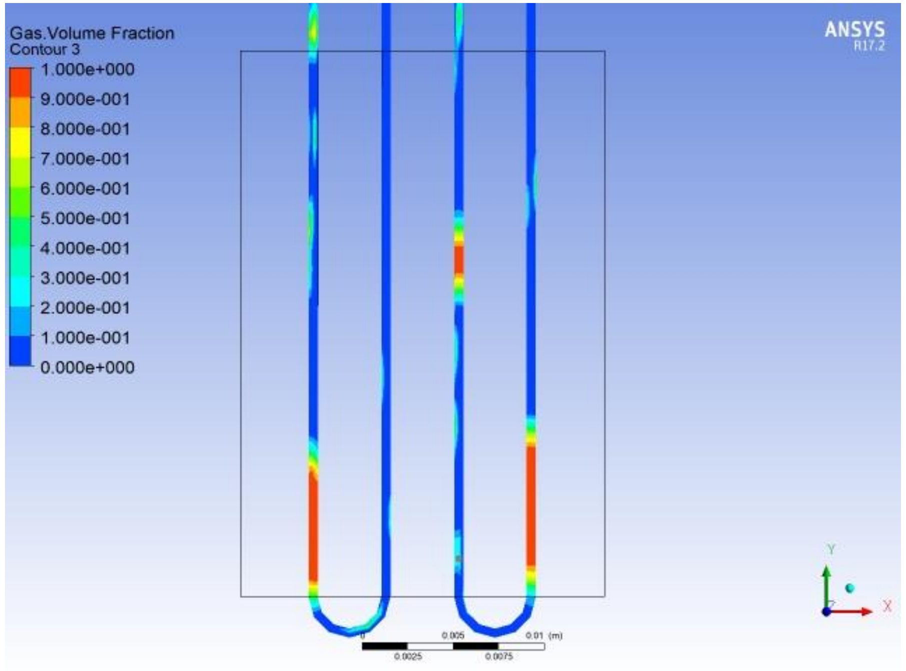


vof

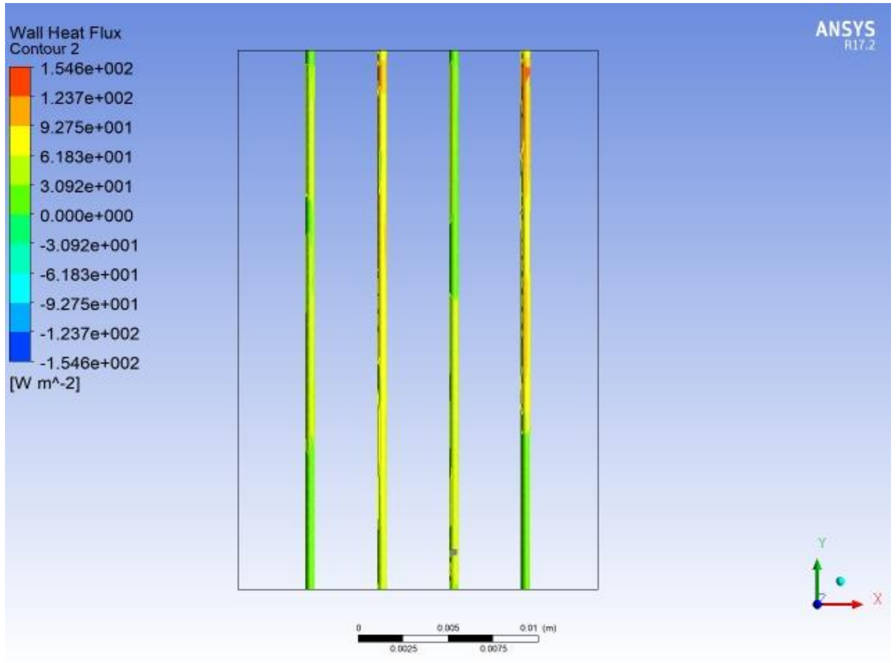


Wall Heat
flux

12 second



vof

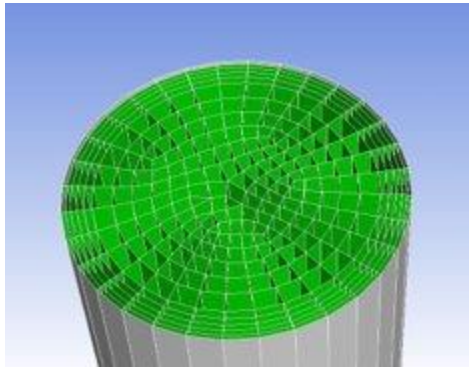


Wall Heat flux

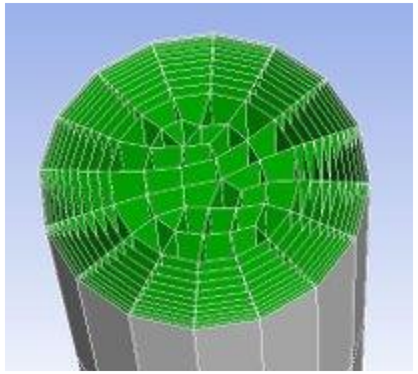
Future Work

- Include realistic boundary conditions. (Evaporator and condenser on copper plates with fixed heater power on evaporator plate and fixed temperature on condenser plate)
- Continue to validate model results with existing experimental data
- Investigate impact of fluid details on thermal behavior
- Once validation is complete, extend modeling to unique configurations such as,
  - Non-uniform orientation of components in gravity
  - Helium PHP operating above the critical pressure as has been demonstrated experimentally.

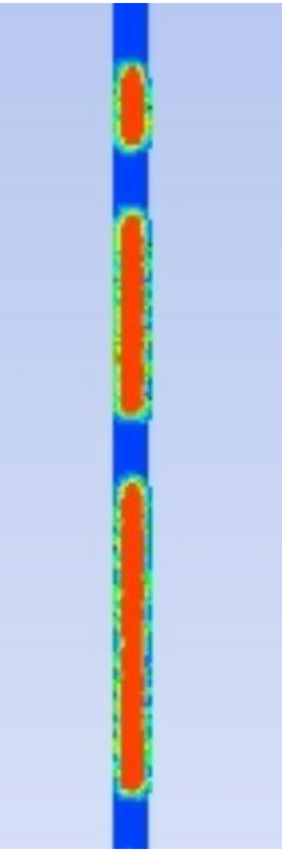
Mesh size investigation

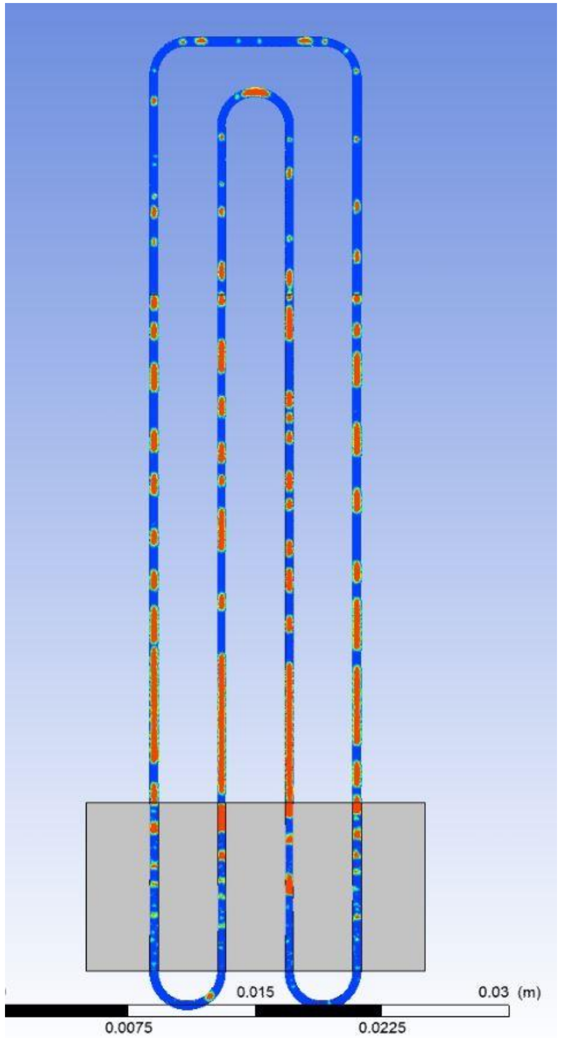


0.025mm radial node separation
inflation layer (5)



0.05mm radial node separation
inflation layer (10)





Capturing detail of liquid film layer

Any change of thermal behavior?

Salient Observations

- Cryogenic PHPs display unique behavior:
  - Performance persists into supercritical regime
  - Length independent conductance
  - Orientation sensitivity persists to large number of turns
- CFD modeling for helium PHP:
  - Use real gas properties
  - Lee model approximates mass transfer but requires attention
  - HPC necessary for full scale characterization
  - Copper’s large thermal diffusivity at 4 K smooths temperatures

Questions or Comments?