UNH – CCTVAL Collaboration on Cryogenic Fridge Design and Simulation

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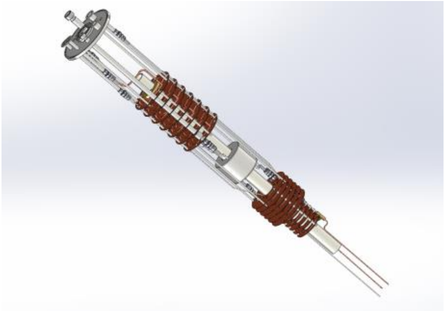
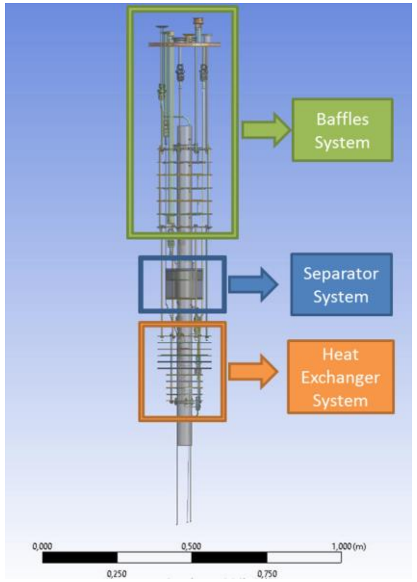
ELENA LONG





Cryogenic Fridge Modeling

General Goals

- 1. Design strategy to simulating
- 2. Analysis of theoricals and numericals models to physical problems
- 3. Make CAD models of devices to simulating
- 4. Performs first group of simulations

Problems in design found
(baffles system)

- 1. Design problems to construction
- 2.Design problems to generate meshing in simulation softwares

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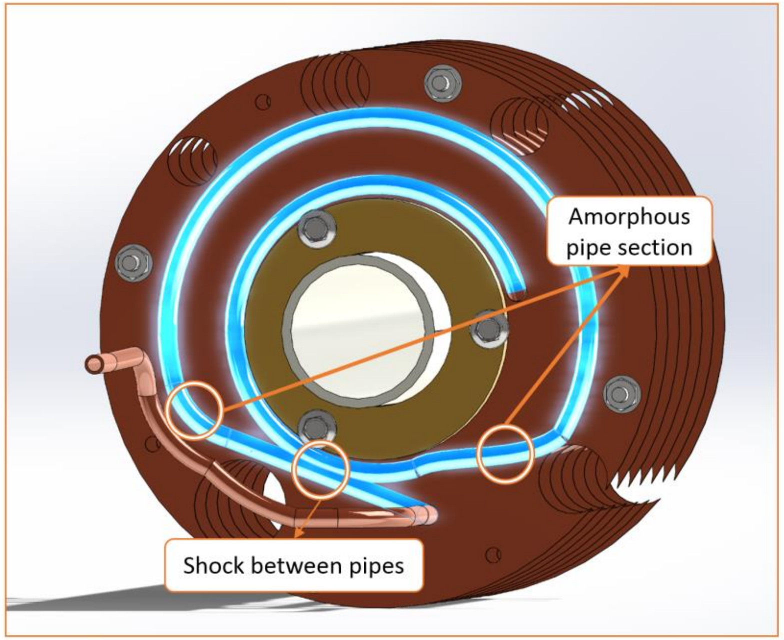
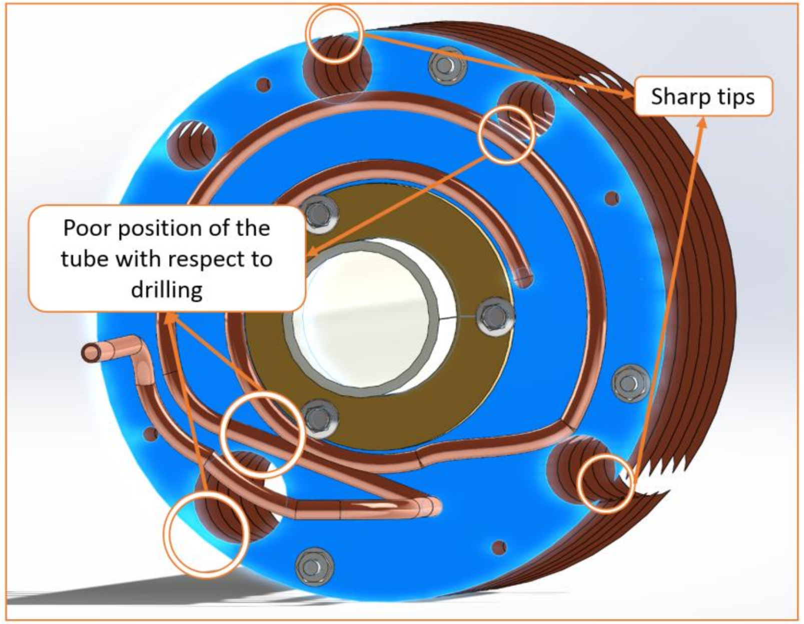
Baffles & HE Modeling : Baffle and HE Geometrical Details





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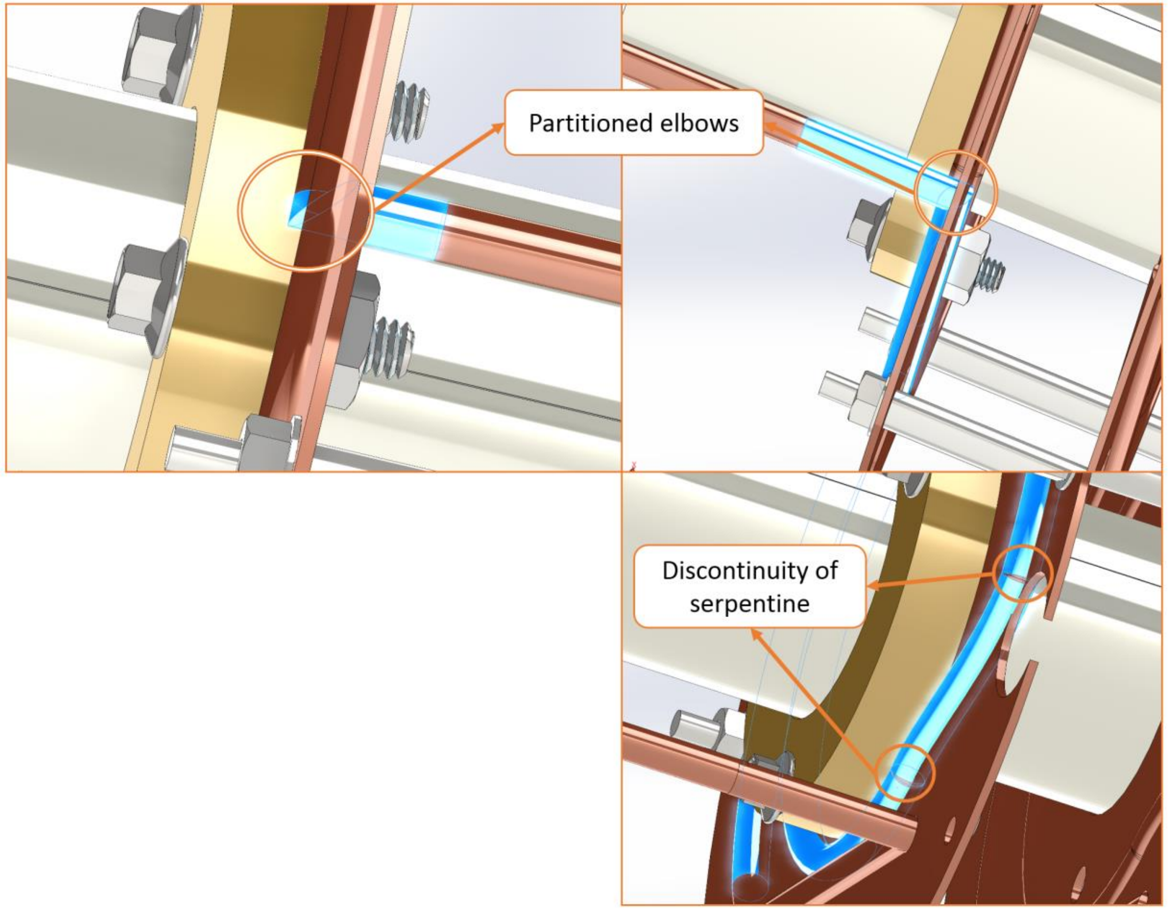

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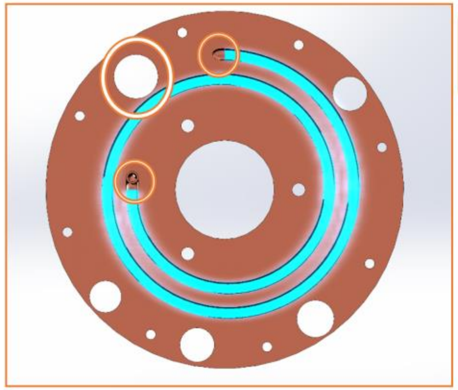
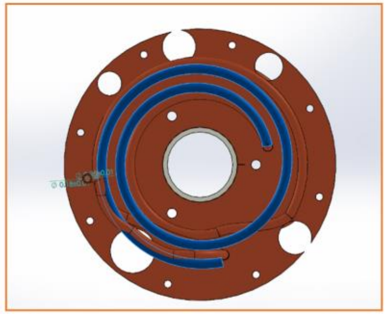
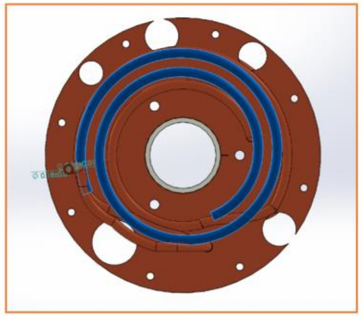


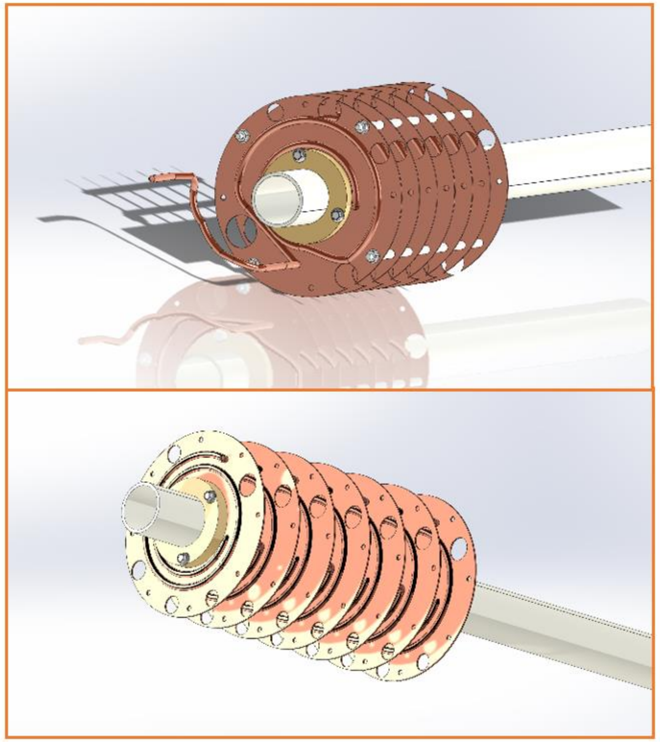
Rotation of pipe position with respect drilling in baffle

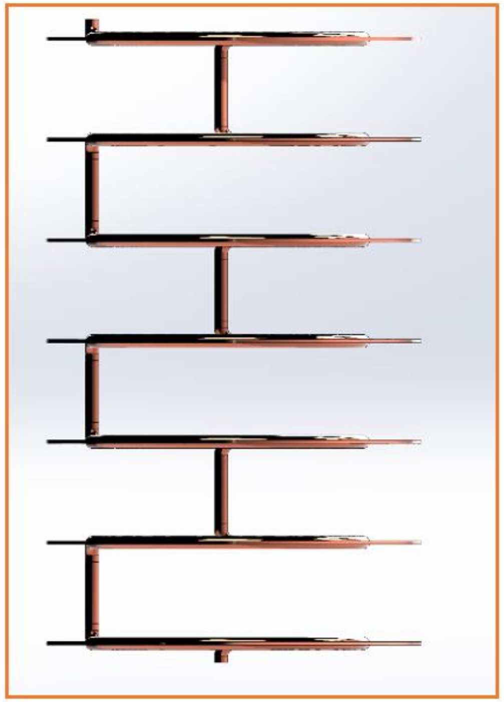




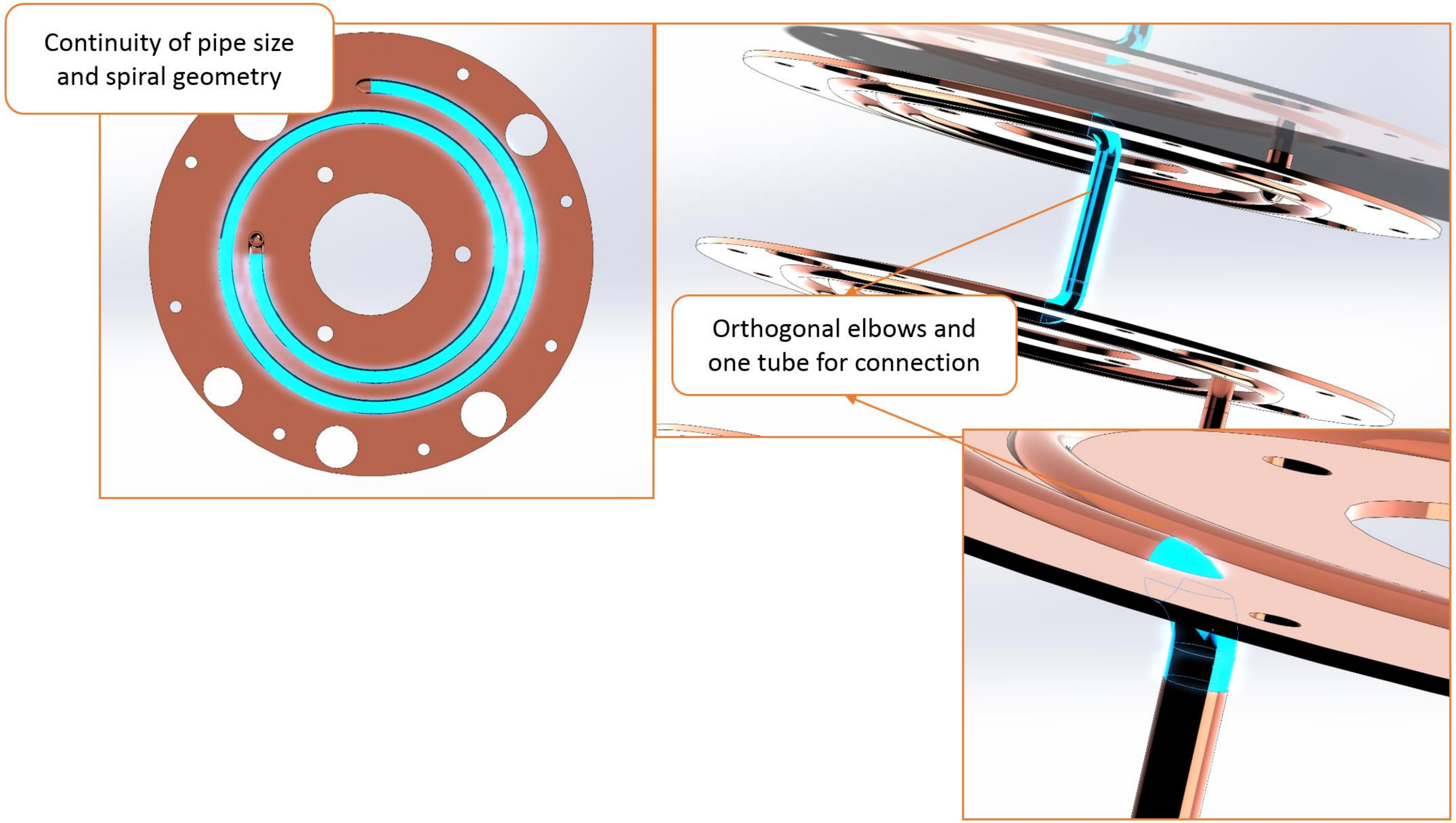
Actually position of pipe with respect baffle

New position of pipe with respect baffle

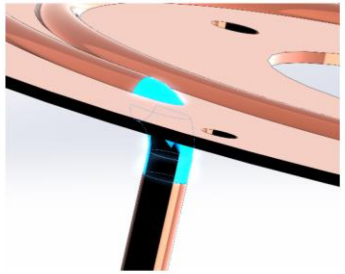


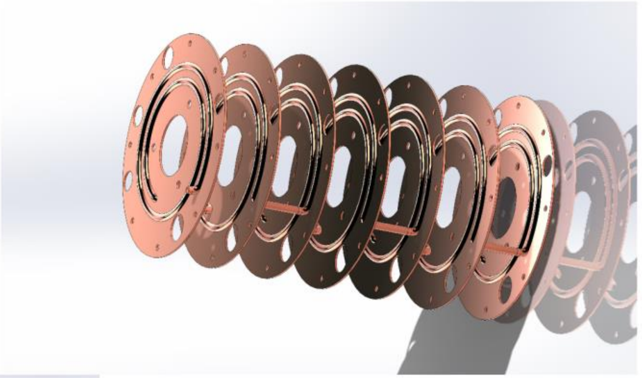


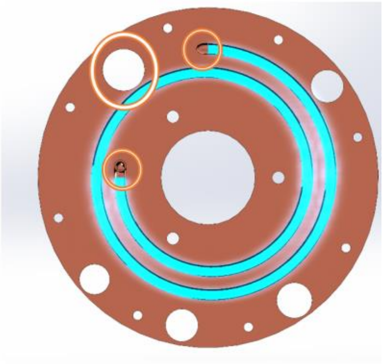
Baffles & HE Modeling : Baffle and HE geometrical modifications

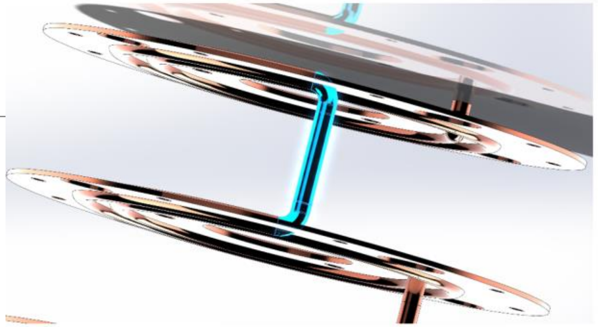


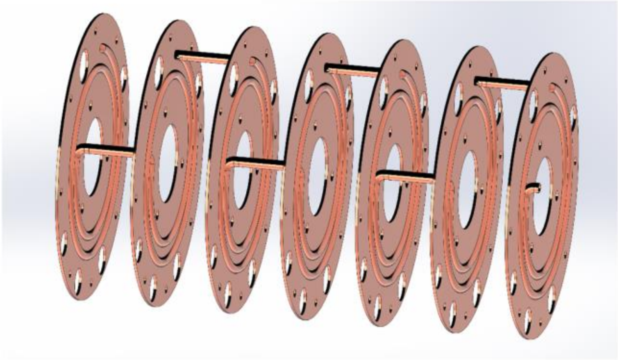
Baffles & HE Modeling : Baffle and HE geometrical modifications



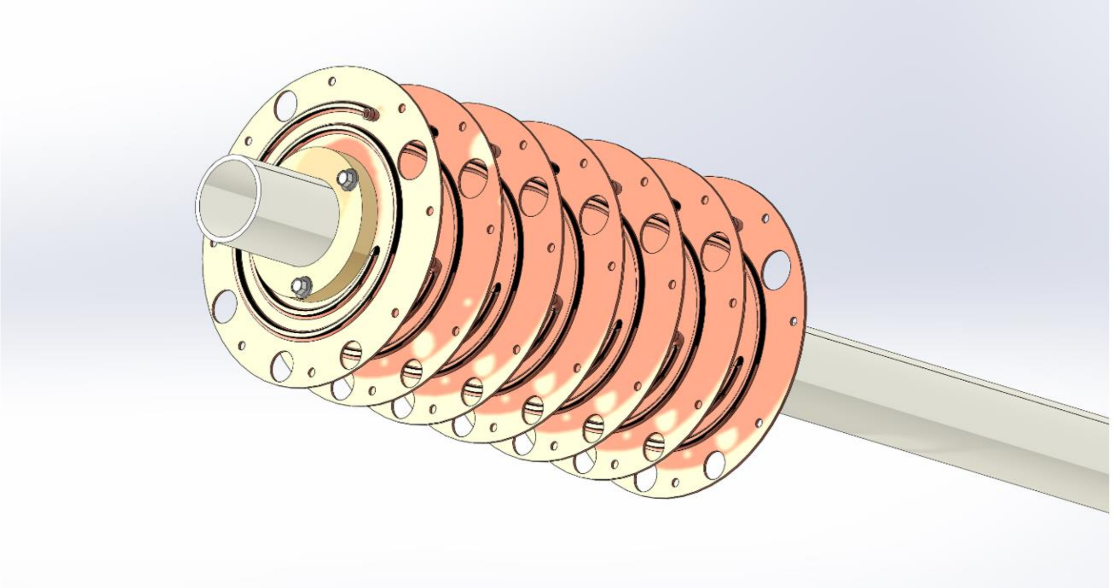


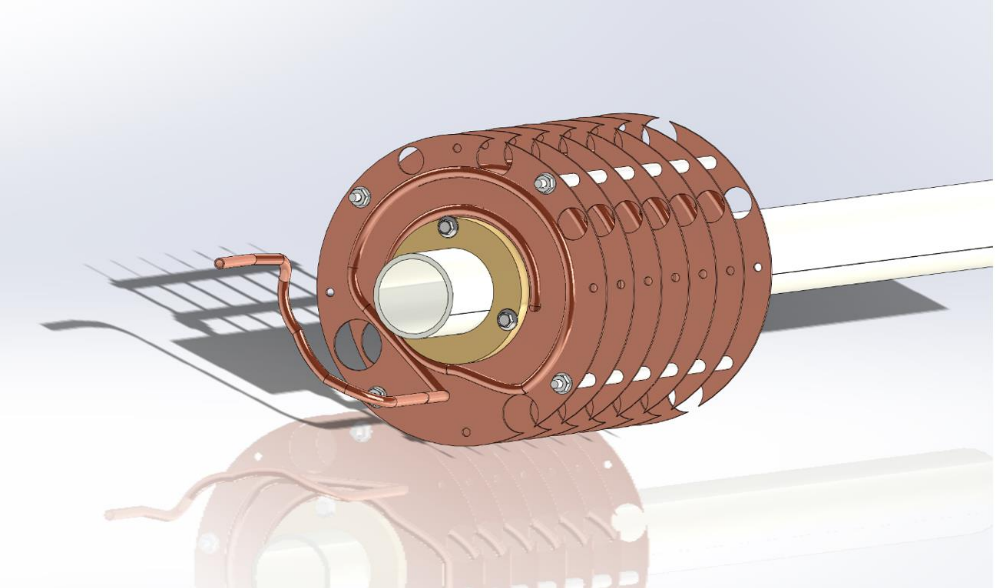






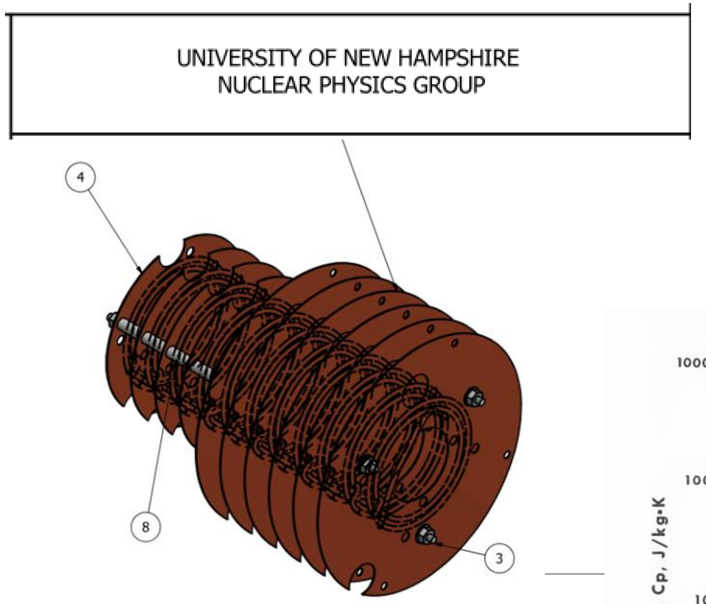
Baffles & HE Modeling : Baffle and HE geometrical modifications





Baffles & HE Modeling : Material Thermal Properties

- Cooper C10200 (ASTM B152) (Oxygen Free 0,001% max)



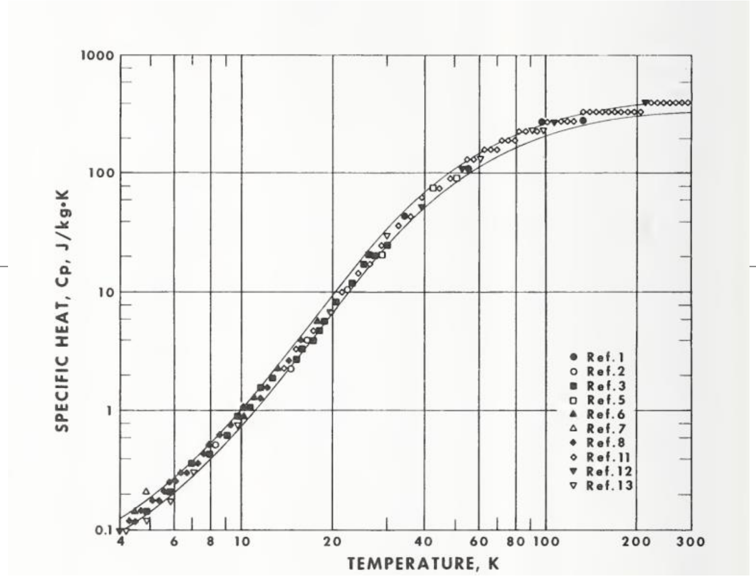
PARTS LIST			
ITEM	QTY	PART NUMBER	MATERIAL
1	6	NPG-1000-0054	C102 Copper
2	6	91343A104	SST 316
3	3	NPG-1000-0006	SST 316
4	5	NPG-1000-0055	C102 Copper
5	1	NPG-1000-0019	Aluminum
6	4	91720A197	SST 316
7	4	90205A309	SST 316

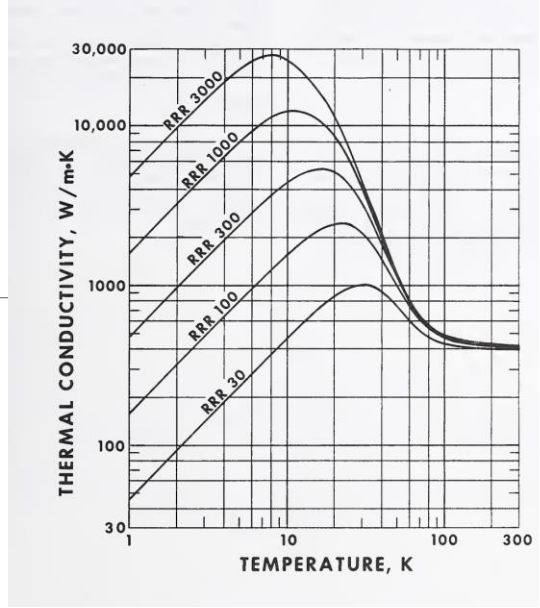
[1]

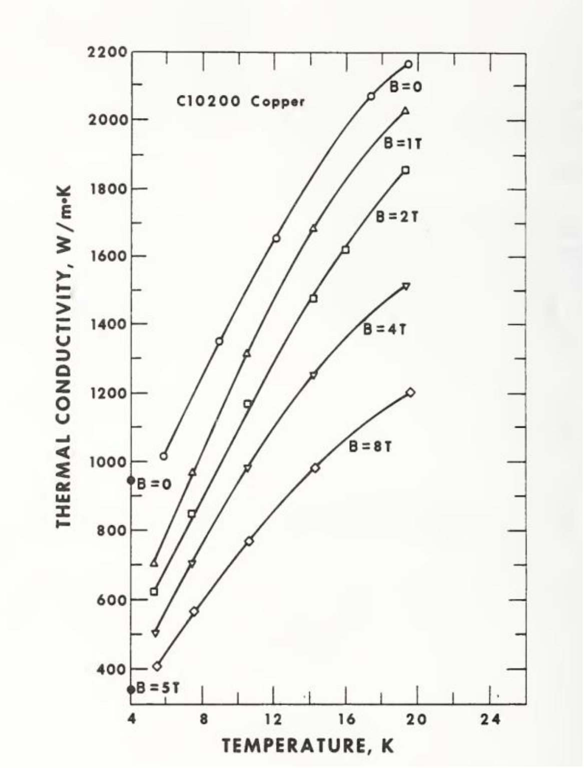
WROUGHT ALLOYS

ALLOY NO.	DESIG-NATION	DESCRIPTION	Cu (Incl. Ag) (% Min)	Ag % Min	Ag Troy Oz Min	As	Sb	P	Te	OTHER NAMED ELEMENTS
C10200 (c)	OF	Oxygen Free	99.95	—	—	—	—	—	—	—

(c) These are high conductivity coppers which have in the annealed condition a minimum conductivity of 100% IACS.







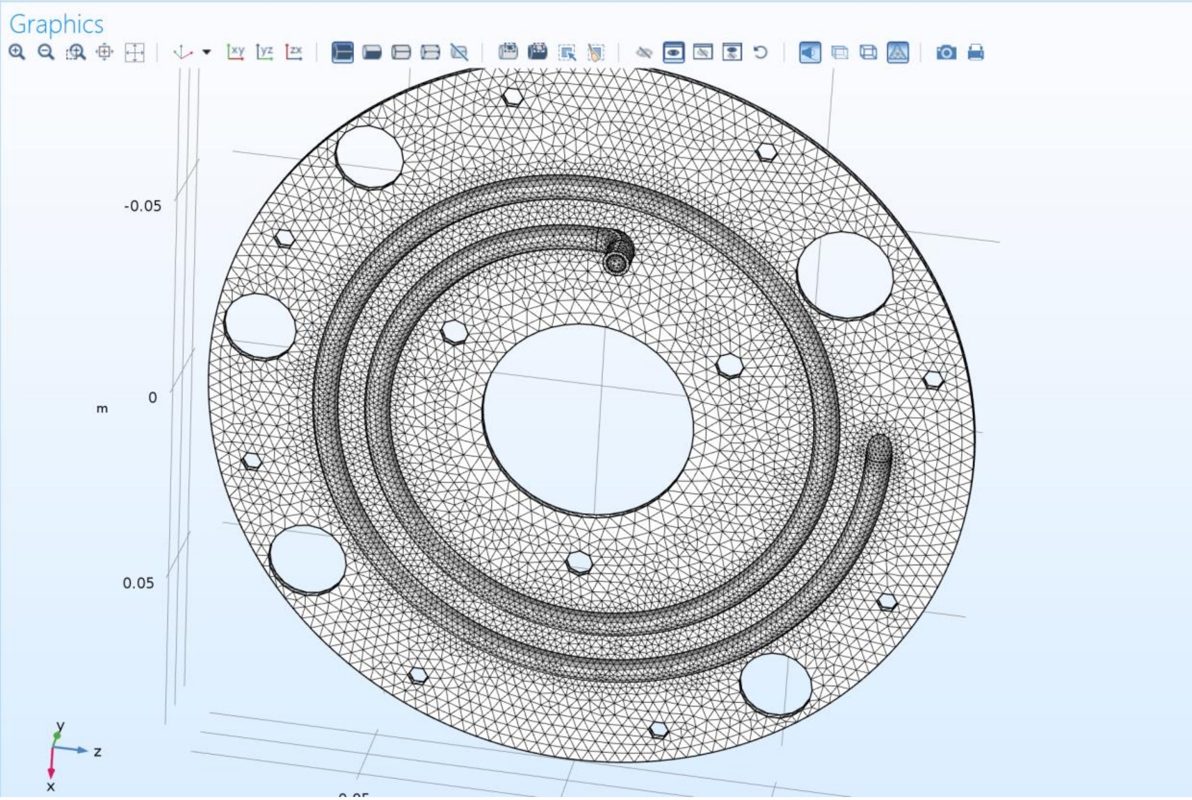
[1] Simon, N, J., Drexler , E, S., Reed, R, P., 1992. Properties of Copper and Copper Alloys at Cryogenic Temperatures. NIST Monograph 177.

Baffles & HE Modeling : Meshing

Mesh Domain

Mesh Statistics :

Mesh consists of 278.753 elements. Minimum quality: 0.1106; average quality: 0.6606.



Baffles & HE Modeling : EQS solver & BC

Fluid and Solid Domain (Helium Gas & Copper)

<u>Laminar Incompressible Flow Solver</u>

Inlet: 5 SLPM
Outlet = Open Boundary ;
Wall = no slip

<u>Heat Transfer fluid-solid Solver</u>

Inlet: T = 4.2 K
Outlet = Open Boundary ;
Thermal Insulation BC
Initial Conditios: Fluid@ T=5 K
Baffle @T = 77 K

Boundary Condition

Mass flow

Mass Flow

Mass flow type:

Standard flow rate

Standard flow rate defined by:

Standard pressure and temperature

Standard flow rate:

Q_{sv} 8.3e-5[m^3/s] m^3/s

Standard pressure:

P_{st} 1[atm] Pa

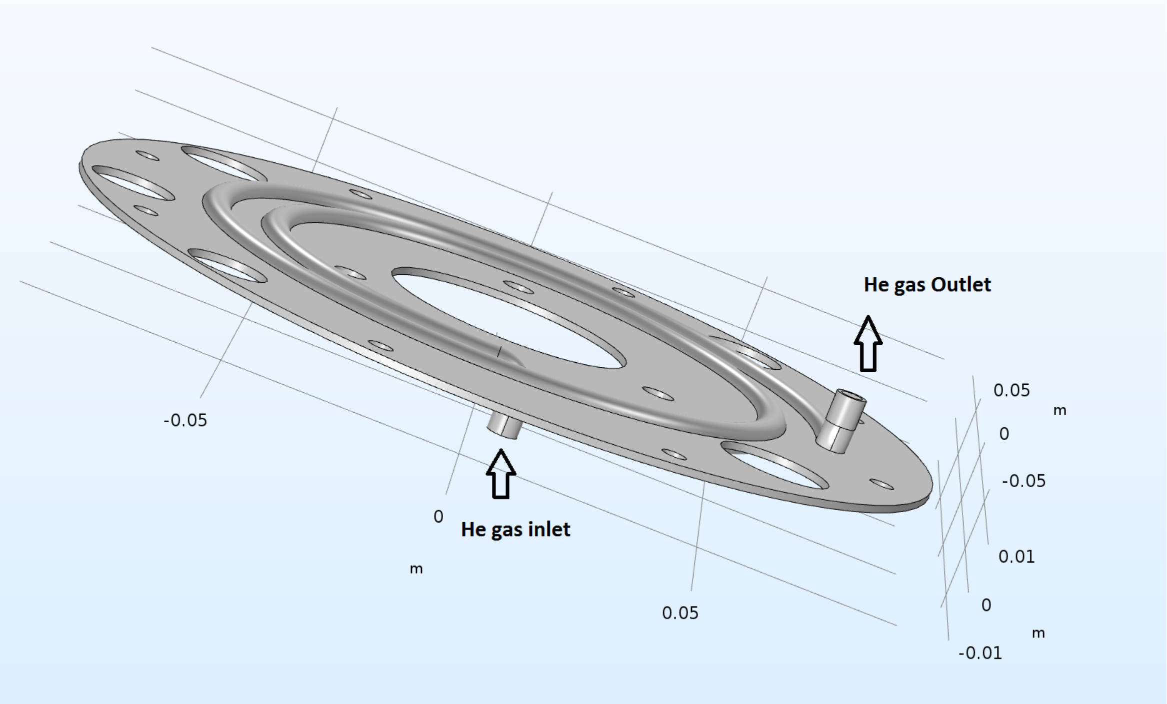
Standard temperature:

T_{st} 293.15[K] K

Mean molar mass:

M_n User defined

0.004[kg/mol] kg/mol



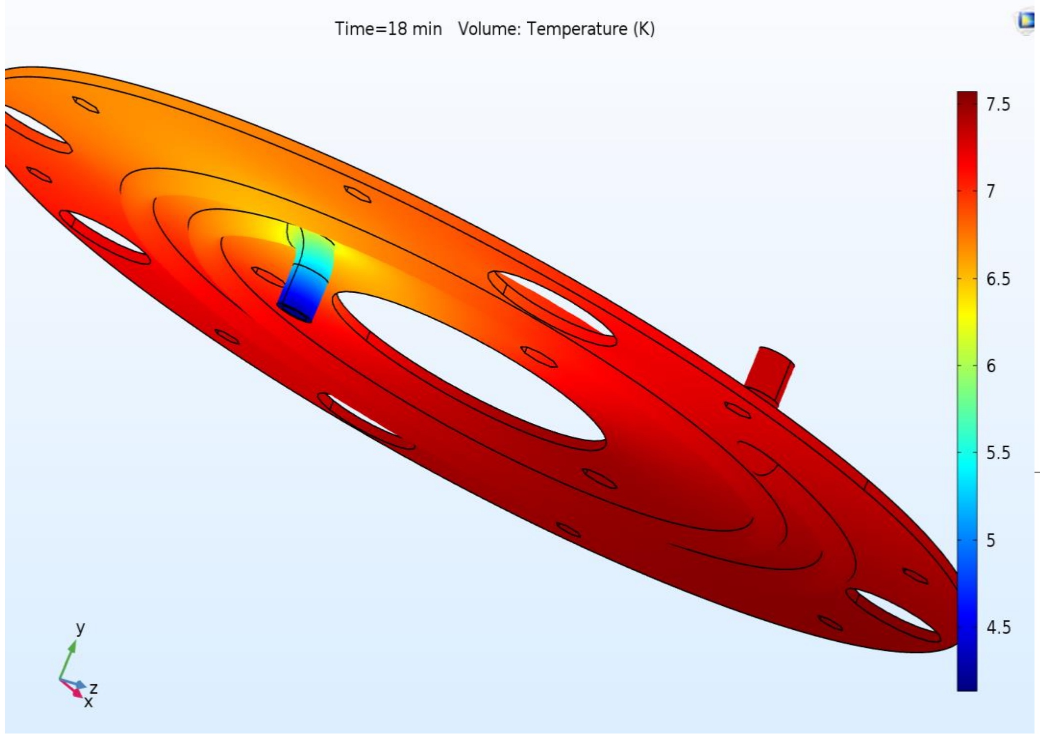
Linear System of 290.440 DOF

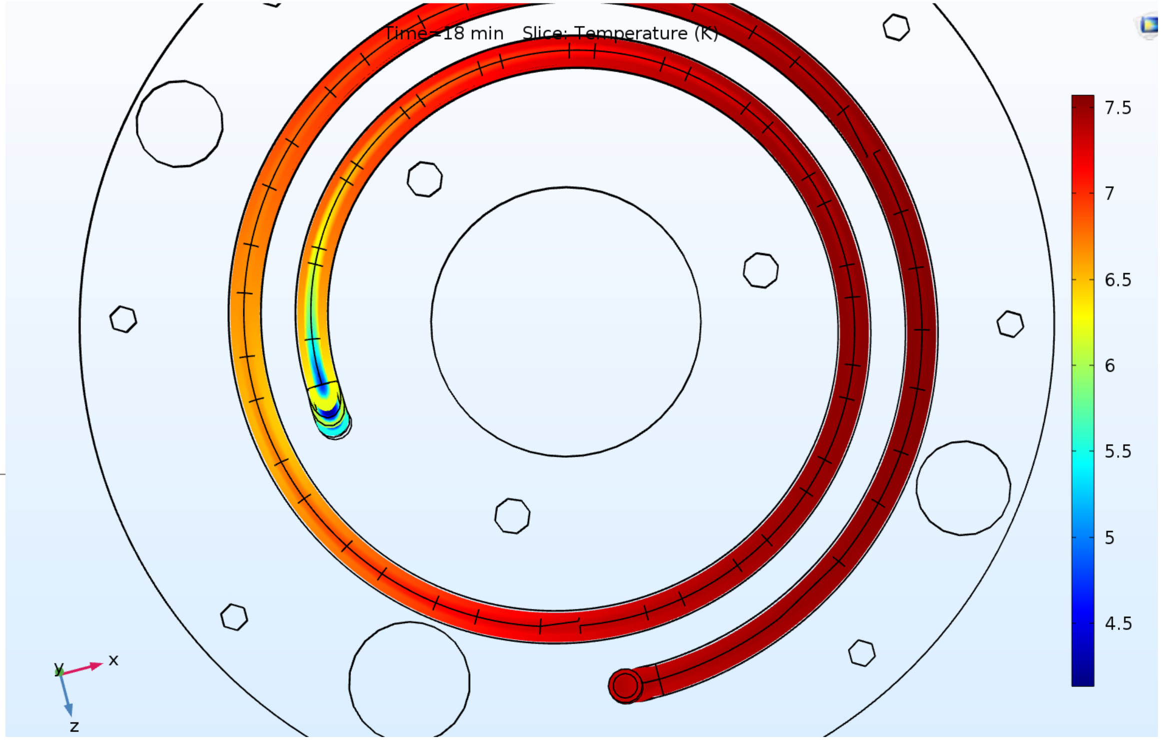
```
Time-dependent solver (BDF)
Number of degrees of freedom solved for: 290440 (plus 50445 internal DOFs).
```

Last computation time:
14 min 37 s

Baffles & HE Modeling : Results

Temperature

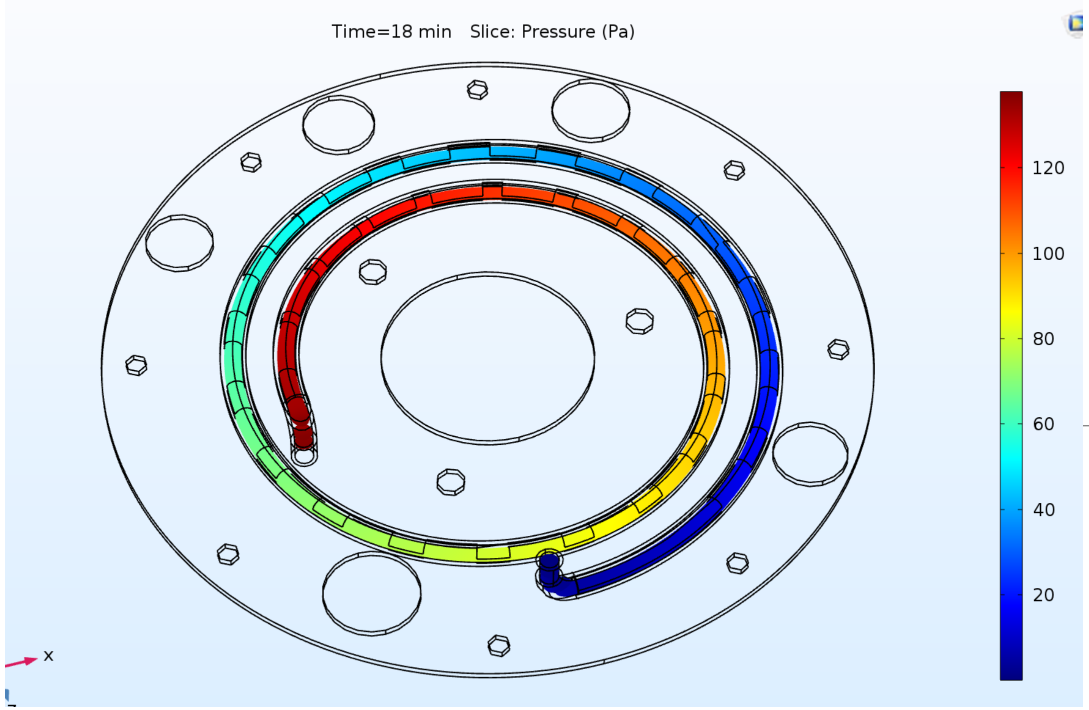


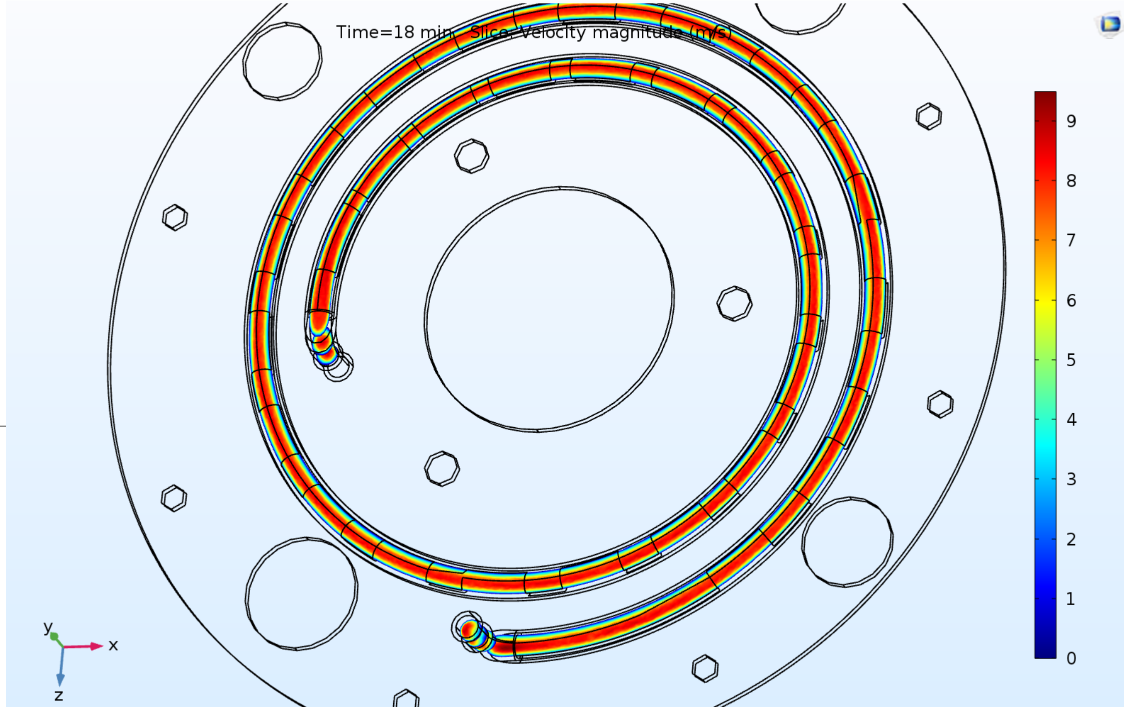


Baffles & HE Modeling : Results

Pressure

Velocity

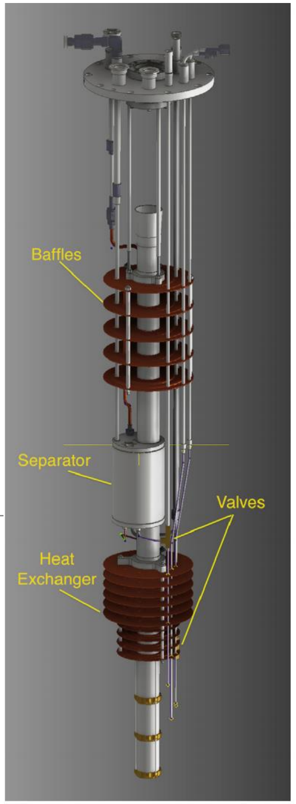




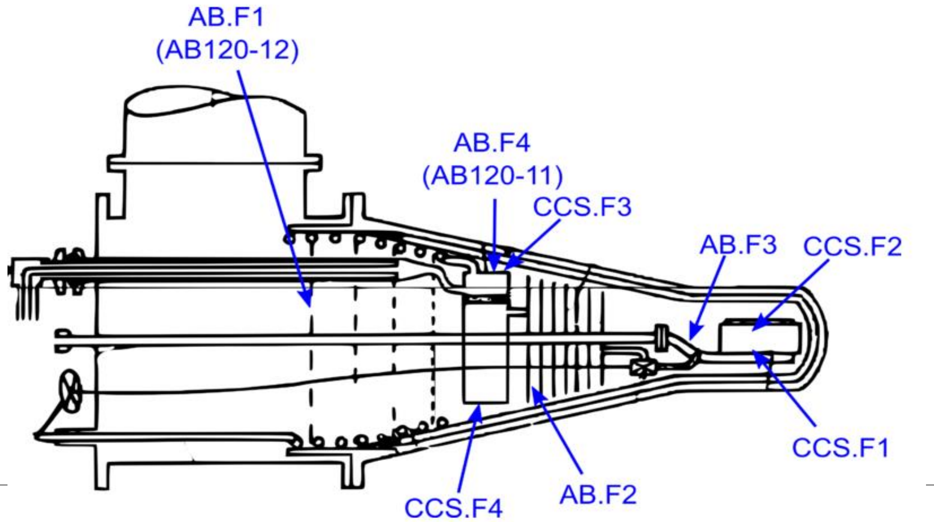
Baffles & HE Modeling: Fridge test

- First Evaporation Fridge Cool-Down

2015-09 Cool Down Analysis



[3] Fig. 3. The 1 K evaporation refrigerator.



[4]

[3] Pierce,j., Maxwell,J., Badman,T. et all . 2014. Dynamically polarized target for the g2p and GEp experiments at Jefferson Lab. Nuclear Instruments and Methods in Physics Research A738 54-60.

[4] UNH-NPG http://nuclear.unh.edu/wiki/index.php?title=2015-09_Cool_Down_Analysis

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Baffles & HE Modeling : Temperature Analysis

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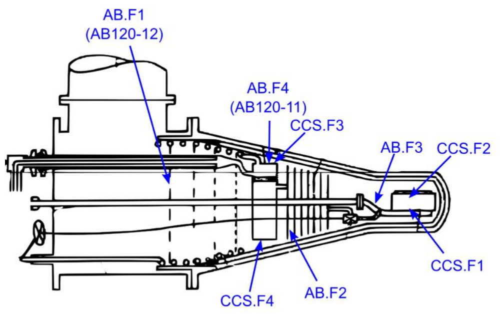
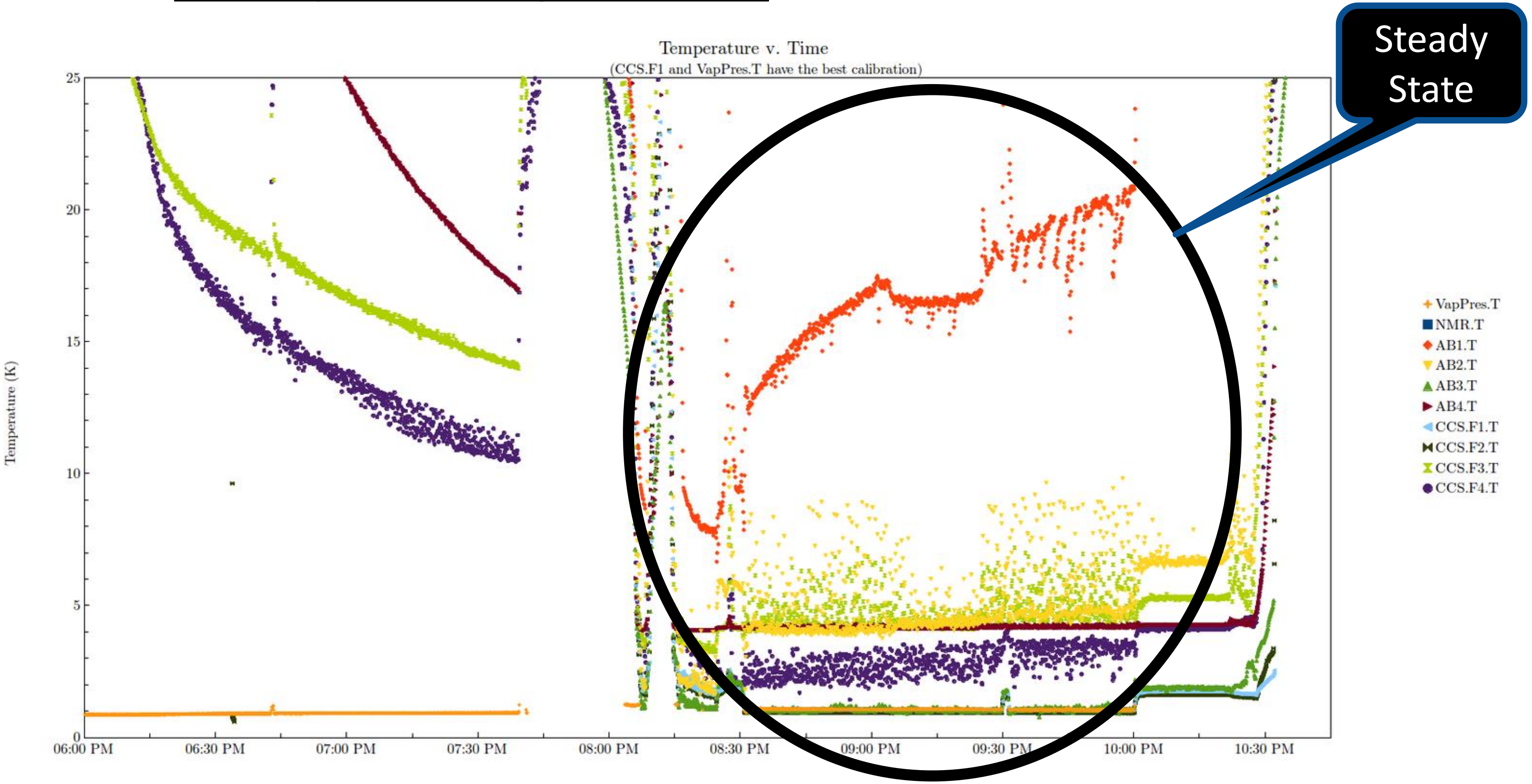
- First Evaporation Fridge Cool-Down



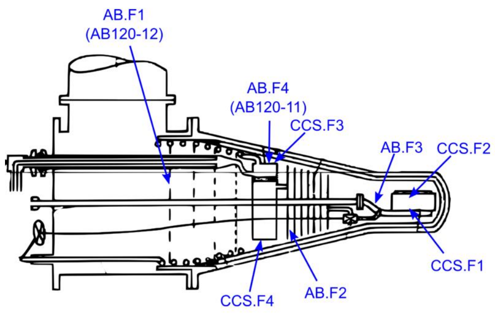
[4]

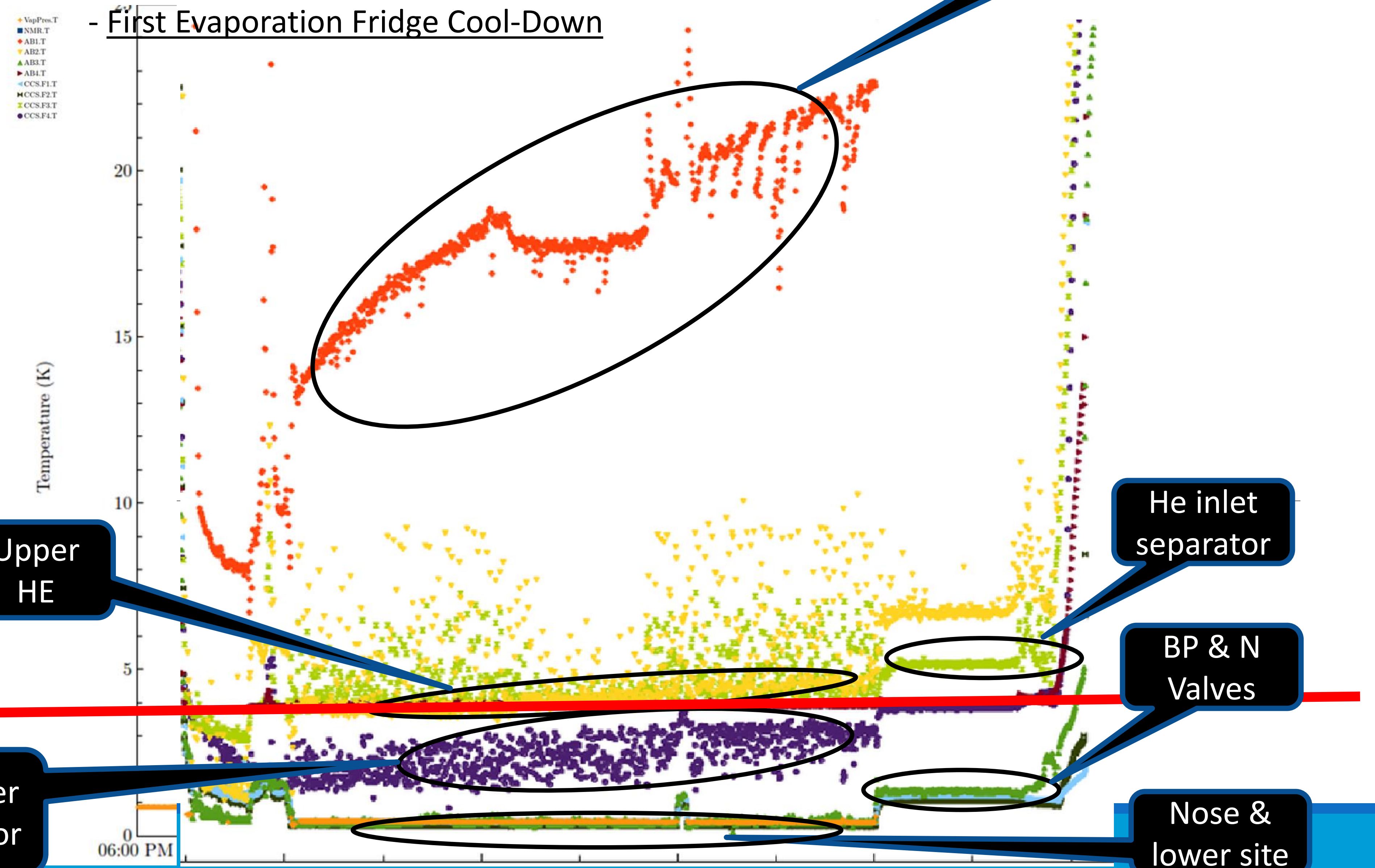


[4] UNH-NPG http://nuclear.unh.edu/wiki/index.php?title=2015-09_Cool_Down_Analysis

Baffles & HE Modeling : Operation Curve

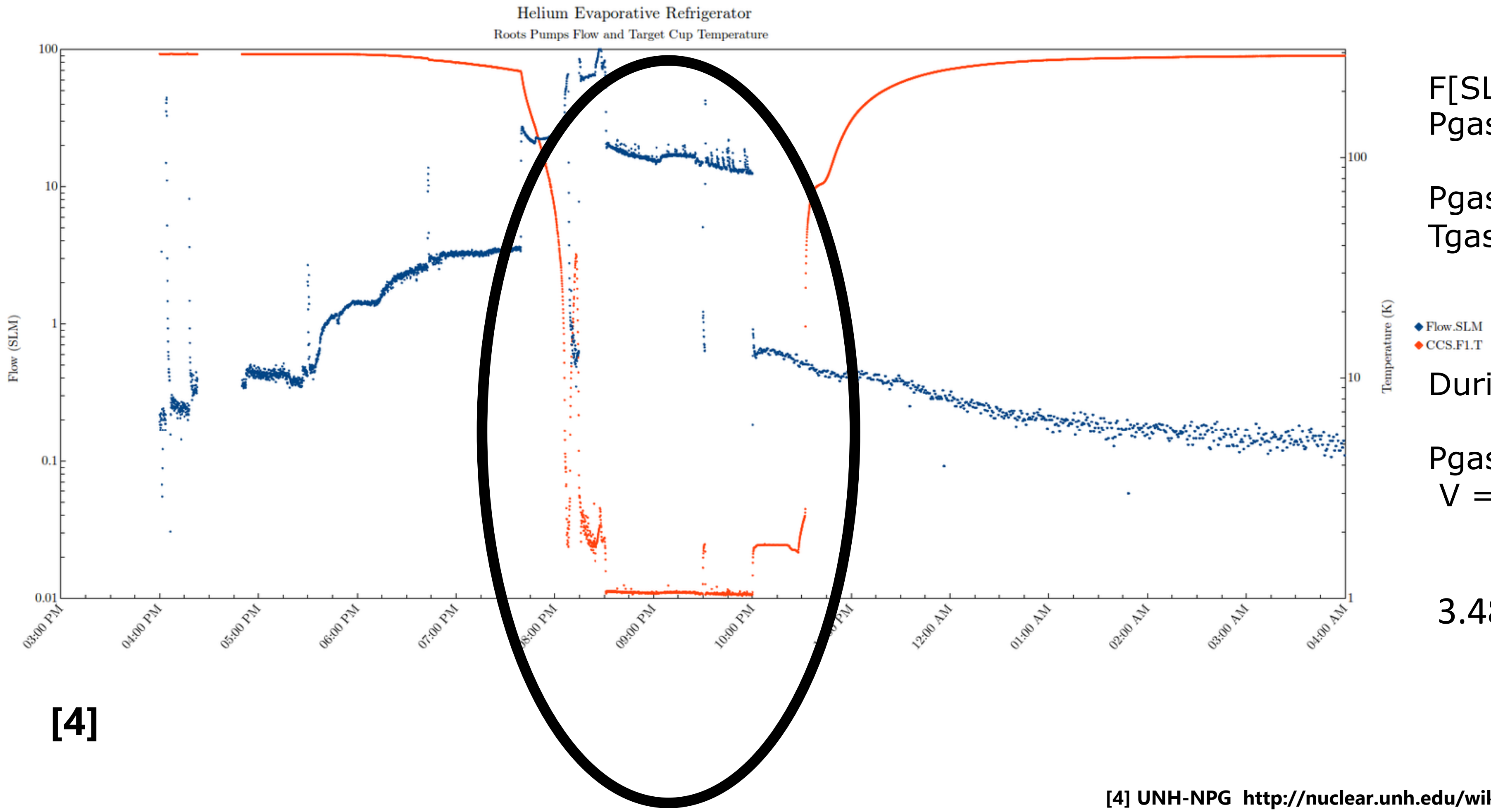
- First Evaporation Fridge Cool-Down





Baffles & HE Modeling: Pumped Helium

- First Evaporation Fridge Cool-Down



[4]

F[SLPM] = F[LPM] x (294.26 / Tgas) x (Pgas / 14.696)

Pgas – Absolute gas pressure in Psia
Tgas – Gas Temperature in K

During operation :

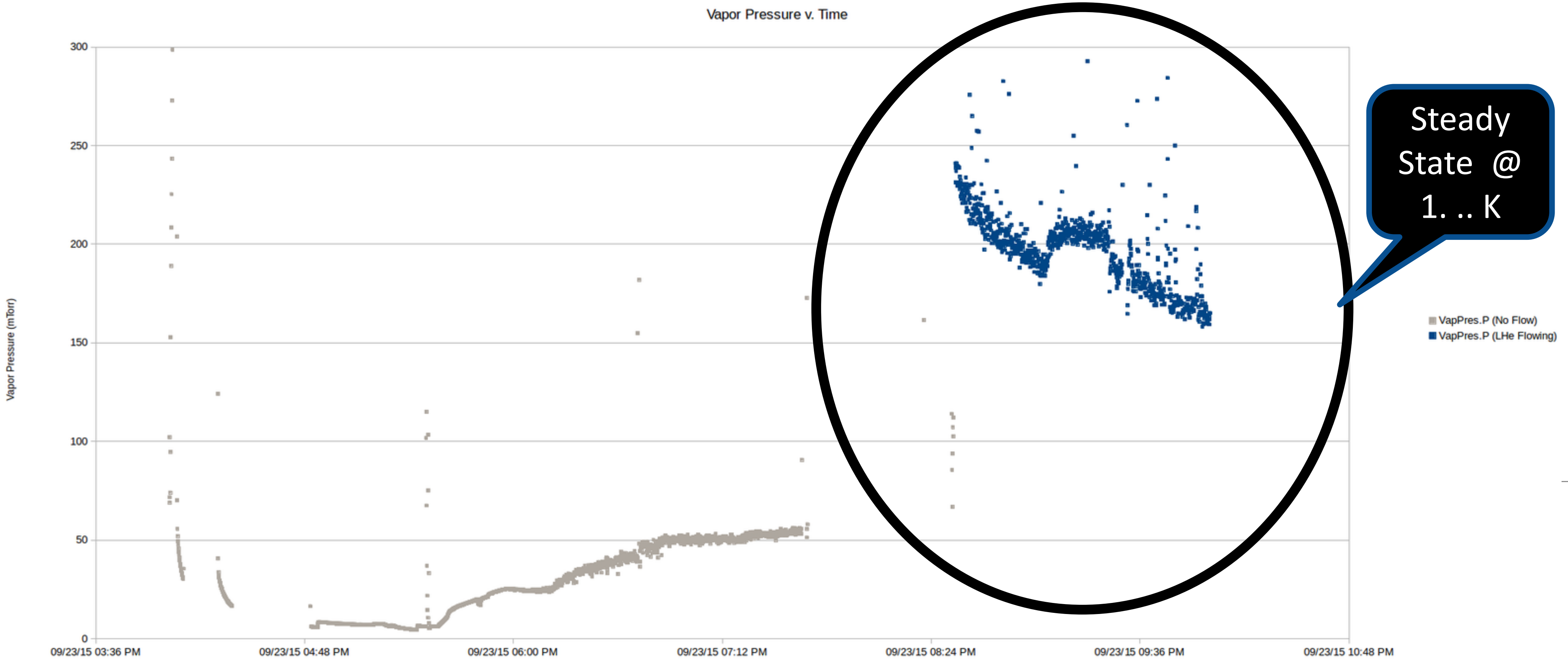
Pgas= 200 [mtorr] T gas room = 300 K.
V = 12 [SLPM]

3.487 [m3/hr] Root Pumping

[4] UNH-NPG http://nuclear.unh.edu/wiki/index.php?title=2015-09_Cool_Down_Analysis

Baffles & HE Modeling: Pumped Helium

- First Evaporation Fridge Cool-Down



[4]

[4] UNH-NPG http://nuclear.unh.edu/wiki/index.php?title=2015-09_Cool_Down_Analysis

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Baffles & HE Modeling: Pumped Helium

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- First Evaporation Fridge Cool-Down

- Pumping liquid helium @ 1 K,

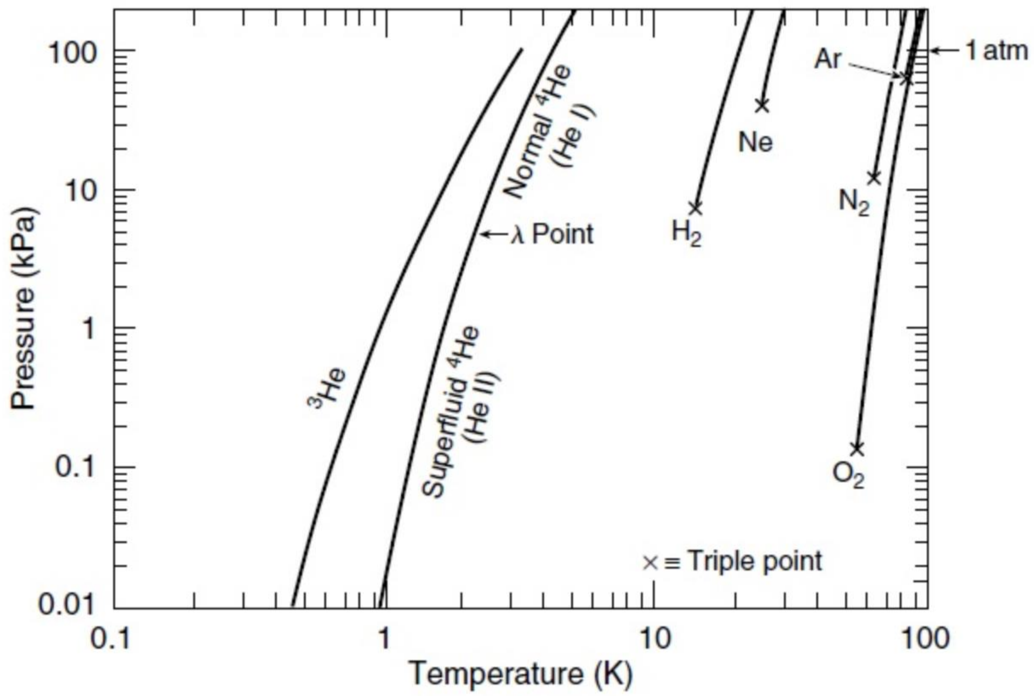
VP = 160 [ubar]
= 0.016 [kPas]
= 1.2 E-1 [Torr] = 120 [mTorr]

- Choose Pumping speed (depends on heat load of system (0.1 -3 W)

$H_{\text{evap He @ 1K}}$ = 80 - 92 [J/mol]

- Pump speed= Heat load / H_{evap}

[mol/s] or [m3/hr] --→ by ideal gas law



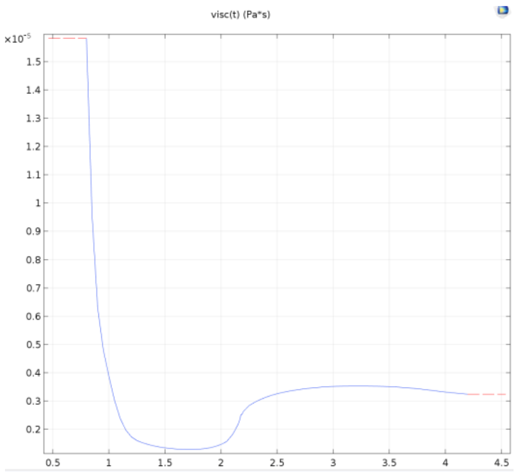
[5]

Heat Load Pumped		
pump speed	3487	m3/hr
pump speed	0,97	m3/s
pump speed	968,61	lt/s
R	8,31	Ctant
T	295,00	K
P	26,66	Pa
pump speed	968,61	lt/s
pump speed	0,01	mol/s
heat load	**1,23**	**W**
H helium	83	J/mol
for [4.2K- 1.4K]		

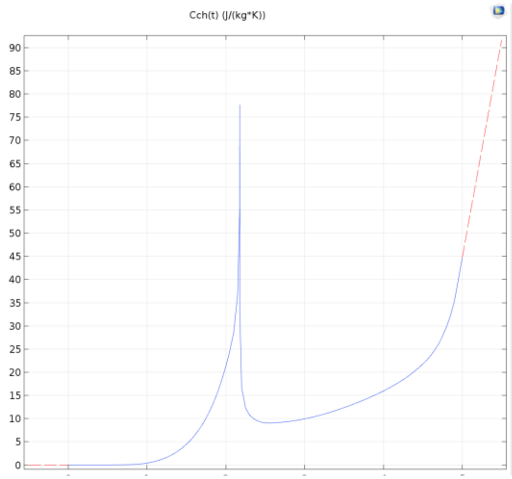
[5] Ekin, J, W.2006. Experimental Techniques for Low- Temperature Measurements, Cryostat Designs, Material Properties, and Superconductor Critical- Current Testing. Oxford University Press. p, 673.

Baffles & HE Modeling : Liquid Helium Properties

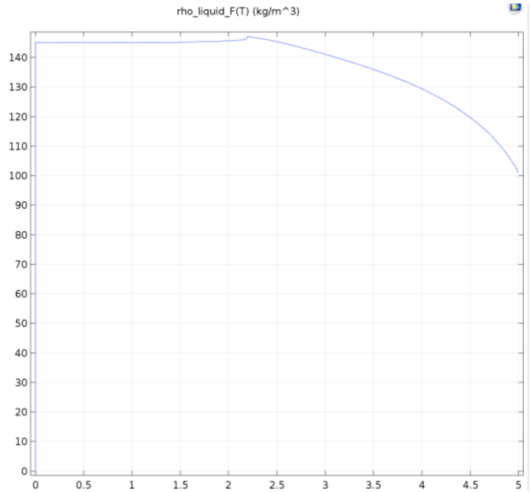
Dinamic Viscosity



Heat Capacity



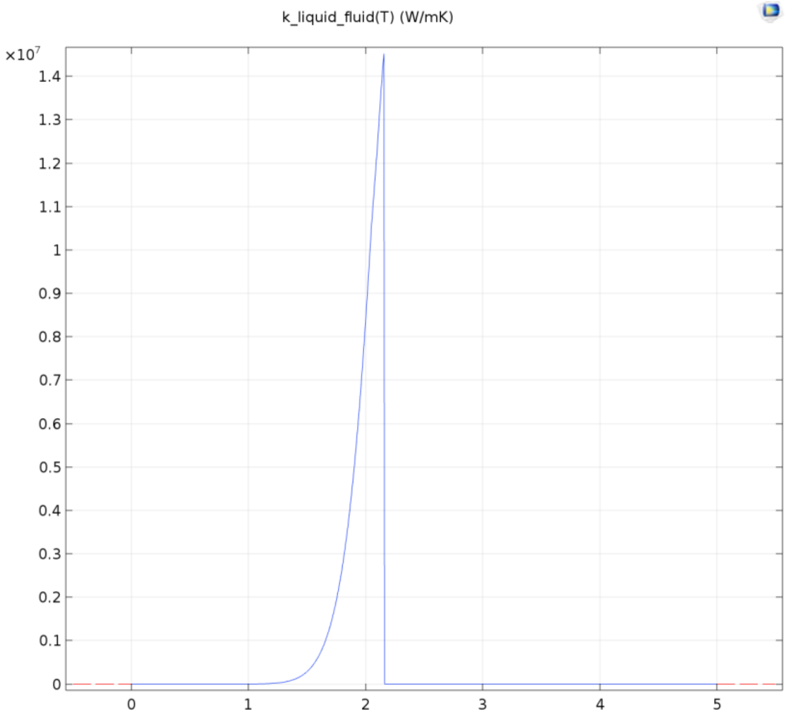
Density



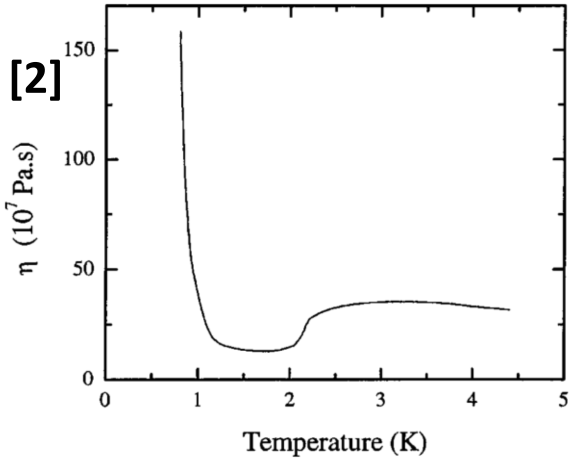
Thermal Conductivity

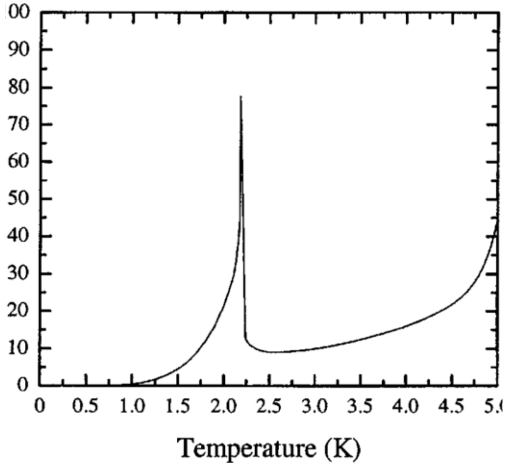
$$K_{eff} = \frac{\dot{Q}}{\pi R^2}\frac{l}{\Delta T} = \frac{R^2}{8\beta^2 T^3 \eta} = \frac{R^2 \rho^2 T S^2}{8\eta}.$$

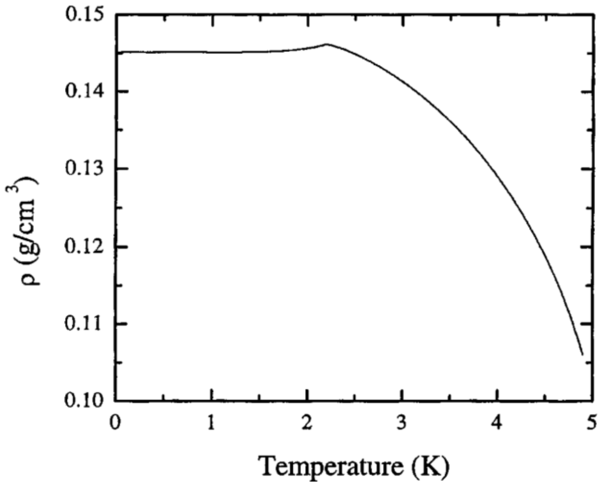
Laminar situation: Landau regime



[2]





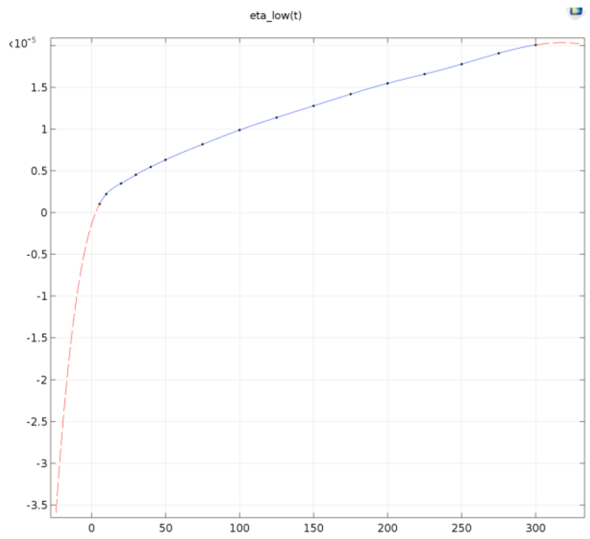


[2] Russell J. Donnelly and Carlo F. Barenghi. 1998.The Observed Properties of Liquid Helium at the Saturated Vapor Pressure ,Journal of Physical and Chemical Reference Data 27, 1217 (1998)

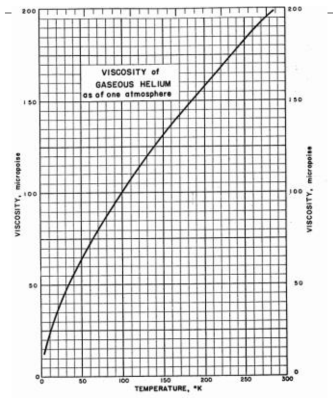
[3] Sciacca,M. Jou, D. Mongiovi, M. S. 2013. Effective thermal conductivity of helium II: from Landau to Gotter- Mellink regimes. Cornell University Library.

Baffles & HE Modeling : Gas Helium Properties

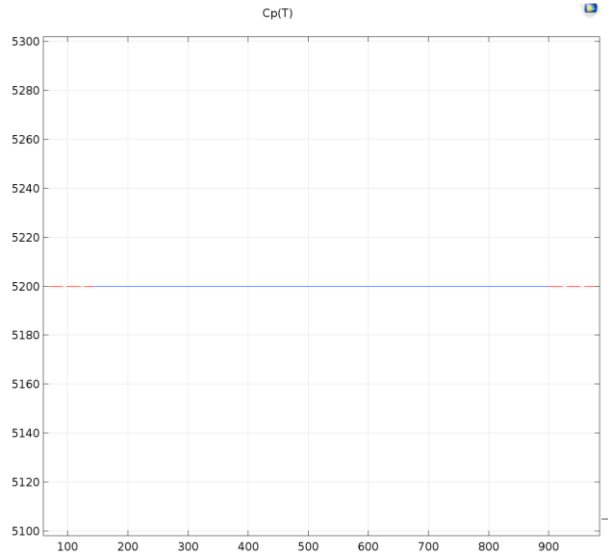
Dinamic Viscosity



[4]

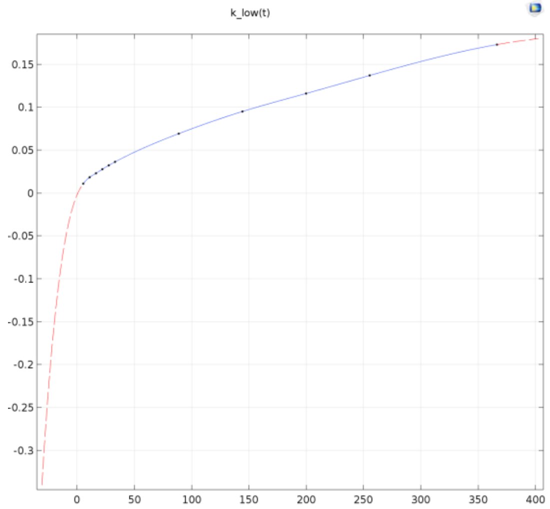


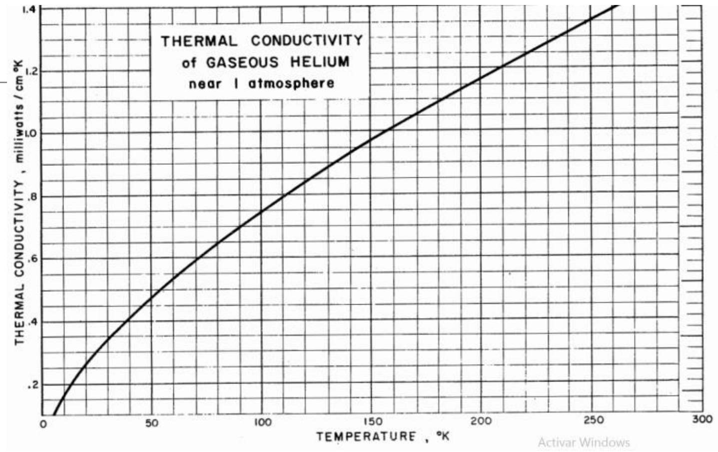
Constant Heat Capacity



* With Ideal Gas :Density

Thermal Conductivity

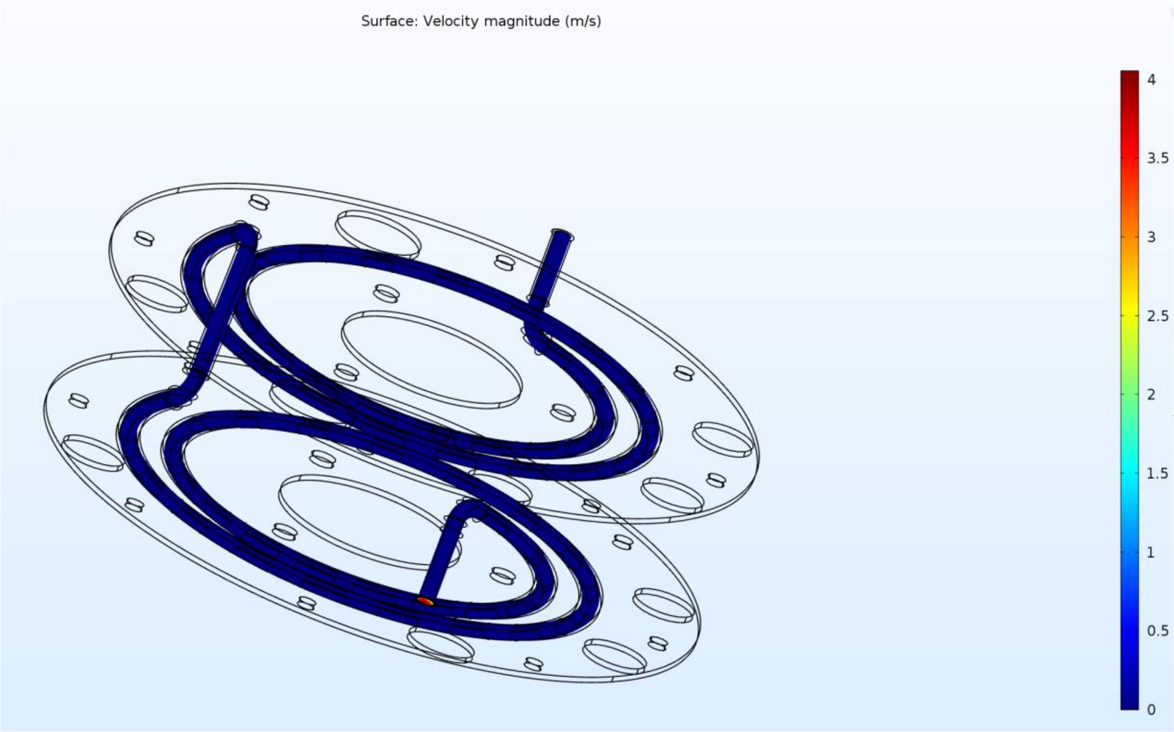


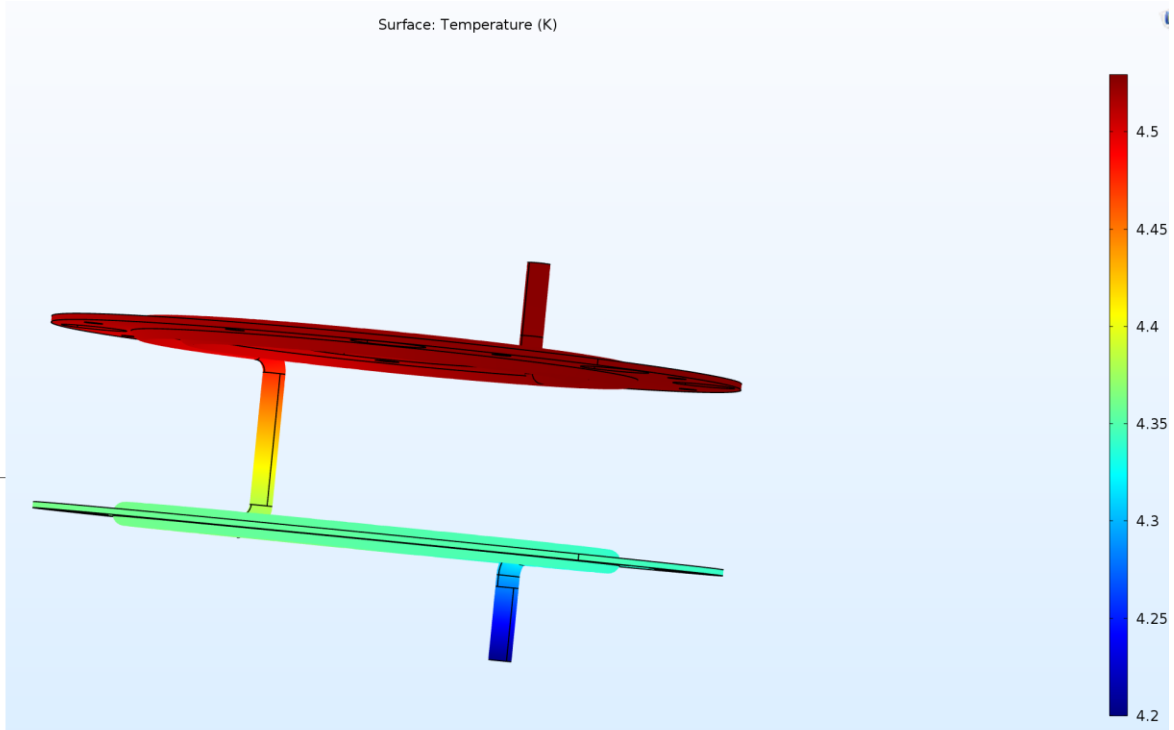


[4] J.E. Jensen, W.A. Tuttle, R.B. Stewart, H. Brechna and A.G. Prodell. 1980. Brookhaven National Laboratory Selected Cryogenic Data Notebook. Vol 1 Sec I- IX.

Baffles & HE Modeling: Pumped Helium

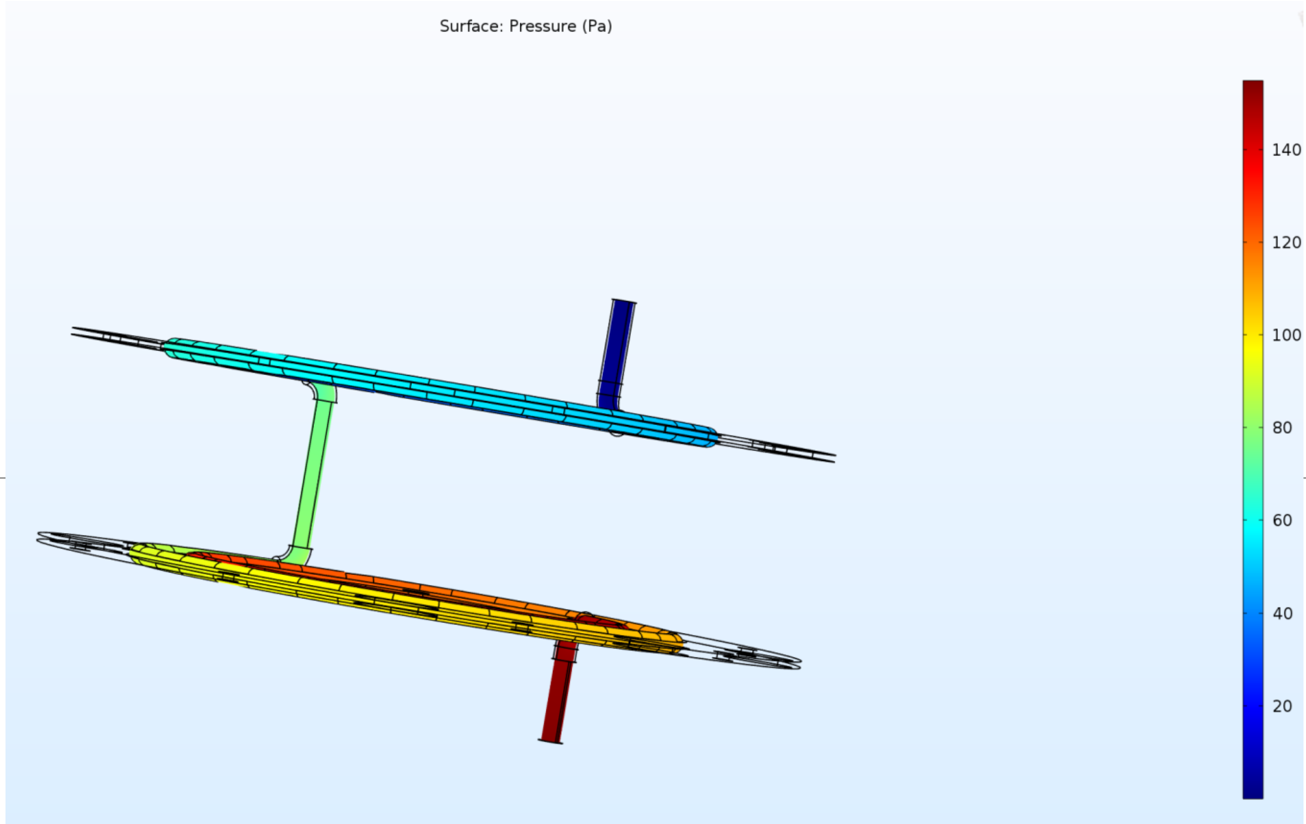
0.1 W overall (16 SLPM) T in=4.2 K





Baffles & HE Modeling: Pumped Helium

- First Evaporation Fridge Cool-Down



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Baffles & HE Modeling: Mesh Improvement

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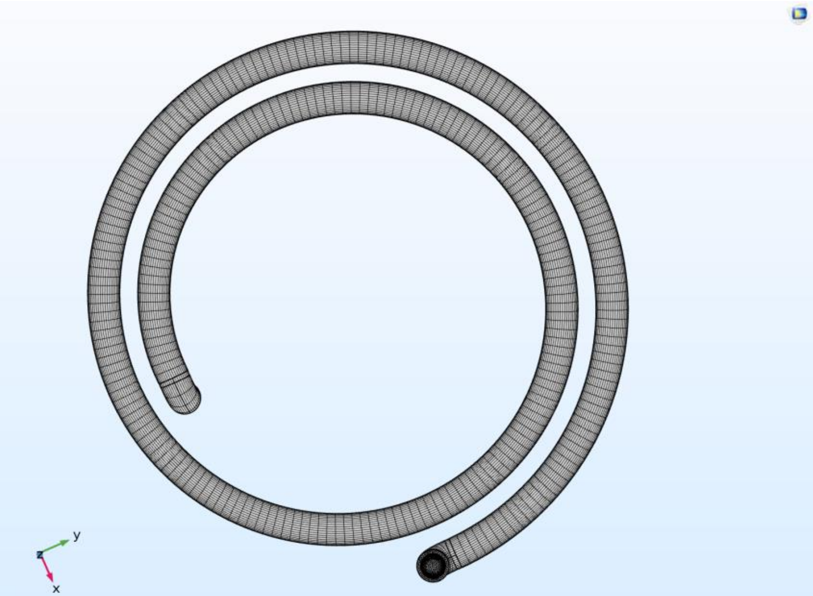
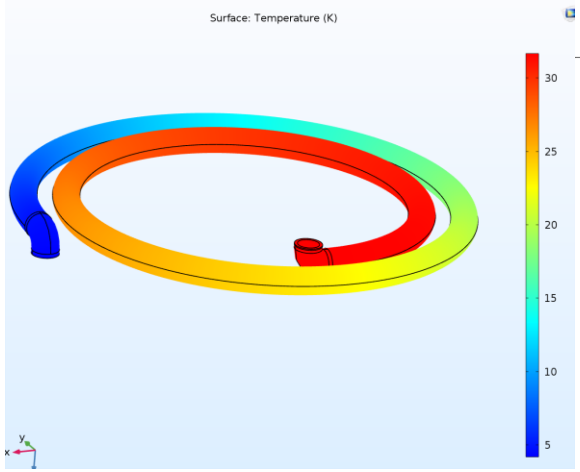
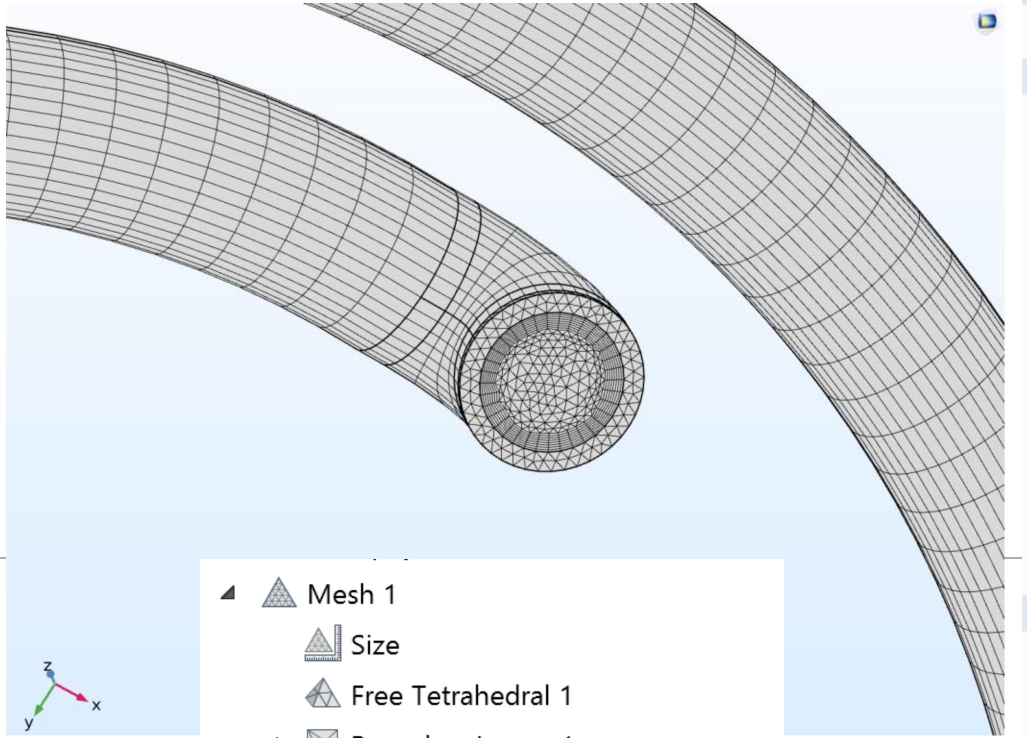






- Mesh 1
  - Size
  - Free Tetrahedral 1
  - Boundary Layers 1
    - Boundary Layer Properties
  - Distribution 1
  - Swept 1

Element Quality

Quality measure: Skewness

Statistics

Complete mesh

Mesh vertices: 156167

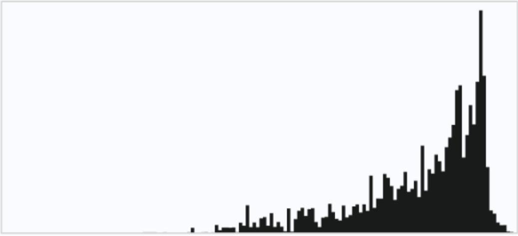
Element type: All elements

Tetrahedral elements:	1317
Prism elements:	132054
Hexahedral elements:	82416
Triangular elements:	1445
Quadrilateral elements:	24458
Edge elements:	1919
Vertex elements:	61

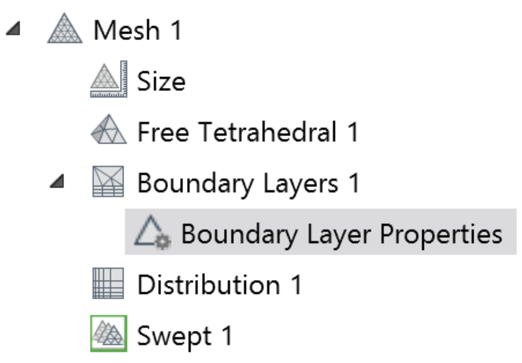
Domain element statistics

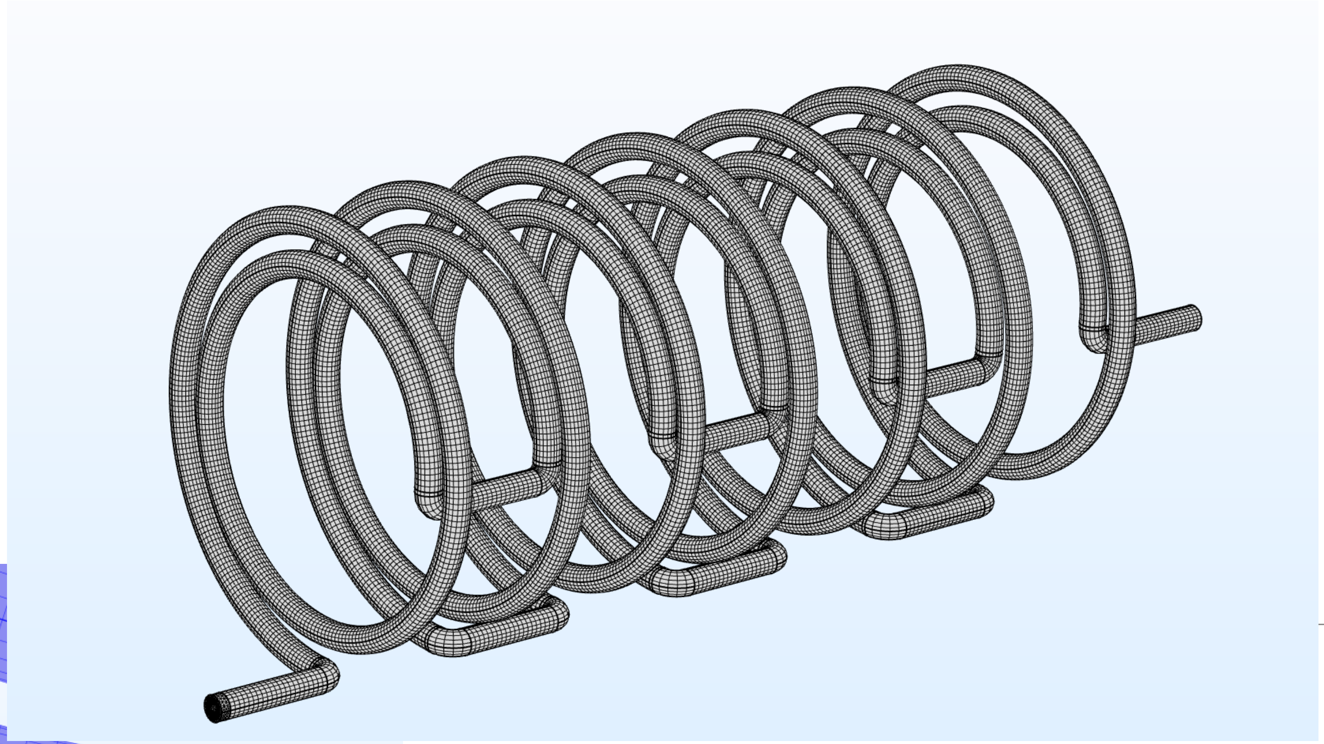
Number of elements:	215787
Minimum element quality:	0.2239
Average element quality:	0.8124
Element volume ratio:	0.005385
Mesh volume:	34480.0 mm^3

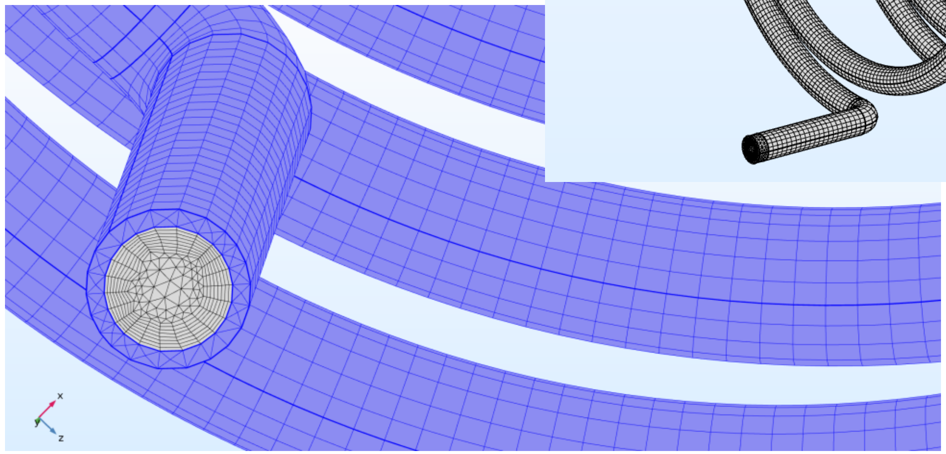
Element Quality Histogram

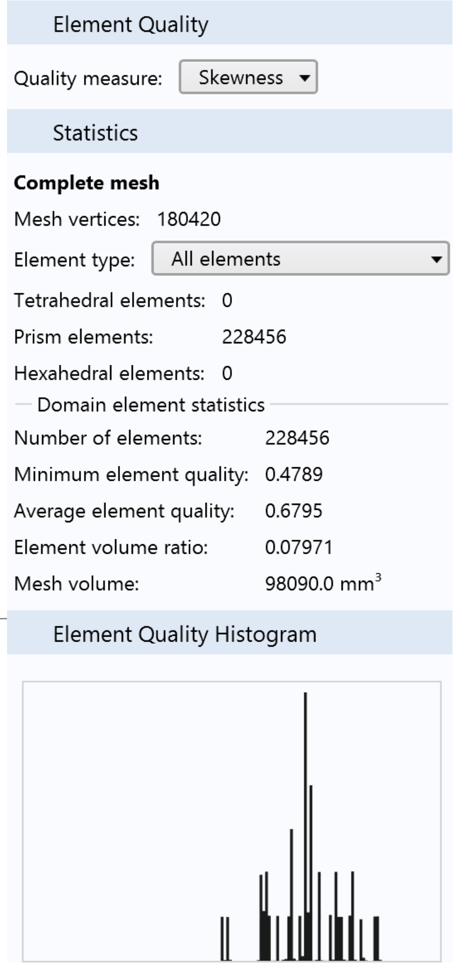


Baffles & HE Modeling: Mesh Improvement



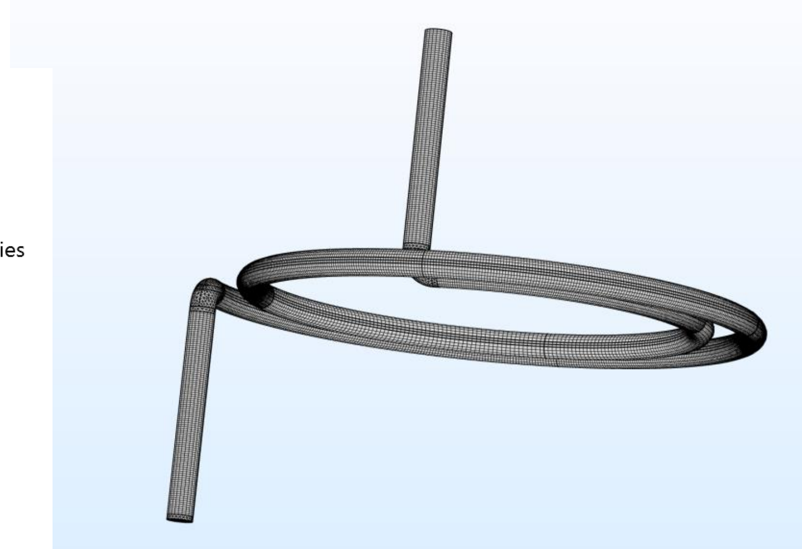


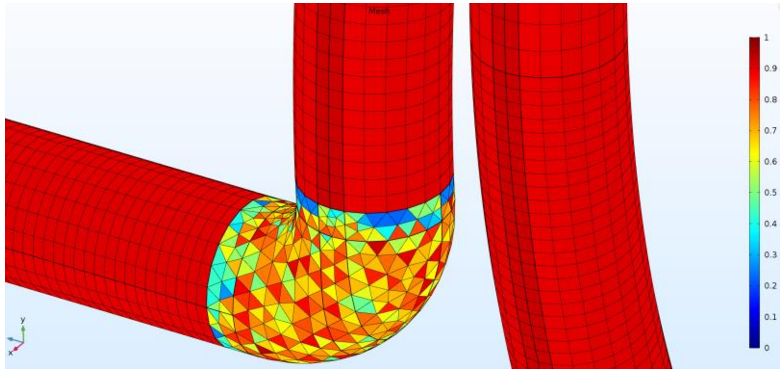


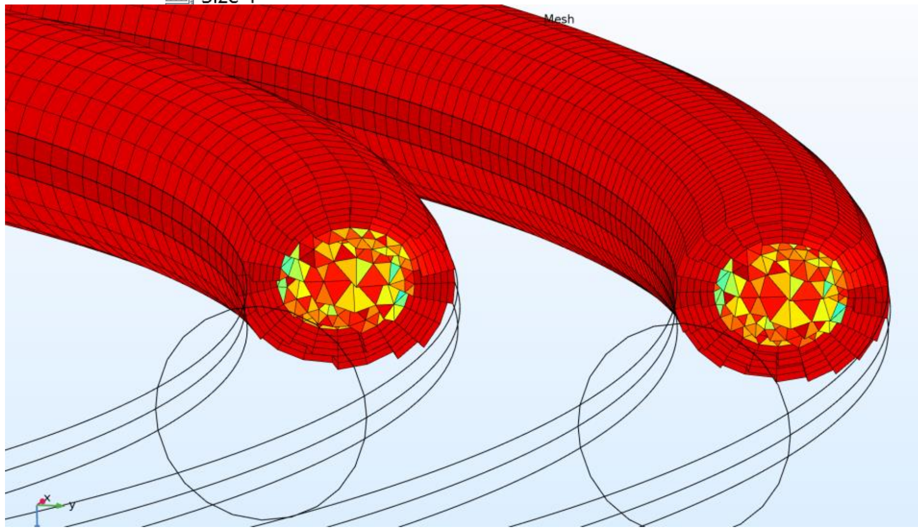


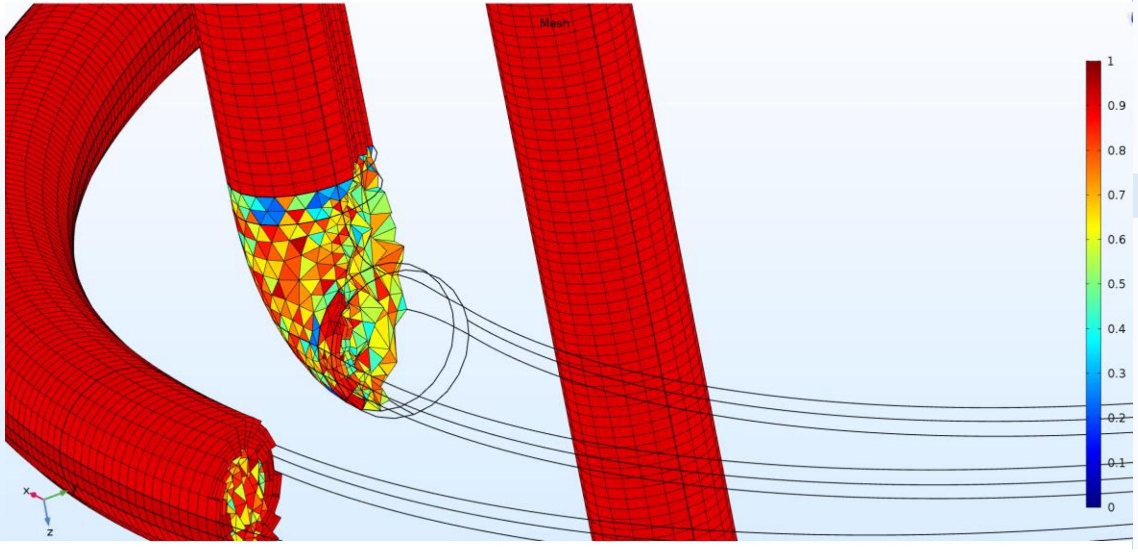
Baffles & HE Modeling: Mesh Improvement

- Mesh 1
  - Size
  - Free Tetrahedral 1
  - Boundary Layers 1
    - Boundary Layer Properties
  - Swept 3
    - Distribution 1
  - Distribution 1
  - Swept 1
  - Copy Face 1
  - Swept 2
  - Free Tetrahedral 3
    - Size 1









Statistics

Partial mesh

Mesh vertices:	230741
Element type:	All elements
Tetrahedral elements:	12043
Pyramid elements:	552
Prism elements:	115636
Hexahedral elements:	156000
Triangular elements:	3044
Quadrilateral elements:	27812
Edge elements:	6354
Vertex elements:	84

Domain element statistics

Number of elements:	284231
Minimum element quality:	0.1334
Average element quality:	0.8248
Element volume ratio:	0.001346
Mesh volume:	24060.0 mm^3

Element Quality Histogram

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Baffles & HE Modeling: Mesh Improvement

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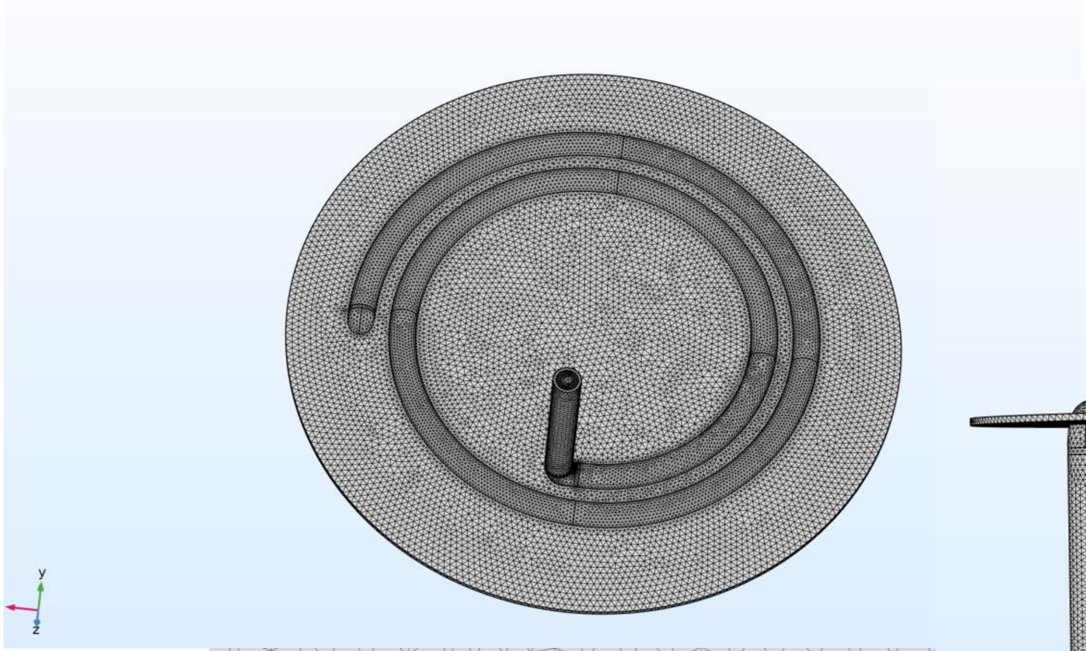
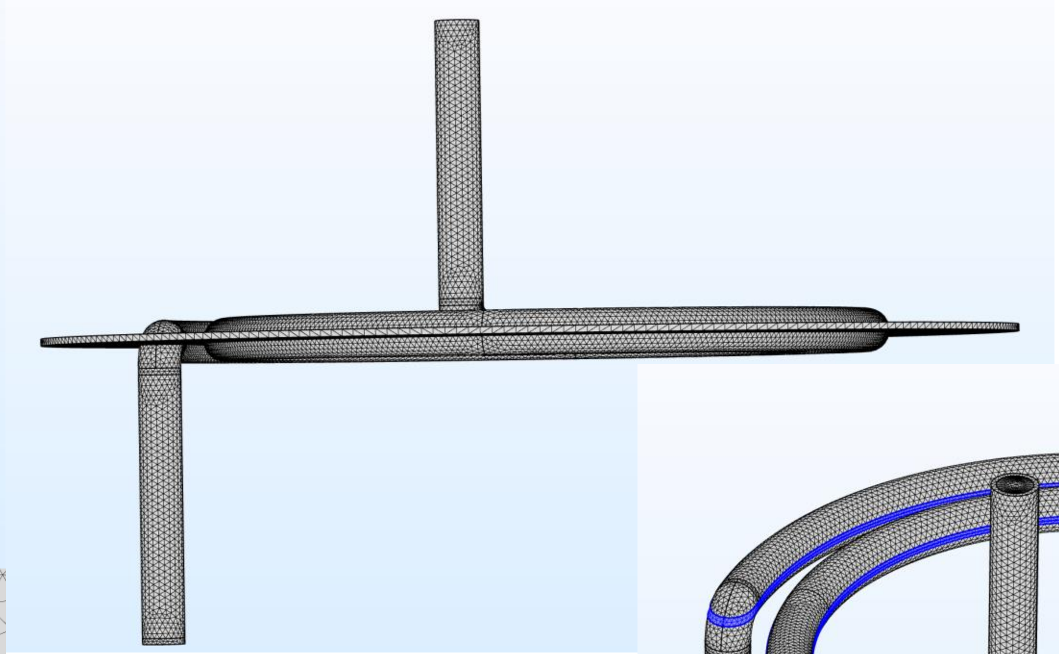
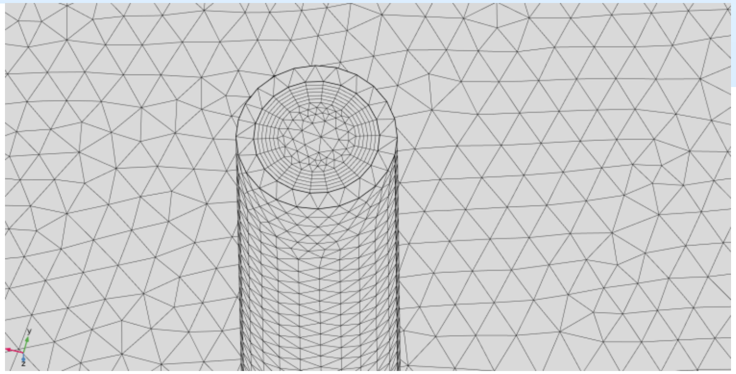
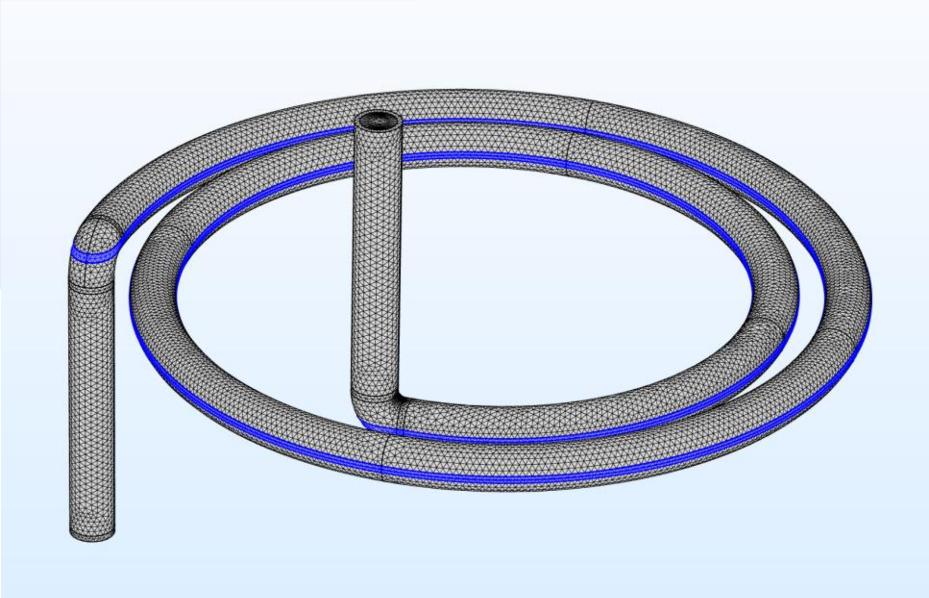






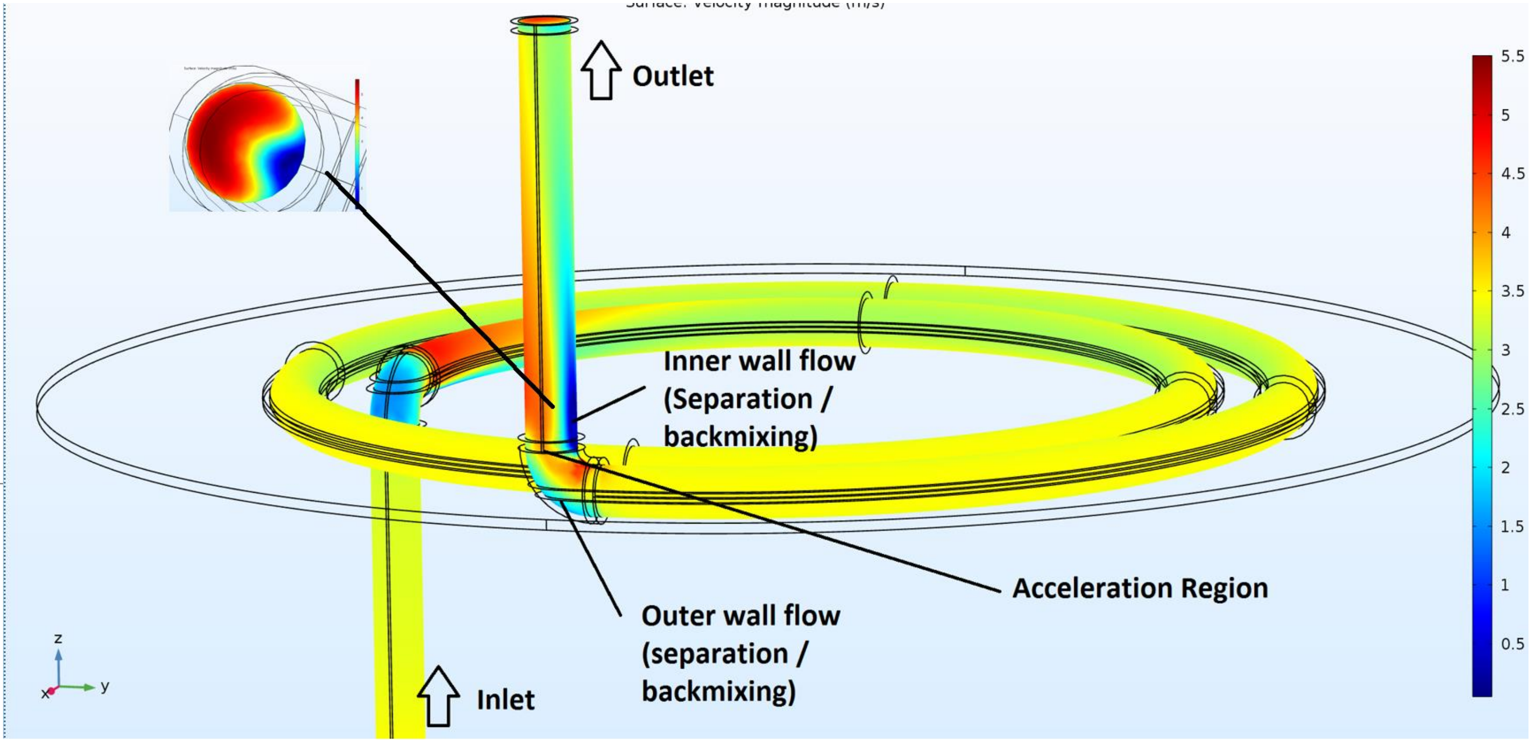


Baffles & HE Modeling: Incompressible NS with K-epsilon Turbulence model

Navier Stokes Equations with K-e turbulent eddy viscosity model

$$\rho(\mathbf{u}\cdot\nabla)\mathbf{u} =$$
$$\nabla\cdot\left[-p\mathbf{I} + (\mu+\mu_T)\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right)\right] + \mathbf{F}$$
$$\rho\nabla\cdot(\mathbf{u}) = 0$$
$$\rho(\mathbf{u}\cdot\nabla)k = \nabla\cdot\left[\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla k\right] + P_k - \rho\epsilon$$
$$\rho(\mathbf{u}\cdot\nabla)\epsilon = \nabla\cdot\left[\left(\mu + \frac{\mu_T}{\sigma_\epsilon}\right)\nabla\epsilon\right] + C_{\epsilon 1}\frac{\epsilon}{k}P_k - C_{\epsilon 2}\rho\frac{\epsilon^2}{k}, \quad \epsilon = \mathrm{ep}$$

$$\mu_T = \rho C_\mu \frac{k^2}{\epsilon}$$
$$P_k = \mu_T\left[\nabla\mathbf{u} : \left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right)\right]$$



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Baffles & HE Modeling: Heat trasfer

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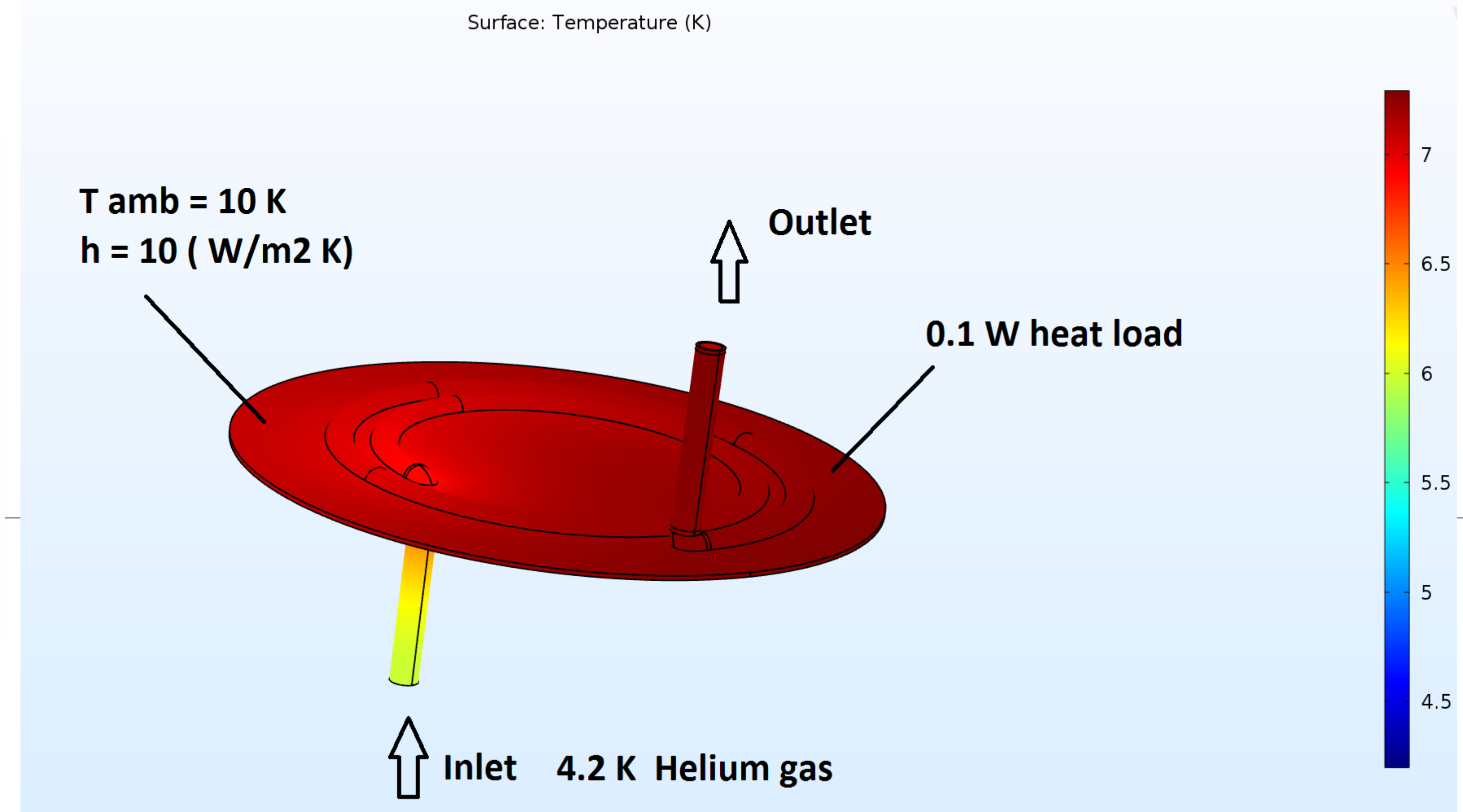
Convective heat flux

$$q_0 = h \cdot (T_{ext} - T)$$

Table 1. Approximate values of heat transfer coefficient

Conditions of heat transfer	W/(m²K)
Gases in free convection	5–37
Water in free convection	100–1200
Oil under free convection	50–350
Gas flow in tubes and between tubes	10–350
Water flowing in tubes	500–1200
Oil flowing in tubes	300–1700
Molten metals flowing in tubes	2000–45000
Water nucleate boiling	2000–45000
Water film boiling	100–300
Film-type condensation of water vapor	4000–17000
Dropsize condensation of water vapor	30000–140000
Condensation of organic liquids	500–2300



Baffles & HE Modeling: Measurement Points

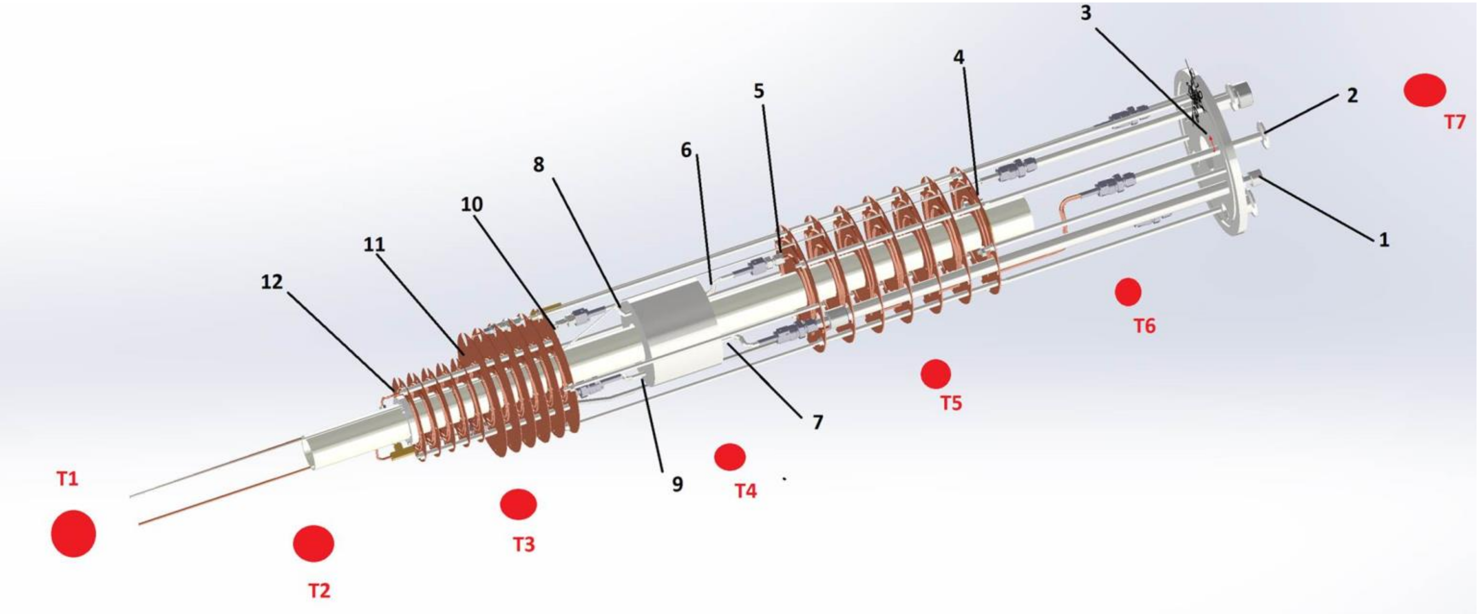
Rank of priority:

*** Very necessary
** Necessary
* Not that all (could be supposed)

Point Description:

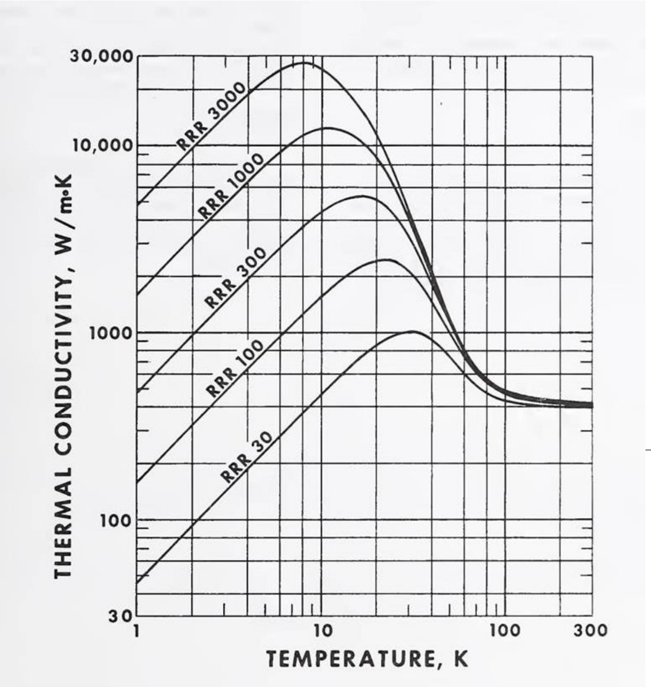
1) Helium inlet (mixture) : *** Mass flow (LPM), ***Temperature.
2) Helium outlet (gas): ***Vacuum pressure, ***Speed Pump(LPM), ***Temperature.
3) **Flange top Inner wall Temperature
4) ***Baffle outer wall temperature
5) ***Baffle lower wall temperature
6) Separator gas outlet : *Temperature
7) Separator Mixture inlet: *Temperature
8) Separator Liquid Bypass Outlet: **Temperature.
9) Separator Liquid Outlet: ***Temperature, ***mass flow.
10) ***HE outer wall temperature.
11) ***HE lower wall temperature
12) ***HE low low temperature wall.

Temperature Zones (red points) : ** Locally Wall or Vapor bed Temperature measurements



Baffles & HE Modeling: Free Oxigen Copper

RRR



Properties of copper change a lot depending on its purity, and also if it is immersed in to a magnetic field.
The purity of free oxygen copper is measured by the value RRR, which means Residual Resistivity Ratio. This quantity is calculated as the ratio of electrical resistivity at 273K to the resistivity at 4 K. The RRR gives a measure of purity
And the extent of physical defects such as lattice imperfections due to cold-working also electrical resistivity is function of the chemical and physical imperfection of the material.

Vacuum Viscous Flow Modeling

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[Main free path Helium]

Mean Free Path Calculator

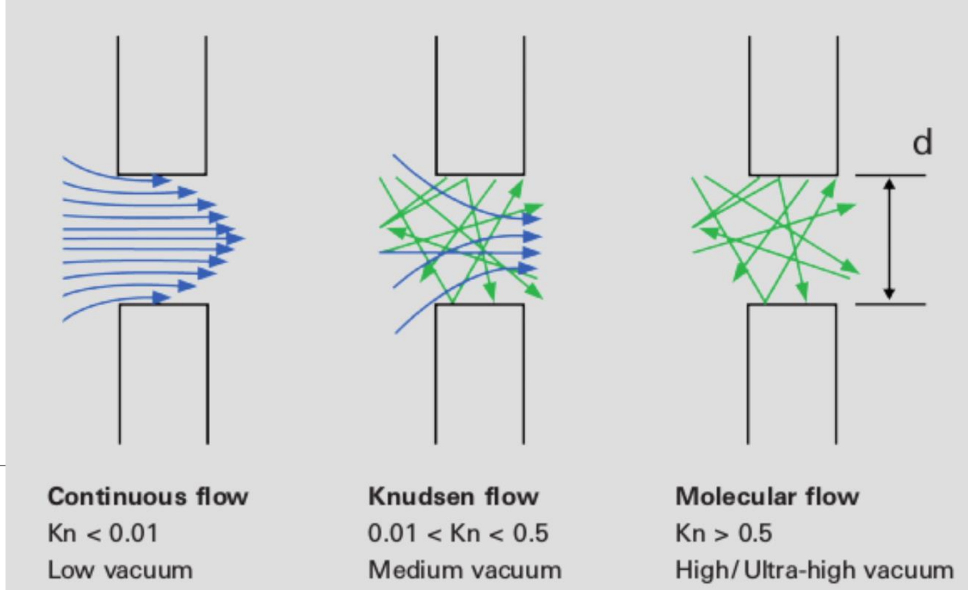
radius of molecule, r = 130 pm (It is assumed that all particles are spherical !!!)

diameter of molecule, d = 0,260 nm

Temperature, T = 4,2 K

Pressure, P = 0,03 Kpa

mean free path, λ = 6,44E-06 m 6437,39 nm



$$\ell = \frac{k_B T}{\sqrt{2}\pi d^2 p},$$

$$Kn = \frac{\bar{l}}{d}$$

For 6 [mm] channel **Kn = 0,001073**

Continuous Flow

Vacuum Viscous Flow Modeling

Laminar Compressible Flow CFD Modeling

2D Axisymmetric Domain

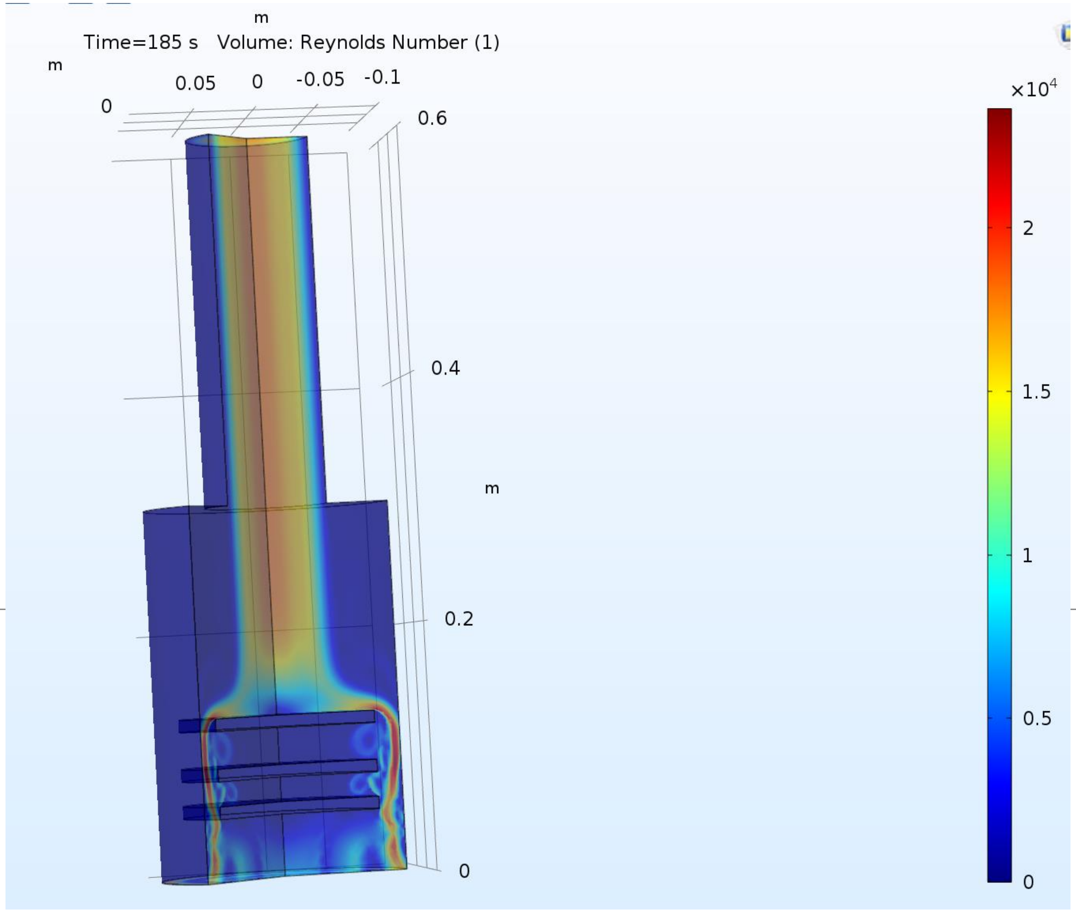
Fluid: Air
BC in = Mass Flow Inlet [6 m3/s]
BC outlet = Mass Flow Inlet [6 m3/s]
Initial Pressure field = 300 [Pa] (2.25 [Torr])

For pipe Flow:

For $Re < 2000$ the flow is laminar
For $4000 > Re > 2000$ the flow is transient
For $Re > 4000$ the flow is turbulent

$$Re = \frac{\rho V L}{\mu} = \frac{VL}{v}$$

$$Re = \frac{F_{inertia}}{F_{viscous}} = \frac{\frac{kg}{m^3} \times \frac{m}{s} \times m}{Pa \times s} = \frac{F}{F}$$



Vacuum Viscous Flow Modeling

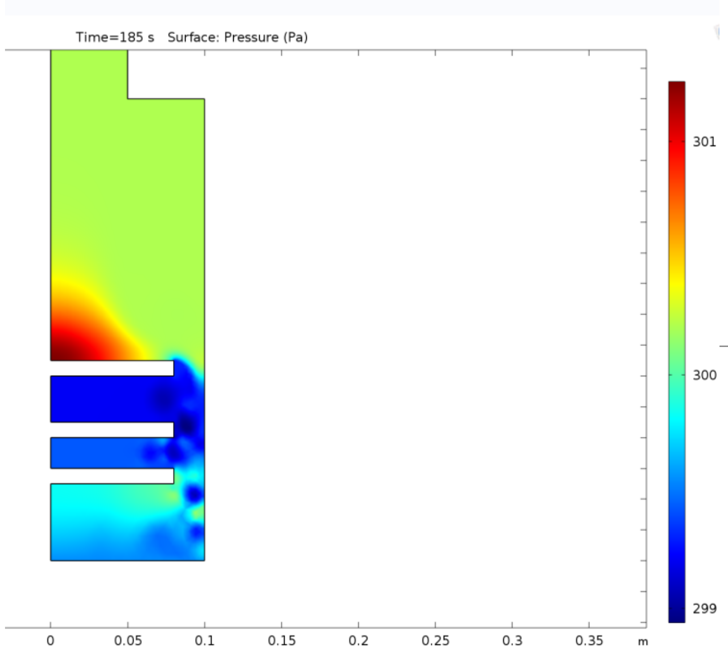
Compressible Flow

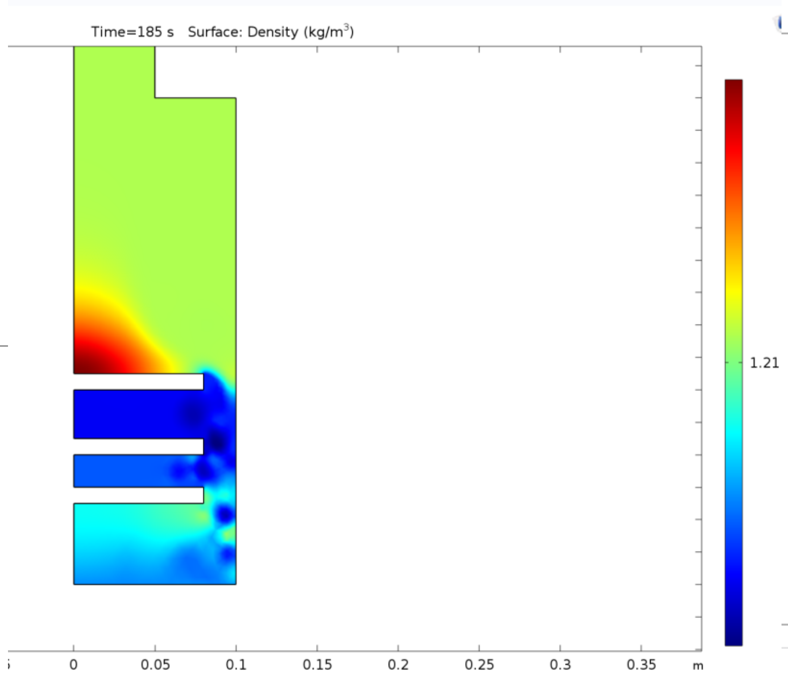
Pressure

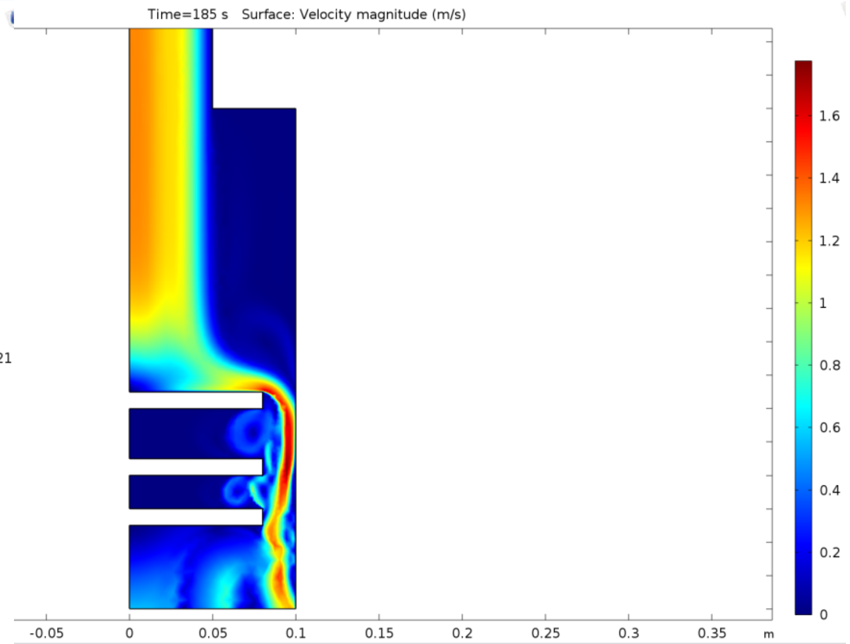
Pressure Drop: 2.32 [Pa]
(17[mTorr])

Density

Velocity



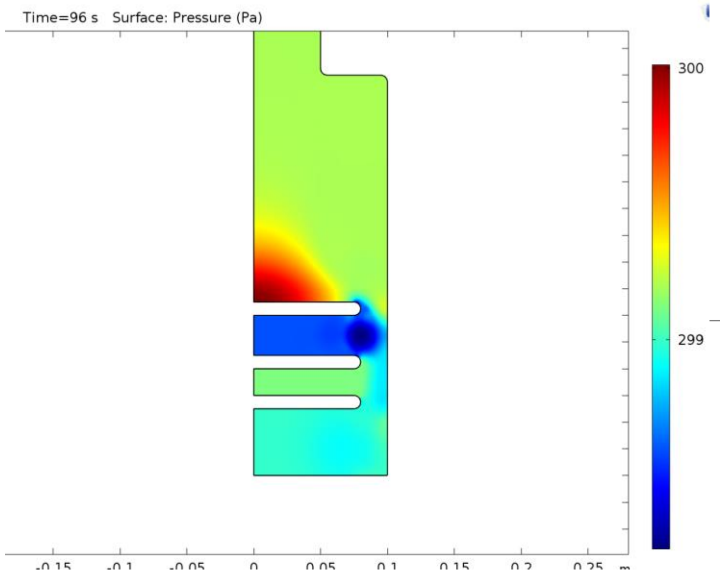




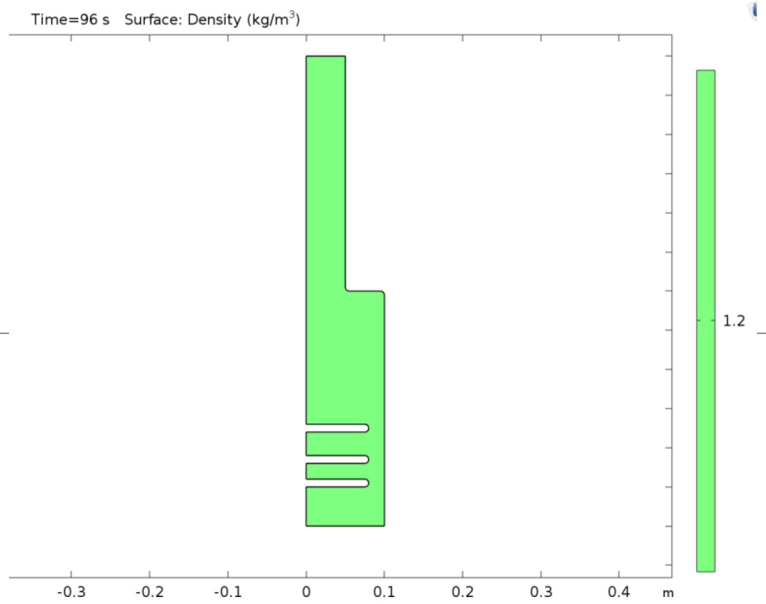
Vacuum Viscous Flow Modeling

Incompresible Flow (Change of P outlet BC=299 Pa)

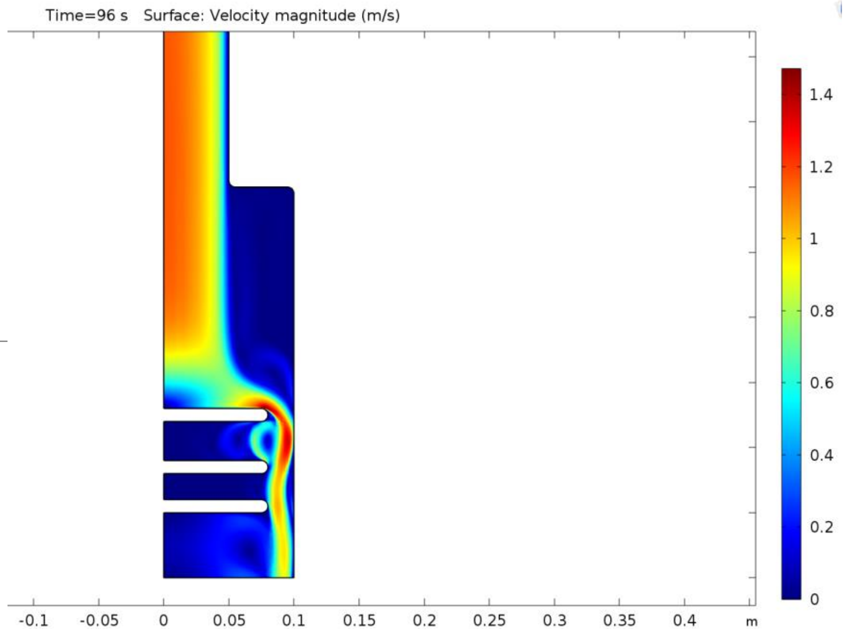
Pressure



Density



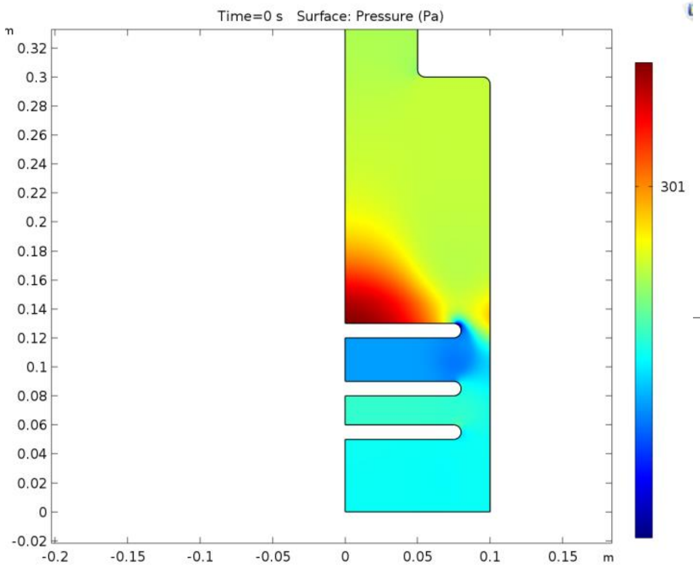
Velocity



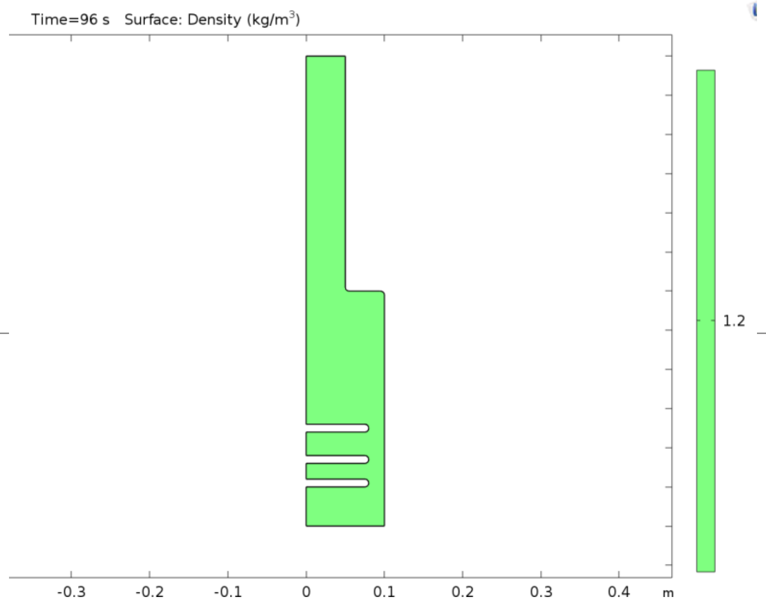
Vacuum Viscous Flow Modeling

Stationary K-e Turbulent Compressible Flow

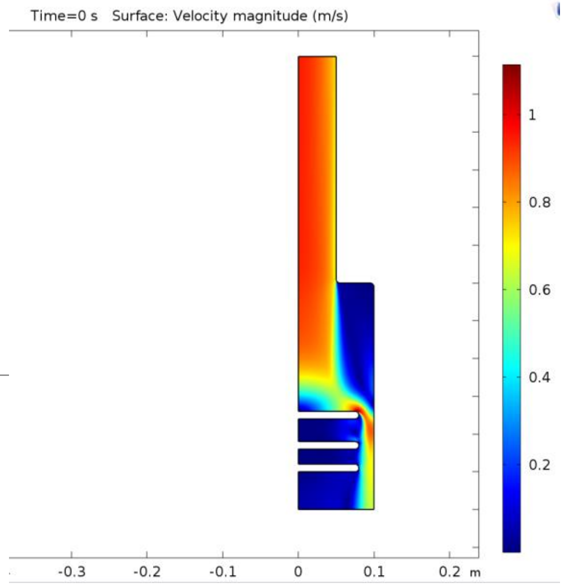
Pressure



Density



Velocity



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CAD Modeling

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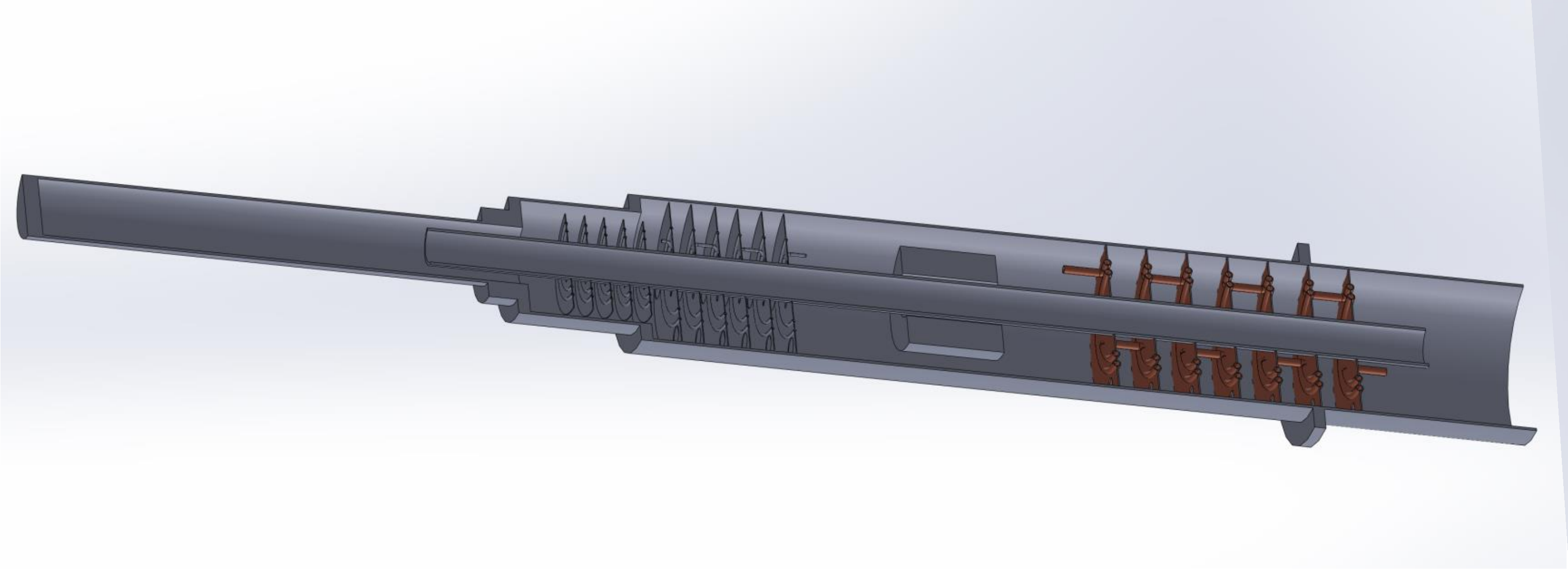

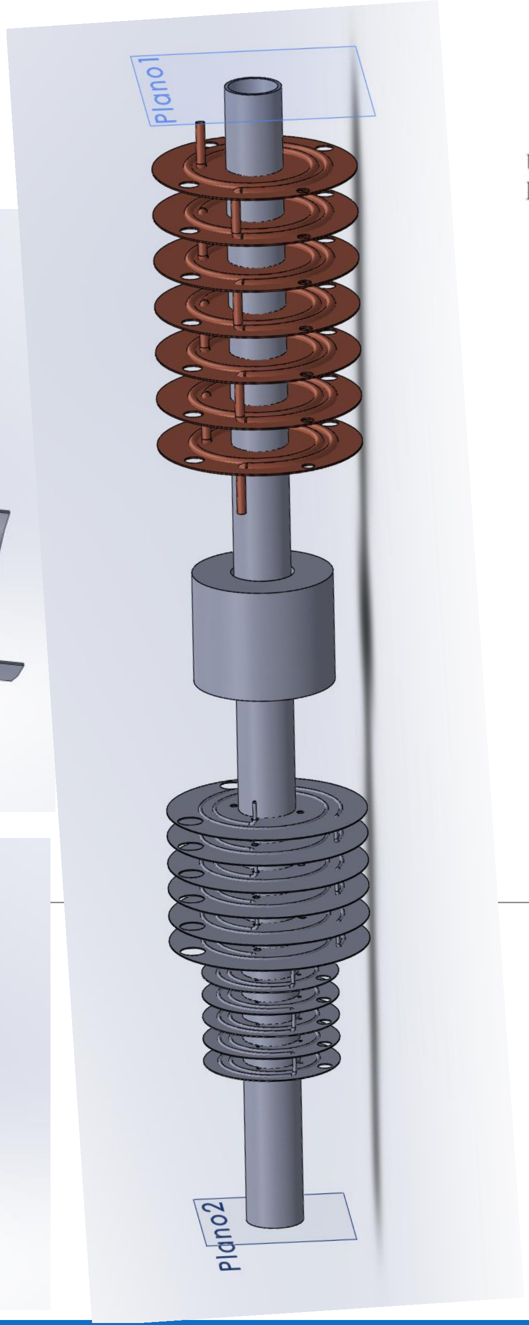

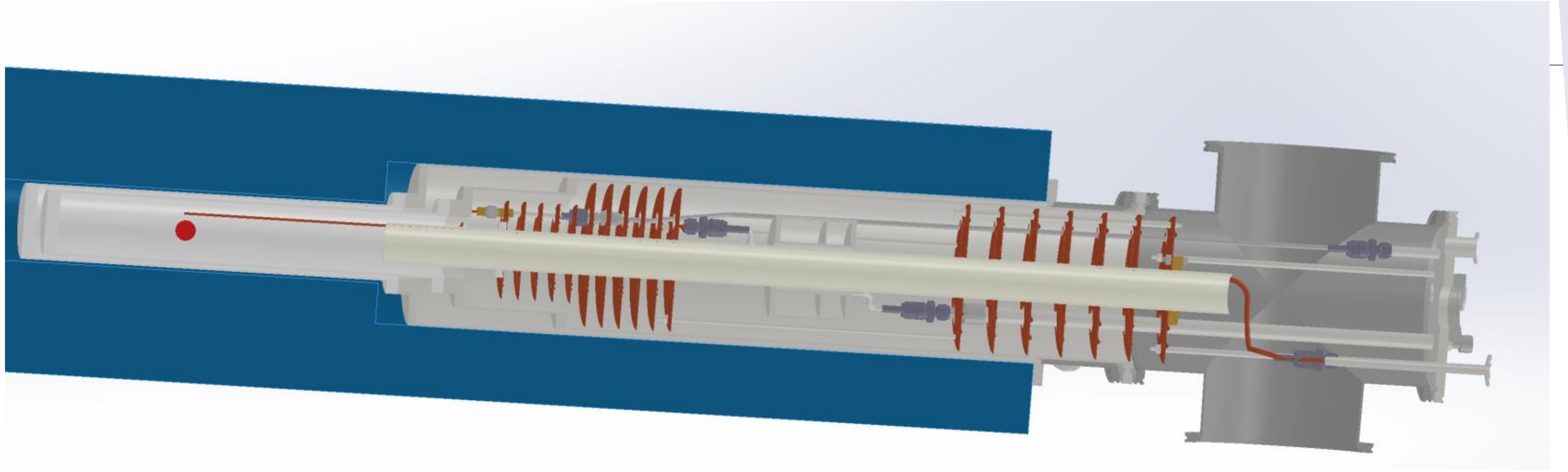

The Mesh