Center of Science and Technology of Valparaíso (Chile)

CFD Modeling Of A 4-He Evaporation Refrigerator For Polarized Target Experiments

Eng. David Aliaga
COMSOL Conference Boston 2019
10/03/19

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Working in Collaboration with:

University of New Hampshire

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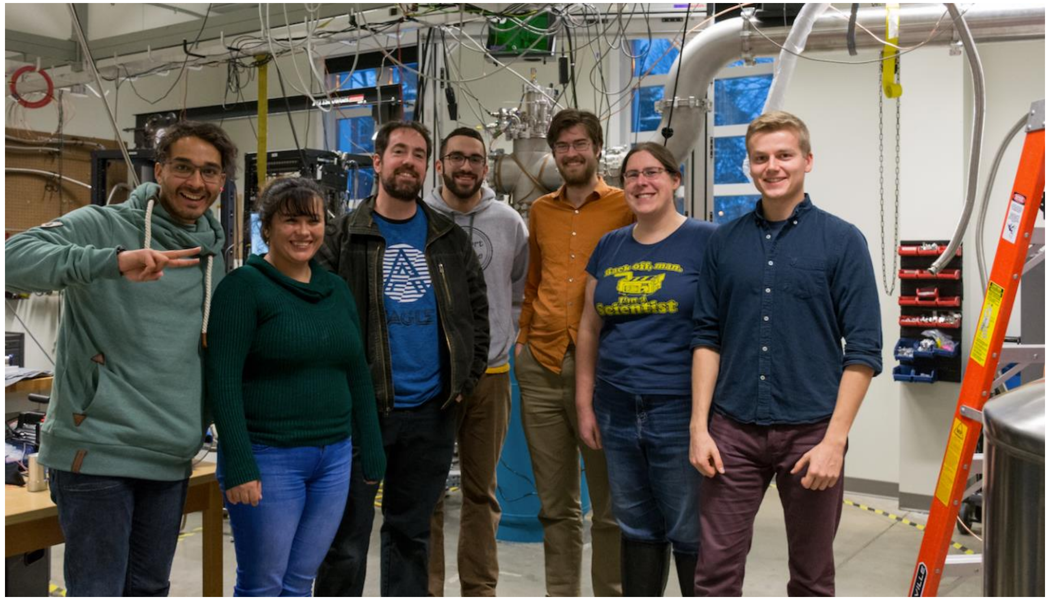

UNH Team: Prof. Karl Slifer, Prof. Elena Long, Nathaly Santiesteban, David Ruth.

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CENTER OF SCIENCE AND TECHNOLOGY OF VALPARAÍSO (CHILE):

Cryogenic Team

CRYOLAB

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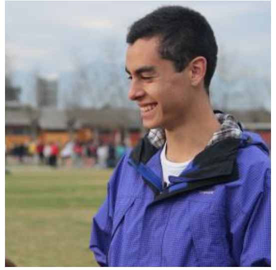


Undergraduate Student
Rafael Mena

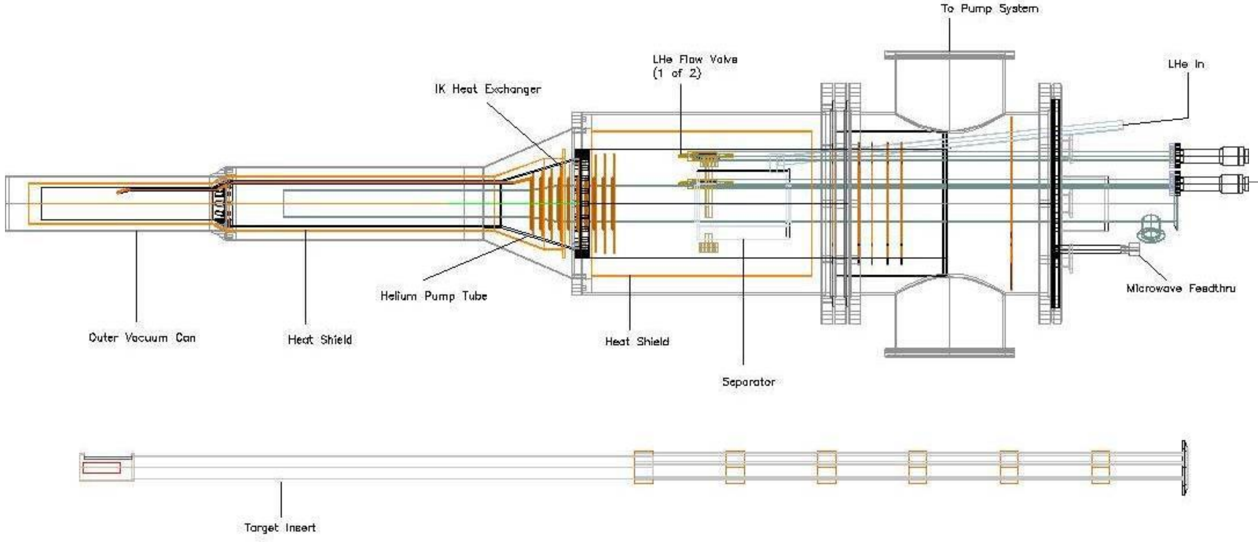
Undergraduate Student
Sebastian Jorquera

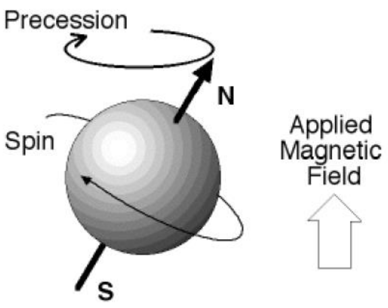
COMSOL Modeling: Introduction

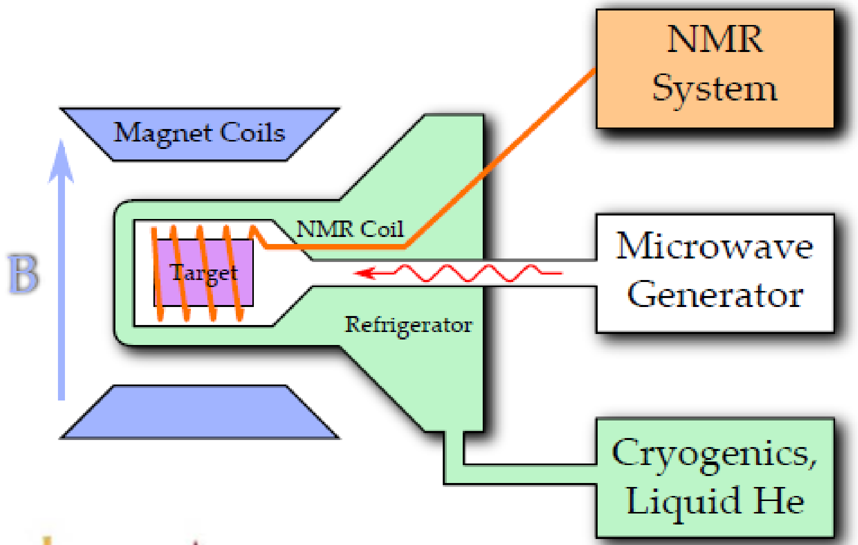
- Evaporation refrigerators are cryogenic equipment that can reach temperatures down to 1K and are used in nuclear physics experiments.

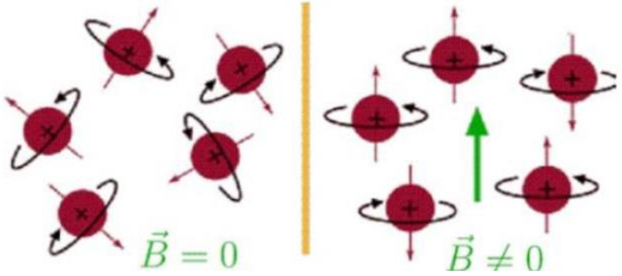
Dynamic Nuclear Polarization with Fixed Target

Jefferson Lab
Thomas Jefferson National Accelerator Facility









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COMSOL Modeling: History

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HORIZONTAL CRYOSTAT FOR POLARIZED PROTON TARGETS

P. ROUBEAU

Department for Solid State and Magnetic Resonance Physics, C.E.N.Saclay, Gif-sur-Yvette, France

Received 24 February 1966

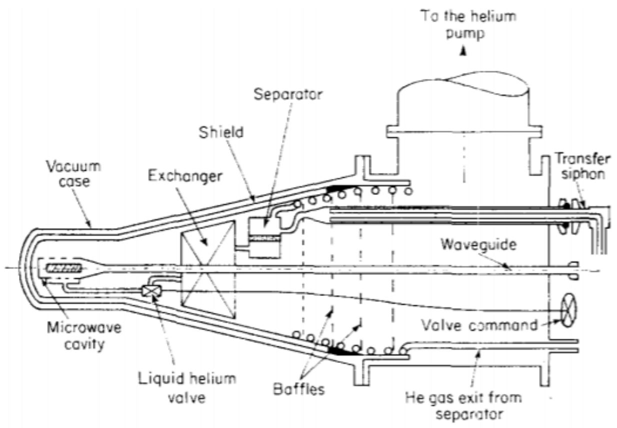


Figure 3. Schematic diagram of the cryostat

Continuously Operating ^{4}He Evaporation Refrigerator*

L. E. DeLong, O. G. Symko, and J. C. Wheatley

Department of Physics, University of California, San Diego, La Jolla, California 92037

(Received 4 August 1970)

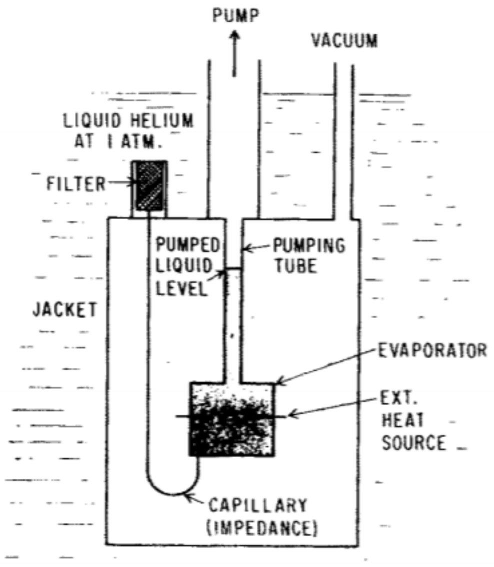
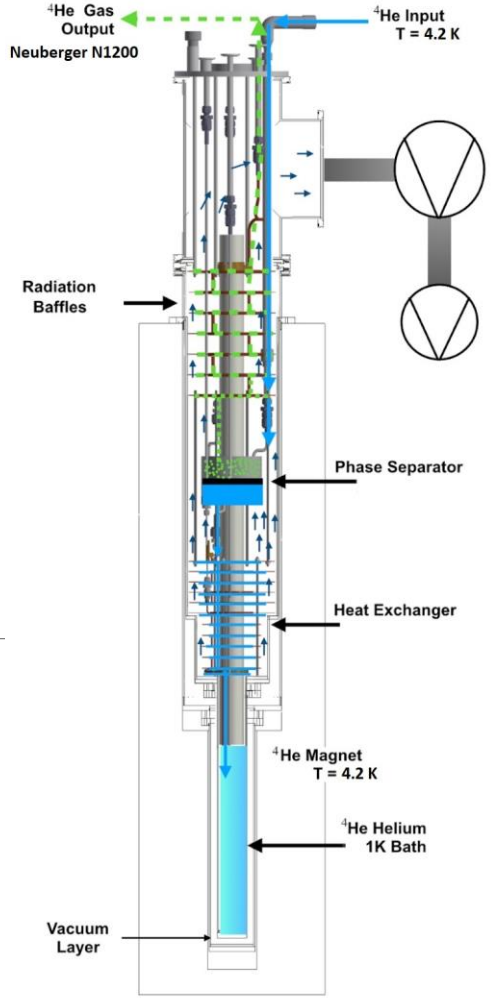


Fig. 1. Schematic drawing of continuously operating ^{4}He refrigerator.

COMSOL Modeling: Objectives

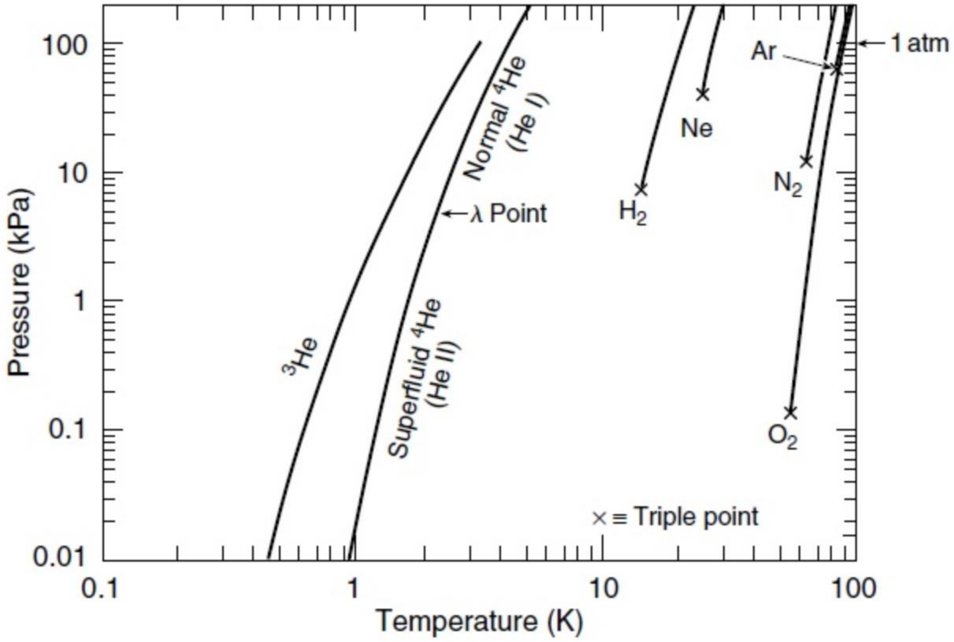
- Predict the cooling power of the UNH cryogenic refrigerator.
- Identify opportunities for improvements in the design.
- Simulate the whole bulk flow of Helium in the UNH refrigerator.
- Validate COMSOL Multiphysics as a design tool for this type of equipment.

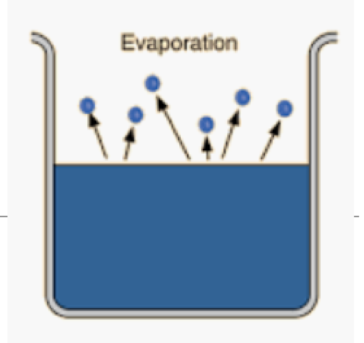
COMSOL Modeling: The Problem



- How does the fridge work??

Answer: Evaporation Cooling Technique





Q cooling= $\dot{m}$* Hfg

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

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COMSOL Modeling: Validation of Flow

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Vacuum Viscous Flow Modeling

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

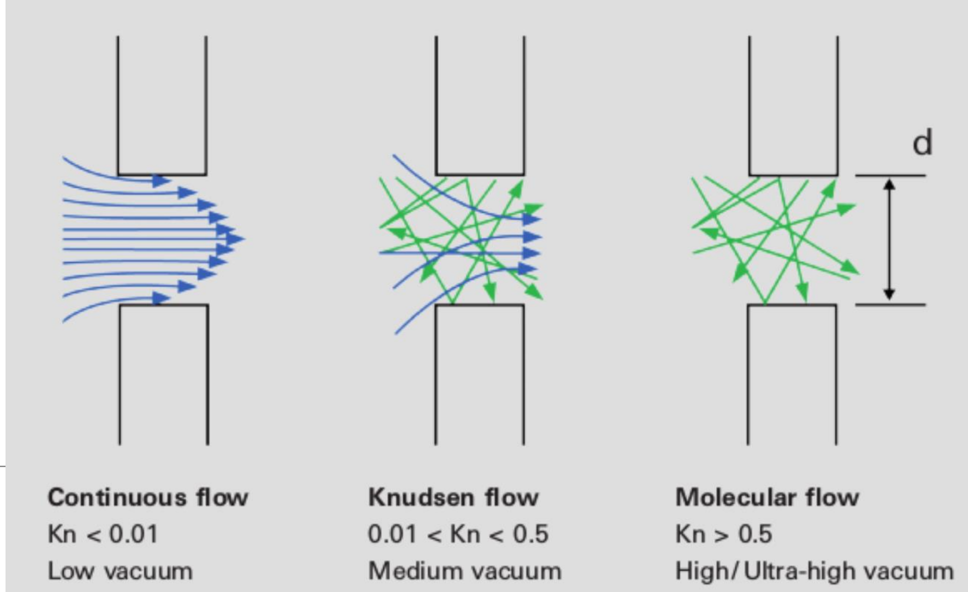
mean free path, λ = 6,44E-06 m 6437,39 nm

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

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

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

Continuous Flow



Academic.pgcc.edu **PFEIFFER VACUUM, website**

COMSOL Modeling: Validation of Flow

Viscous Flow Modeling

a viscous flow can be characterized with the Reynolds number $Re = \frac{\rho_{He} V_{He} d}{\mu_{He}}$. To evaluate the flow regime in the refrigerator the characteristic length d used is the nose diameter 0.0762 m. The properties of ^4He gas are evaluated at experimental conditions of 1.1 K and 286 mTorr. The value for the density ρ_{He} is 0.01647 kg/m^3 and for the molecular viscosity μ_{He} is 1.45×10^{-7} $Pa \cdot s$. The velocity V_{He} can be calculated with the measured mass flow rate $\dot{m}_{He}$:

$$V_{He} = \frac{\dot{m}_{He}}{\rho_{He} A} \quad (1)$$

$$V_{He} = \frac{1.67 \times 10^{-4}}{0.01647 \times \frac{\pi (0.0762)^2}{4}} = 2.21 m/s \quad (2)$$

And calculating the Reynolds number:

$$Re = \frac{0.01647 \times 2.21 \times 0.0762}{1.45 \times 10^{-7}} = 24,542 > 2000 \quad (3)$$

As the value of 2000 corresponds to the upper limit to laminar flow regime, this result shows that a turbulent flow is developed in the nose of the refrigerator. Therefore, to simulate this flow the turbulence phenomena must be considered.

The 4-He gas is considered as a ideal gas and an isotropic Newtonian fluid. Turbulence effects are considered in the modeling.

COMSOL Modeling: CFD Setup

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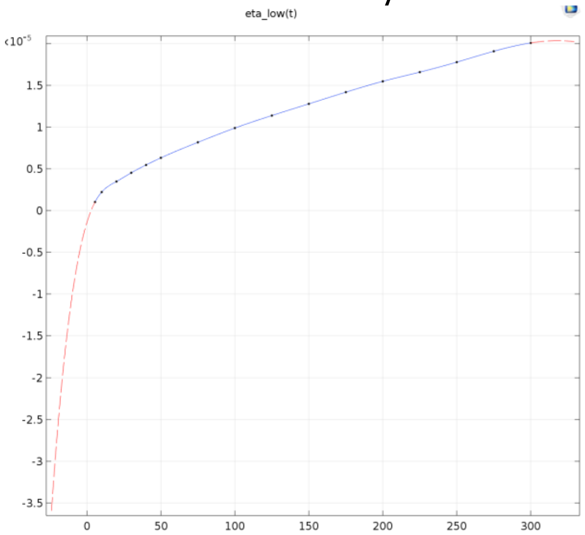
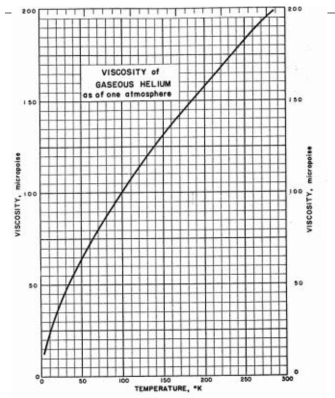
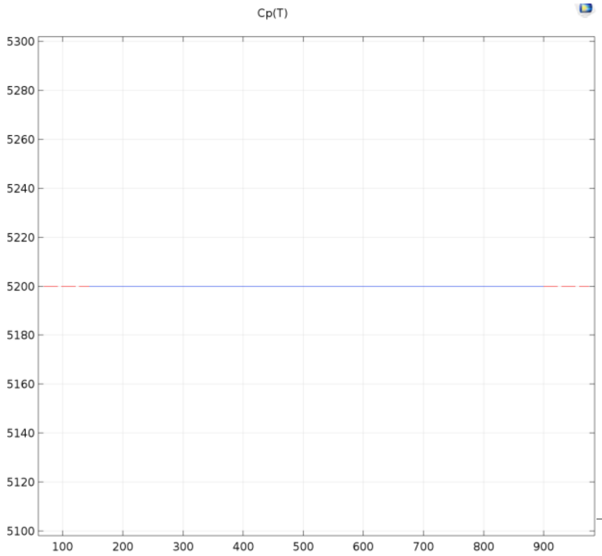
- Helium-4 gas properties

Dinamic Viscosity



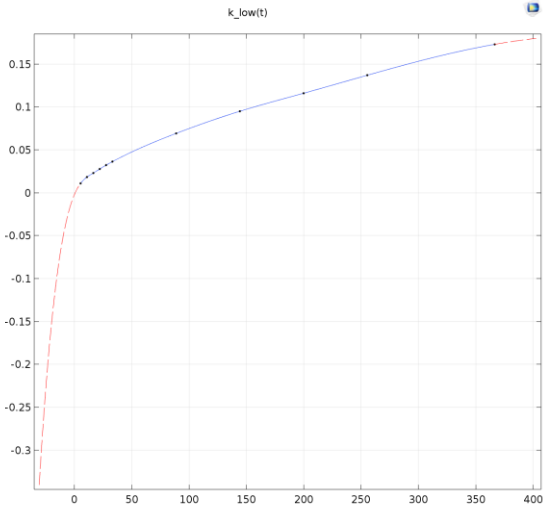


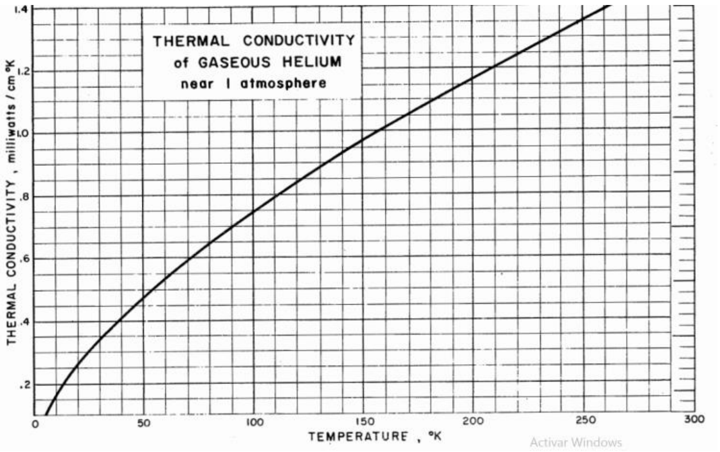
Constant Heat Capacity



* With Ideal Gas :Density

Thermal Conductivity

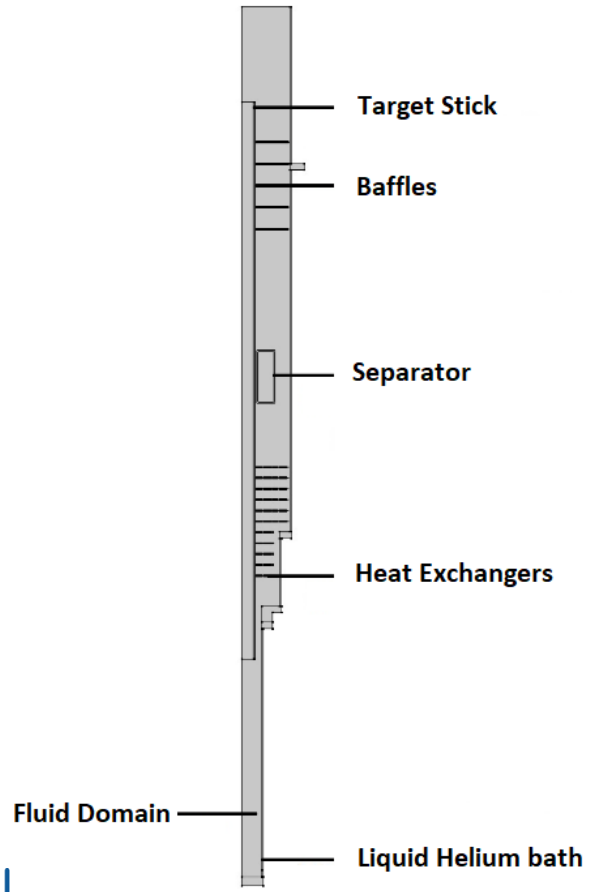


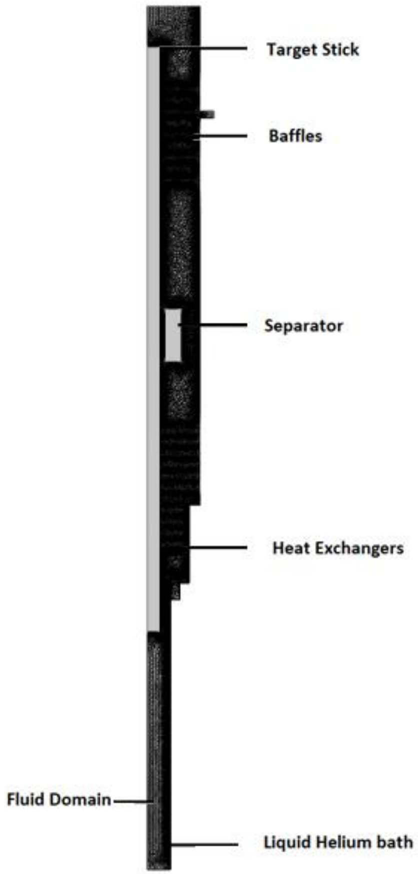


J.E. Jensen, W.A. Tuttle, R.B. Stewart, H. Brechna and A.G. Prodell. 1980. Brookhaven National Laboratory Selected Cryogenic Data Notebook. Vol 1 Sec I- IX.

COMSOL Modeling: CFD Setup

- Domain, Meshing





- A 2D Computer-Aided Design (CAD) model was build in COMSOL based in the geometry and measures of the evaporation refrigerator

- The meshing is done in the COMSOL interface. Three meshes are tested.

COMSOL Modeling: CFD Setup

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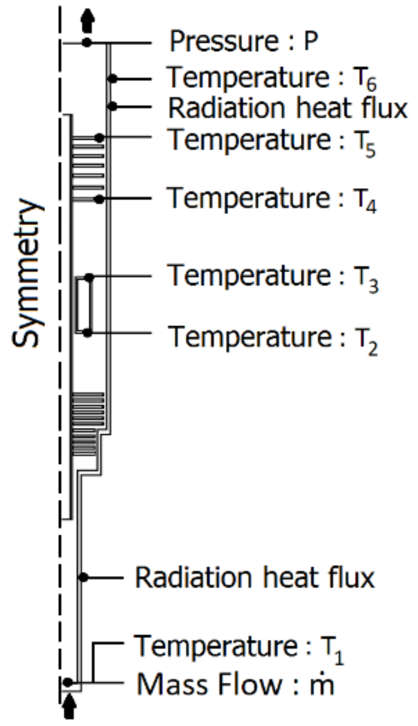
- Boundary Conditions



Geometry and boundary conditions for the cryogenic refrigerator. (T_n,with $n = 1, ..6$ corresponds to temperature node boundary condition)

Boundary Element	Variable	Value [unit]
Inlet	Mass Flow: $\dot{m}$	1.67E-04 [kg/s]
Outlet	Static Pressure: P	0 [Pa]
Inlet	Temperature: T_1	1.11 [K]
Wall (Separator)	Temperature : T_2	3.32 [K]
Wall (Separator)	Temperature :T_3	4.16 [K]
Wall (Baffle)	Temperature : T_4	3.39 [K]
Wall (Baffle)	Temperature :T_5	82.05 [K]
Wall (Inner Shell)	Temperature : T_6	103.60 [K]
Wall	No slip	
Wall	Adiabatic	
Wall (Outer Shell)	Radiation Heat Flux	

Table 1: Boundary conditions.

COMSOL Modeling: CFD Setup

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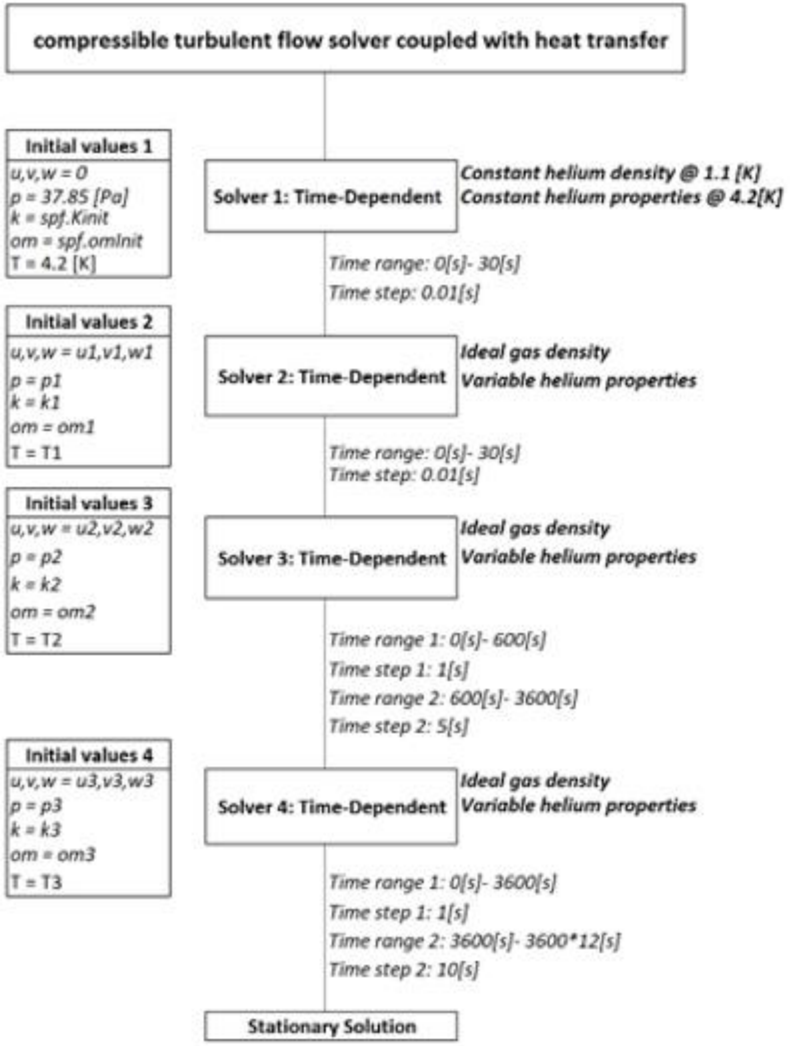
- Solver Setup



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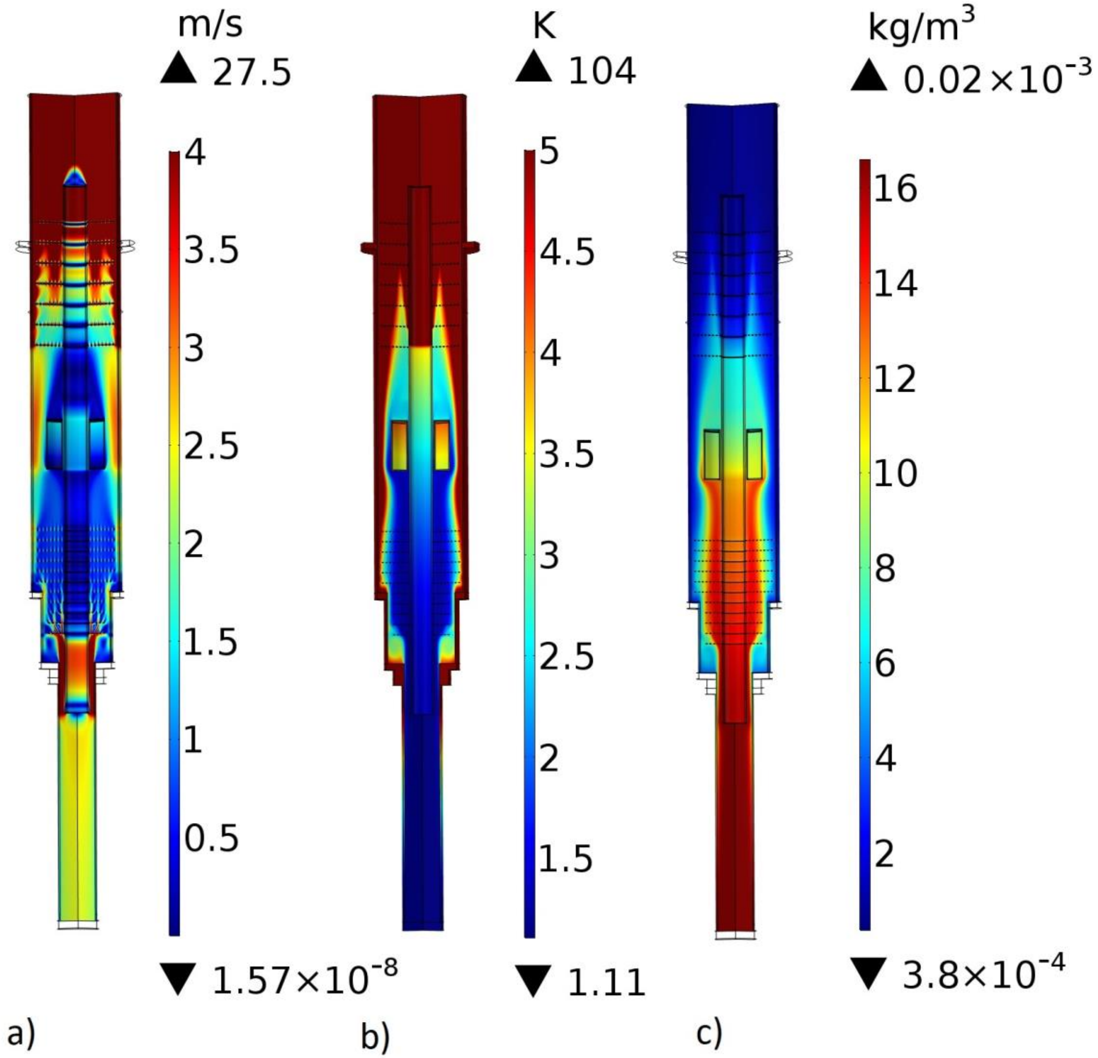
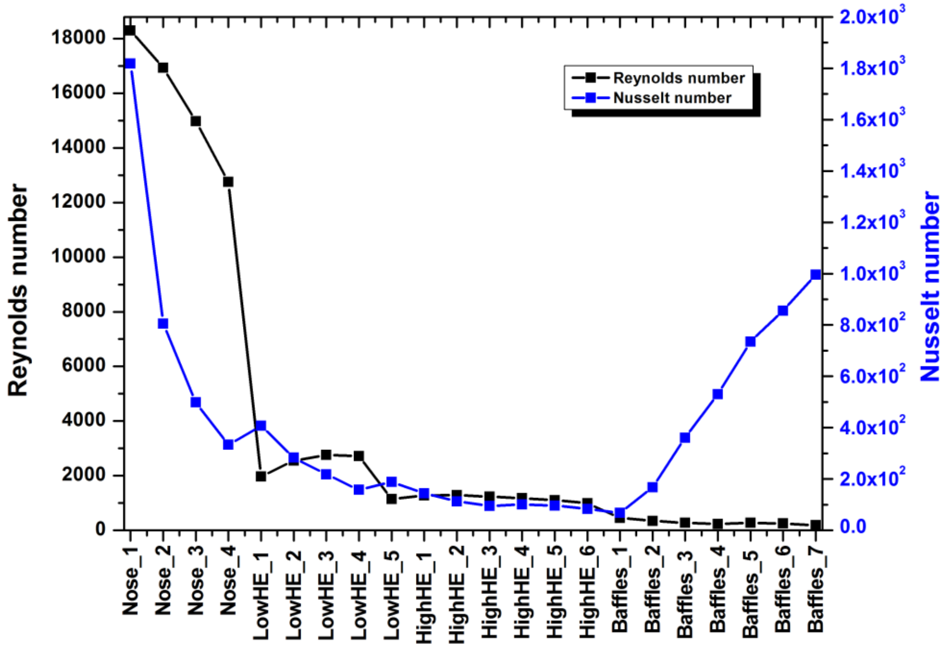
COMSOL Modeling: Results





COMSOL Modeling: Results

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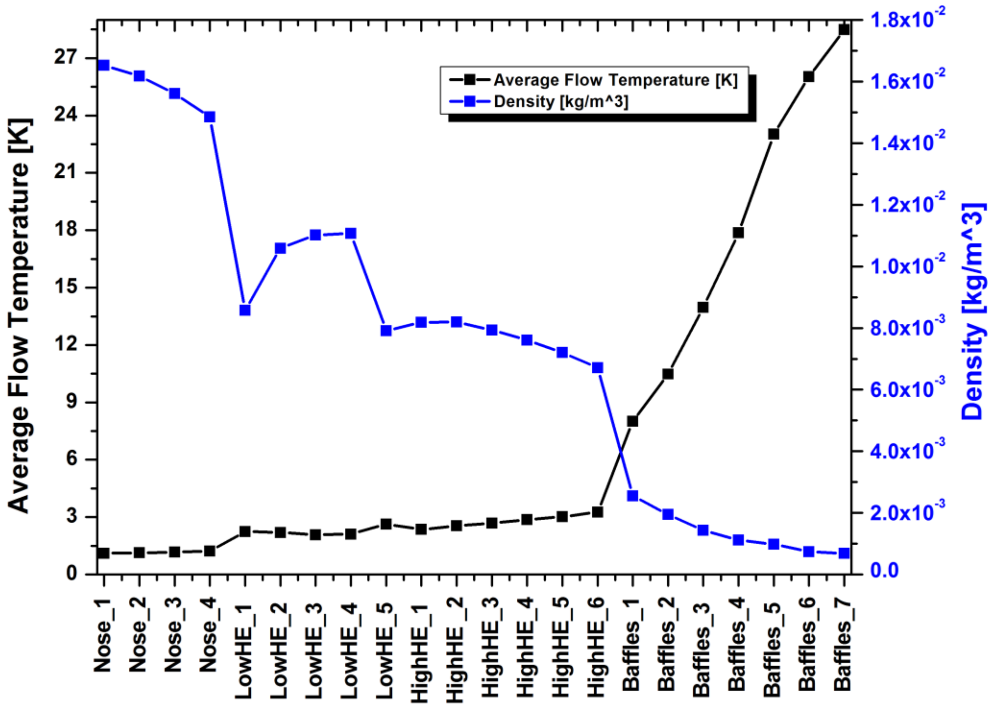

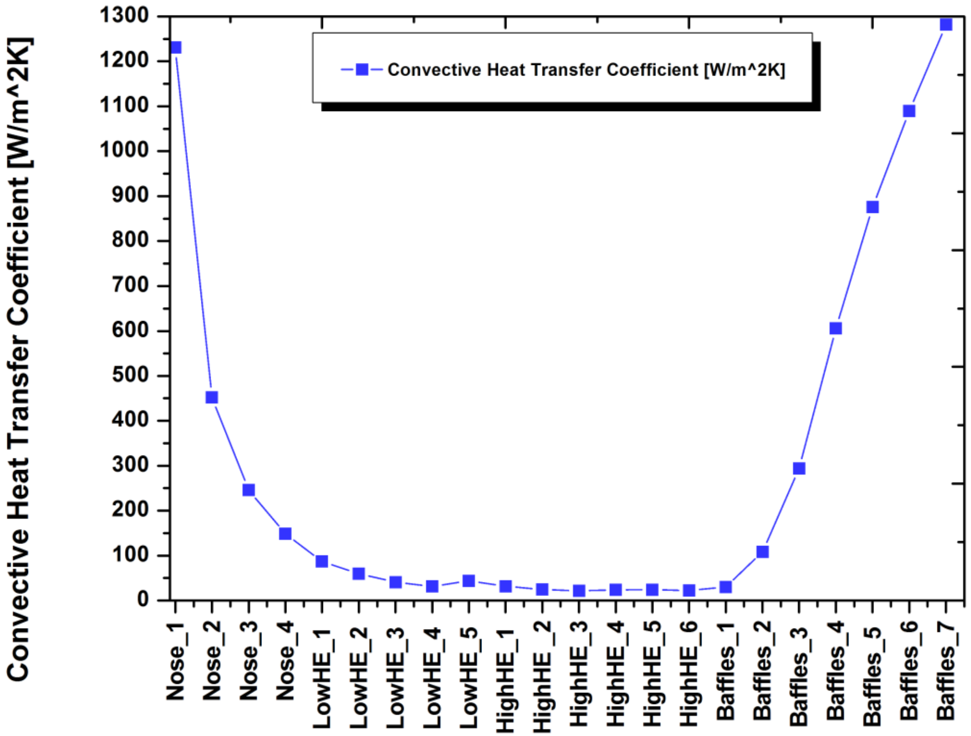

COMSOL Modeling: Conclusions

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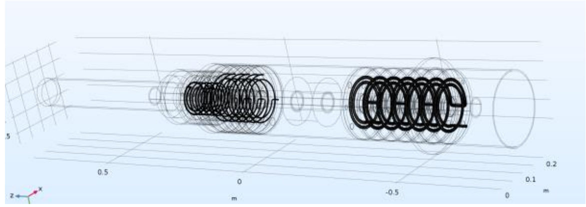
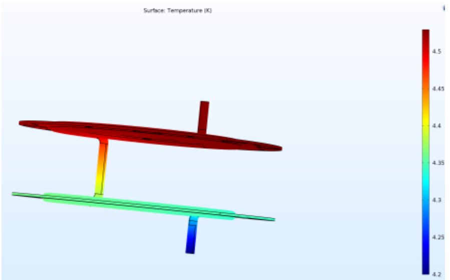
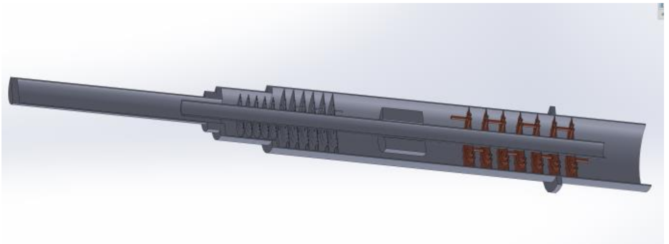
- We successfully develop a CFD simulation using COMSOL® Multiphysics for an 4-He evaporation refrigerator which predicts a cooling power of 2.68W for the superfluid helium bath at 1.11K. The difference between predicted and empirical cooling power was less than 7.5%.

- The parameters extracted from the UNH experiments allowed us to perform a characterization of the main 4He flow.

- From this point, extensive studies can be done to optimize this individual components of the refrigerator. This will improve the cooling capacity of the refrigerator.







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Thank You!

COMSOL Modeling: Annexes

$$T_m = \frac{1}{\rho_m A_c u_m} \int_{A_c} \rho u \cdot T \, dA_c$$

$$\dot{Q}_{\text{conv}} = Ah(T_w - T_m)$$

$$\dot{Q}_T = \int_{A_c} (\rho u E - k\nabla T) \cdot n \, dA_c$$

$$u_m = \frac{\int_{A_c} \rho u \cdot dA_c}{\rho_m A_c}$$

W. M. Rohsenow, J. P. Hartnett, Y. I. Cho, et al., Handbook of heat transfer, Vol. 3, McGraw-Hill New York, 1998