Experimental and numerical investigation of 2 K heat exchanger for superfluid helium cryogenic system at KEK

A Kumar[1,2], H Nakai[1,2], K Nakanishi[1,2], H Shimizu[1,2], Y Kojima[2], K Hara[2] and T Honma[2]

[1]SOKENDAI (The Graduate University for Advanced Studies), 1-1 Oho, Tsukuba, Ibaraki, 305-0801, Japan

[2]High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

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Introduction

- The 1.3 GHz Nb superconducting radio frequency (SRF) cavity operates at temperatures <2.0 K, cooled with superfluid helium (liquid helium 'LHe' < 2.17 K).
- 2 K heat exchanger (2K HX) in series with Joule-Thomson (JT) valve is employed in the cryogenic system, to produce superfluid helium continuously.
- 2K HX recovers sensible heat from outgoing 2.0 K gaseous helium (GHe) from the helium jackets of SRF cavities.
- JT valve maintains the level and pressure of superfluid helium in the He II tank.

2 K Heat Exchanger Requirement	
	LHe temperature reduction : 4.4 K to ≥2.2 K
	Flash loss reduction : 40 to 10%
	Increase superfluid Helium production

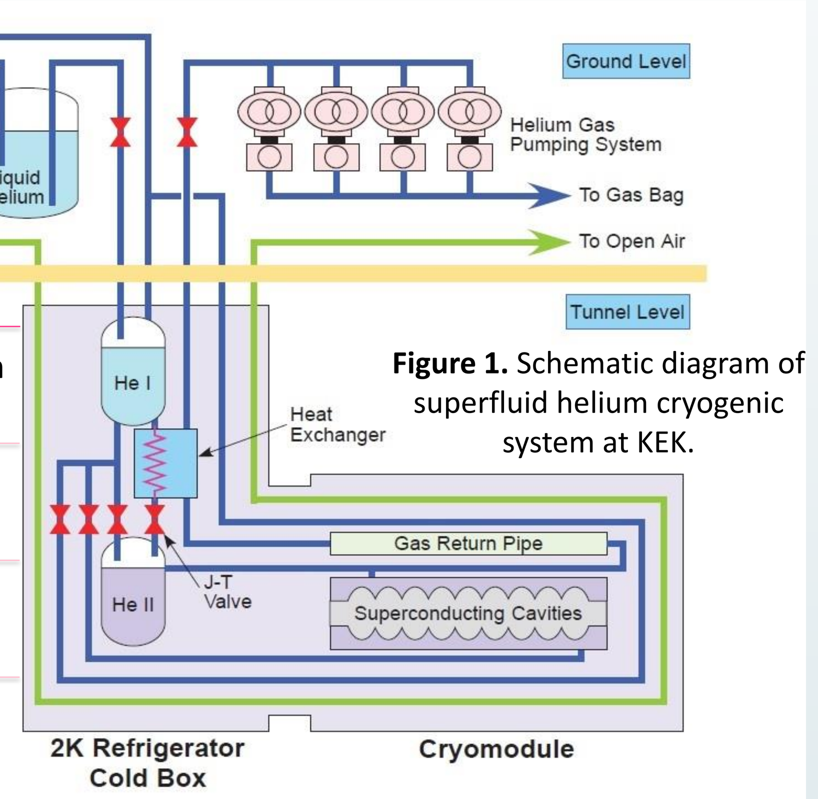

Figure 1. Schematic diagram of superfluid helium cryogenic system at KEK.

Objective

- 2K HX is made of OFC copper with thermal capacity of 100 W (4.5 g/s of mass flow rate).
- Hot LHe flows through the helical coils, recovering sensible heat from the cold GHe flowing over the laminated fins in counterflow direction, with identical mass flow rates (operational mode).
- Performance is needed to be determined by a factor known as ***effectiveness*** $\left(\varepsilon = \frac{\dot{Q}_{LHe\ or\ GHe}}{\dot{Q}_{max}}\right)$.
- Also, the GHe pressure drop through the 2K HX needs to be determined.

Table 1. 2K HX geometric parameters.

Geometric Parameters	Dimensions 2K HX
Helical tube parameters	
Tube outer diameter (thickness)	6 (t1) mm
Helix diameter (pitch)	75 (9) mm
Number of loops	30
Laminated Fin dimensions	
Sector radius	35 mm
Sector angle	50 degrees
Fin thickness	0.5 mm
Hole diameter	10 mm
Total dimensions	
Heat exchanger axial length	270 mm
Heat exchanger diameter	82 mm

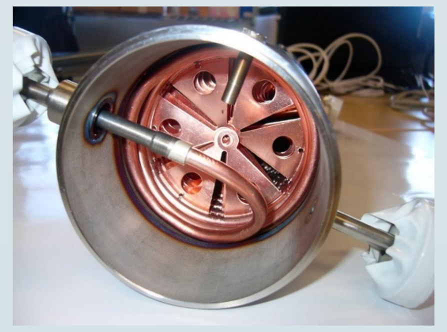

Figure 2. Type II 2K HX

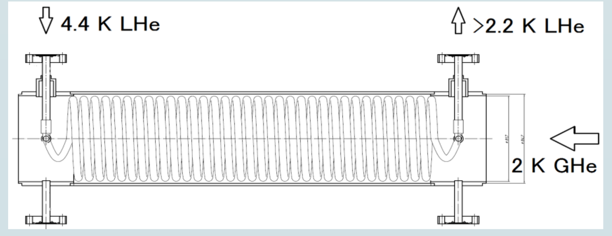

Figure 3. Axial view of 2K HX.

Experimental Methodology – Heat Exchanger Test Stand

- A heat exchanger test stand is designed and manufactured to test the 2K HXs.
- In the test stand, hot LHe flows through the 2K HX to He II tank via JT valve (CV103).
- Hot LHe is subcooled to >2.2 K, recovering coldness from outgoing 2.0 K GHe from He II tank.
- The maximum achievable flow rate is 3 g/s (70 W), limited by GHe pumping system.

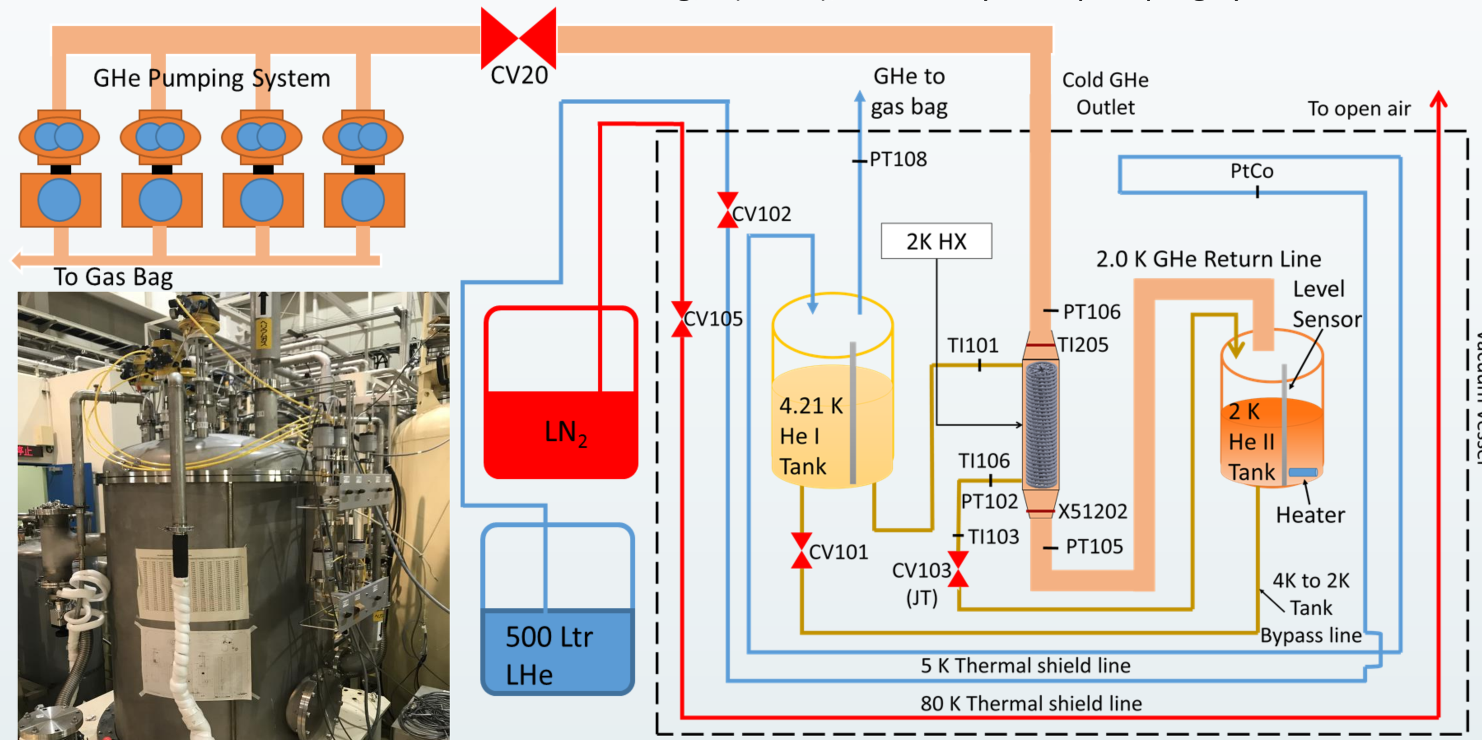

Figure 4. Schematic diagram and a pic of the heat exchanger test stand.

Cooldown of 80K and 5K Shields → Filling both storage tanks → Pumping on He II tank → Open JT Valve & maintain Level → Heater power till 70 W

Numerical Methodology – ANSYS CFX®

- ANSYS CFX is used to simulate the 2K HX.
- Fluid properties are varied with respect to pressure and temperature.
- 2K HX operates in steady state condition.

Table 2. 2K HX domains and initializing conditions.

Domain	Fluid/ Solid	Temperature (K)	Turbulence Intensity (%)	Turbulence Model	Wall Function
GHe	GHe	2	4.4	k-ω SST	Automatic
LHe	LHe	4.4	3.6	k-ϵ	Scalable
OFC	OFC	4.4 K with no fouling resistance			

Table 3. Boundary conditions for 2K HX in ANSYS CFX®.

Boundary	Fluid/ Solid	Mass Flow Rate [gs⁻¹]	Turbulence Intensity [%]	Static Temperature [K]	Total Pressure [kPa]
GHe Inlet	GHe	Upto 3	4.4	2	-
GHe Outlet		-	-	-	3
LHe Inlet	LHe	Upto 3	3.6	4.4	-
LHe Outlet		-	-	-	125
OFC	OFC	Interface between LHe and GHe			
Wall	SS304	-	-	Adiabatic	-

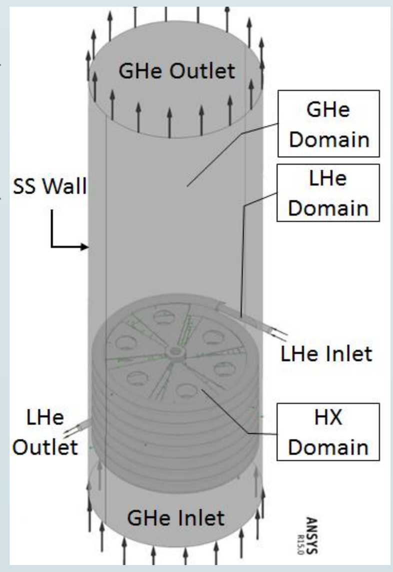

Figure 5. Example of CFD model for 2K HX.

Results & Discussions

Numerical Results

Some important relations

Actual heat transfer, $\dot{Q}_{LHe} = \dot{m}[h_{h,i} - h_{h,o}]$ and $\dot{Q}_{GHe} = \dot{m}[h_{c,o} - h_{c,i}]$ [W] [1]

Maximum possible heat transfer, $\dot{Q}_{max} = \dot{m}[h_{h,i} - h_{h@c,i}]$ [W] [2]

Effectiveness of a heat exchanger, $\varepsilon = \frac{\dot{Q}_{LHe\ or\ GHe}}{\dot{Q}_{max}}$ [3]

Table 4. Summarized results from ANSYS CFX® simulations.

Parameters	2 K Heat Exchanger 20 W	40 W	70 W
Effectiveness (ε-NTU) [%]	88.5	83.3	78.8
Effectiveness (CFD) [%]	75.7	71.8	68.3
Outlet temperature for LHe (CFD) [K]	2.59	2.65	2.78
Outlet temperature for GHe (CFD) [K]	3.17	3.11	3.05
Flash loss for LHe after JT (CFD) [%]	13.6	14.2	15.4
Pressure drop in GHe (CFD) [Pa]	2.5	10.1	31
Enthalpy balance error (%)	0.9	1.1	1.2

- Effectiveness @ 70 W (3 g/s) - 68% and GHe pressure drop @ 70 W (3 g/s) - 31 Pa.
- LHe temperature at the outlet of 2K HX keeps on rising with increasing thermal loads.
- Heat transfer coefficient for fluids, h is α Re^n, where n is <1 and Re = f($\dot{m}$).
- Increase in mass flow rate for both fluids reduces effectiveness of the 2K HX.

Experimental Results

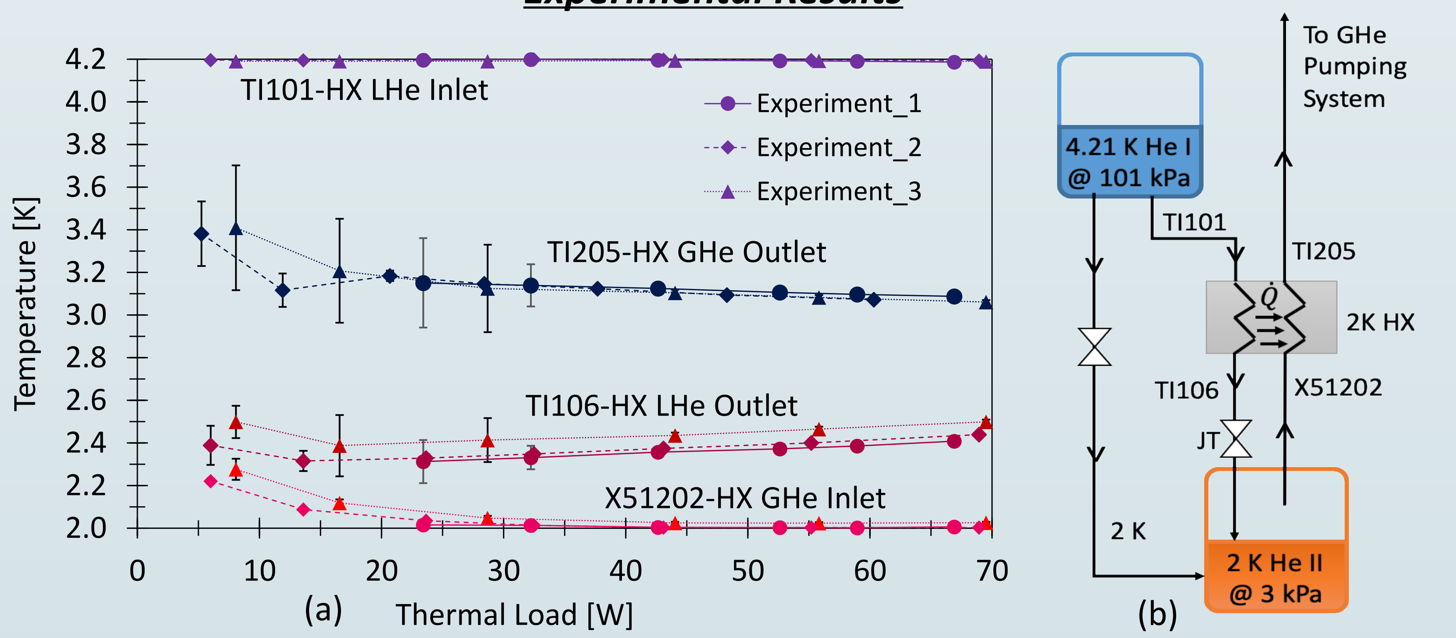

Figure 6. (a) Temperature data w.r.t thermal load to the 2K HX, (b) Schematic view of the fluid flow through the heat exchanger test stand.

- LHe temperature (TI101) at the inlet of 2K HX remains constant throughout the experiment.
- LHe temperature (TI106) at the outlet of 2K HX keeps on rising with increasing thermal loads.
- GHe temperature (X51202) at the inlet of 2K HX, initially is >2.0 K due to excess heat from level sensor (above He II level) and low flow rate.
- GHe temperature (TI205) at the outlet of 2K HX always reduces with increasing mass flow rate.

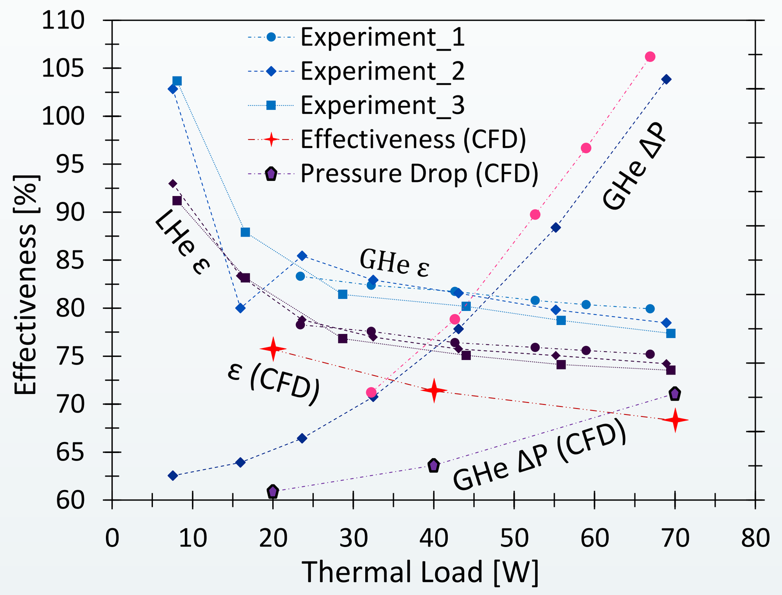

Figure 7. Experimental effectiveness and pressure drop of 2K HX compared with CFD results.

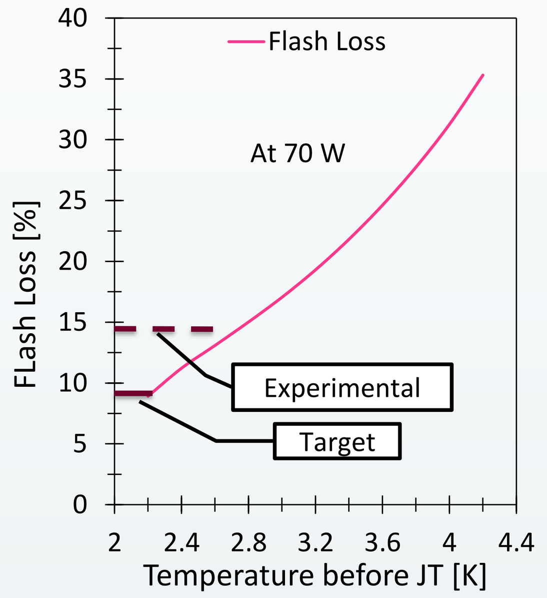

Figure 8. Flash loss w.r.t temperature of LHe before JT.

- Effectiveness (from LHe) @ 70 W (3 g/s) - 74% and GHe pressure drop @ 70 W - 123 Pa.
- 2K HX's LHe outlet temperature (TI106) at 70 W is 2.45 K, with GHe inlet temperature of 2.0 K.
- Enthalpy balance error of the 2K HX is 5% at 70 W, with $\dot{Q}_{GHe} > \dot{Q}_{LHe}$.
- Compared to the CFD simulations, experimental effectiveness is 6% higher.
- Flash loss (amount of vapor generated during JT expansion) @ 70 W - 14% .
- Increase in mass flow rate for both fluids reduces effectiveness.

Conclusion

- Required effective operation (>83%) possible below 20 W (0.855 g/s) of thermal load.
- GHe pressure drop of <100 Pa is possible below 65 W of thermal load.
- Losses after JT expansion are smaller and gives 86% of superfluid helium (experimental).
- Effectiveness reduces as the thermal load to the 2K HX increases.
- Design will be optimized to increase its effectiveness and reduce the GHe pressure drop.
- Effectiveness error between experiments and CFD is 6%.

Future Studies

- Current results will act as the benchmark for the optimization of the current design.
- Modifications required to reduce error between CFD simulation and the experimental results.
- Experiments will be performed to determine the heat transfer coefficient of GHe.

Contact Information

- Name – Ashish Kumar
- Email – ashish@post.kek.jp, 179ashish1989@gmail.com