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

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Abstract. Superfluid helium cryogenic systems at KEK are constructed for research and development of cryomodules of the compact Energy Recovery Linac (cERL) and the International Linear Collider (ILC). The niobium superconducting radio frequency (SRF) cavities in cERL and ILC operate at temperatures of 2.0 K or below. The SRF cavities are cooled with saturated superfluid helium, which is another phase of the liquid helium (LHe), when it is cooled below 2.17 K under saturation condition. To produce superfluid helium continuously, a Joule-Thomson (JT) valve is employed in the cryogenic system. Also, a 2 K heat exchanger (2K HX) is introduced in series with the JT valve to recover the coldness from 2.0 K gaseous helium (GHe) evaporating from the helium tanks of the SRF cavities. This increases the production rate of superfluid helium by reducing the incoming LHe temperature from 4.4 K to 2.2 K or above before the JT valve. At KEK, we have a 2K HX consisting of a helical coil and laminated fins for thermal loads up to 100 W. Its performance needs to be determined and is characterized by a factor known as effectiveness, which is the ratio of actual heat transfer to the maximum possible heat transfer between the fluids. The performance of the 2K HX has been determined experimentally using the heat exchanger test stand and numerically by computational fluid dynamics (ANSYS CFX®), respectively. In the heat exchanger test stand, the mass flow rate of incoming LHe is kept identical to the outgoing GHe through the 2K HX, using the level and pressure control of superfluid helium. An electric cartridge heater is immersed in the superfluid helium to vary the mass flow rate of evaporating superfluid helium. In the future, the optimization of the 2K HX design will be performed to improve its performance.

1. Introduction

Superfluid helium cryogenic systems are widely employed for the operation of cryomodules of 1.3 GHz niobium superconducting radio frequency cavities (SRF) at 2.0 K. These cavities are used for electron beam acceleration at the compact Energy Recovery Linac (cERL) and the SRF Test Facility (STF) for the International Linear Collider (ILC) at KEK. A 2 K heat exchanger (2K HX) in series with a Joule-Thomson (JT) valve is an integral part of the superfluid helium cryogenics system to subcool liquid helium (LHe), as it recovers the coldness from the outgoing 2.0 K gaseous helium (GHe) at 3.1 kPa, evaporating from the helium tanks of the SRF cavities. This reduces the LHe temperature from 4.4 K to ~2.2 K or above before the JT valve, using the sensible heat of the cold GHe at 2.0 K. Lower inlet
temperature results in a flash loss (dryness) reduction from 40% to ~10% during the JT expansion, and hence a higher production rate of superfluid helium (He II) [1]. At KEK, a 2K heat exchanger test stand was designed and manufactured to measure the performance of the 2K HXs. The setup consists of a 2K refrigerator coldbox basically enclosing two tanks to store LHe (He I) and superfluid helium (He II) at 4.4 K and 2.0 K respectively, and a 2K HX in series with a JT valve to produce and maintain the level of superfluid helium (operational mode). To cool LHe to approximately 2.2 K or above before the JT valve, the minimum effectiveness of 83% is required for the 2K HX. The thermal load, in turn the mass flow rate, to the 2K HX can be adjusted with an electric heater inserted in the He II tank.

1.1. 2K heat exchanger at KEK

The 2K HX consists of helically coiled tubes and laminated fins made of oxygen-free copper (OFC) capable of handling thermal loads up to 100 W (corresponding to 4.5 g/s of mass flow rate) in counterflow arrangement, as shown in figures 1 and 2. The laminated fins, as seen in the figure 1, provide larger surface area for more efficient extraction of enthalpy from hot LHe flowing through the helical tube. The flow of cold GHe over the fins and helical coil is periodic in nature, as described in Ref. [2]. The surface area density of the 2K HX is approximately 220 m²/m³, which can be improved by the optimization of the 2K HX design. The focus of this study will be on the determination of effectiveness and the GHe pressure drop of the 2K HX. Computational fluid dynamics (CFD) studies were conducted to validate the claims of the behavior of GHe flow through the 2K HX [2]. In this paper, the performance of the 2K HX determined through extensive experimentation will be presented and the results will be compared to computational fluid dynamics (CFD) simulations.

| 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 |
| Fin dimensions (circle sector) |
| 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 |

2. Problem formulation

Effectiveness is the factor employed for measuring the performance of the 2K HX. Effectiveness of a heat exchanger is defined as the ratio of the actual heat transfer to the maximum possible heat transfer between the fluids. Due to the large variation of specific heat capacity of LHe in the operational temperature range, effectiveness will be calculated using enthalpies of the fluids [3]. Experimental effectiveness of the 2K HX can only be determined up to 70 W of thermal load, generated by the electric heater in the He II tank (corresponding to 3 g/s of the mass flow rate). It is due to the limitation of the helium gas pumping system, hence the CFD simulations are also executed up to the same. The mass flow rates of both fluids remain identical, which are the actual operational mode for the 2K HXs. The maximum possible heat transfer for CFD and experimental data are calculated using the enthalpy data from HEPAK® software. The known operating conditions of the fluids and the heat exchanger material properties are shown in table 2.
2.1. Basic discussion for analysis for the 2K HX

To determine the heat transfer between fluids by calculation, individual average heat transfer coefficients, \( h \), for the fluids need to be specified. For heat transfer coefficient of LHe, flow through a helical tube was considered. For that of GHe, cases of perpendicular flow over a single flat plate, cylinders in cross external flow and parallel flow over slots were considered, and then they are area-averaged to get an estimated value. The empirical correlations for both fluid cases are shown below \([4,5]\),

\[
\text{Nusselt number, } \text{Nu}_i = \frac{h_i D}{k} = \left\{ 1 + 3.6 \left[ 1 - \frac{0.12}{R} \left( \frac{0.12}{R} \right)^{0.8} \right] \right\} \text{Nu}_i \text{, and } \text{Nu}_o = 0.023 \times \text{Re}^{0.8} \times \text{Pr}^{0.3},
\]

\[
\text{Nu}_c = \frac{h_c D}{k} \text{ and } \text{Nu}_e = \begin{cases} 0.228 \times \text{Re}^{0.731} \times \text{Pr}^{0.33}, & \text{perpendicular flow over the fins} \\ 0.664 \times \text{Re}^{0.5} \times \text{Pr}^{0.33}, & \text{flow over the slots and holes on fins} \\ 0.414 \times \text{Re}^{0.586} \times \text{Pr}^{0.33}, & \text{flow over row of cylinders} \end{cases}
\]

where \( D \) is the hydraulic diameter, \( \text{Re} \) the Reynolds number, \( \text{Pr} \) the Prandtl number and \( k \) the thermal conductivity of the fluid. The subscripts \( h, c \) and \( s \) are for the hot and cold fluid and straight tube, respectively, ‘a’ is the radius of the tube and \( R \) is the curvature radius of the helical tube.

The effectiveness of the 2K HX for counterflow arrangement from effectiveness-NTU method, \( \varepsilon \), is;

\[
\text{Effectiveness, } \varepsilon = \frac{\dot{Q}}{\dot{Q}_{\text{max}}} = \frac{1 - \exp[-\text{NTU}(1 - C^*)]}{1 - C^* \exp[-\text{NTU}(1 - C^*)]} .
\]

Here \( C^* \) is the specific heat capacity ratio of fluids \( \left( \frac{C_{\text{min}}}{C_{\text{max}}} \right) \), where \( C_{\text{min}} \) is for the fluid with lower specific heat capacity and \( C_{\text{max}} \) is for the higher specific heat capacity. The number of transfer units \( \text{NTU} = \frac{UA}{C_{\text{min}}}, \) and \( \text{UA} \) [W/K] is the overall thermal conductance determined from the individual heat transfer coefficients of fluids flowing through the 2K HX \([6]\).

Overall thermal conductance, \[
\frac{1}{\text{UA}} = \frac{1}{h_i A_i} + R_w + \frac{1}{h_c A_c} , \text{ here } R_w \text{ is wall resistance (3)}
\]

The total heat transfer from LHe to GHe, \( \dot{Q} \), is expressed as:

\[
\dot{Q} = \varepsilon \times \dot{Q}_{\text{max}} = \varepsilon \times \left( \text{mc}_{\text{min}} \times \left( T_{h,i} - T_{c,i} \right) \right) \text{ [W]} ,
\]

where \( \dot{m} \) is the mass flow rate, subscripts \( i \) and \( o \) are for the inlet and outlet condition of fluids at the 2K HX, hence \( T_{h,i} \) is the hot fluid inlet temperature and \( T_{c,i} \) is the cold fluid inlet temperature to the 2K HX.

The effectiveness of the 2K HX from the relation above is determined to be 87.3% at 20 W of the thermal load (0.855 g/s) and 78.9% at 70 W (3 g/s). The drop in effectiveness is attributed to the increment of identical mass flow rates for both fluids through the 2K HX and to that the heat transfer coefficient for GHe being directly proportional to \( \text{Re}^n \), where \( n \) is always < 1. Since, the heat transfer

| Fluid/Solid | Inlet Temperature \( (T_i) \) [K] | Outlet Temperature \( (T_o) \) [K] | Pressure \( (P) \) [kPa] | Density \( (p) \) [kg m\(^{-3}\)] | Specific Heat Capacity \( (C_p) \) [Jkg\(^{-1}\)K\(^{-1}\)] | Dynamic Viscosity \( (\mu) \) [\( \mu \text{Pa.s} \)] | Thermal Conductivity \( (k) \) [Wm\(^{-1}\)K\(^{-1}\)] |
|------------|----------------------------------|------------------------------------|-----------------|-----------------|-----------------|----------------|-----------------|
| GHe (c)    | 2.0                              | -                                  | 3               | 0.522           | 5441            | 0.70           | 0.005           |
| LHe (h)    | 4.4                              | >2.2                               | 125             | 138.7           | 3202            | 3.68           | 0.017           |
| OFC        | -                                | -                                  | -               | -               | -               | -              | 1050            |
coefficient for a perpendicular flow over rows of flat fins is unknown, the CFD studies are employed to determine precise heat transfer coefficient for GHe flowing through the 2K HX geometry.

3. **Numerical model for 2K HX in ANSYS CFX®**

Determining the heat transfer between the fluids through the 2K HX is quite difficult with conventional numerical methods, due to the unknown quantity, \( h_e \), the heat transfer coefficient of GHe flowing through the complicated geometry of stacked rows of fins. In Ref. [2], the author determined the effectiveness and the heat transfer coefficient, \( h_e \), of the heat exchanger numerically by simulating the 2K HX section by section up to the 24 loops, and then extrapolating the results for the whole 2K HX (30 loops). This procedure was unavoidable at that time, due to limited computational resources to simulate the whole 2K HX at once. After improvement of the computational setup, now it becomes possible to simulate the whole heat exchanger (30 loops) at once, hence the error introduced from extrapolation of effectiveness-NTU data can be eliminated to ensure more precise results. Also, to determine the heat transfer between fluids through the 2K HX precisely, a fin offset (staggered fins) was introduced in the geometrical model to emulate the actual heat exchanger geometry. The geometrical model for 2K HX is according to the specification given in table 1, and the details about the domains, initial conditions, boundary conditions and the turbulence model employed for simulations are given in tables 3 and 4. Meshing also remains the same while applying proximity and curvature criteria with tetrahedral meshes to the 2K HX geometry, and explained in details in Ref [2] section 3.

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

| Boundary | Fluid/ Solid | Mass flow rate \([\text{g/s}]\) | Turbulence Intensity [%] | Static Temperature [K] | Total Pressure [kPa] |
|----------|--------------|----------------------------------|--------------------------|------------------------|----------------------|
| GHe Inlet | GHe         | Up to 3                         | 4.4                      | 2                      | -                    |
| GHe Outlet | -           | -                                | -                        | -                      | 3                    |
| LHe Inlet | LHe         | Up to 3                         | 3.6                      | 4.4                    | -                    |
| LHe Outlet | -           | -                                | -                        | -                      | 125                  |
| OFC      | OFC         | Interface between LHe and GHe    |                          |                        |                      |
| Wall     | SS304       | -                                | -                        | Adiabatic              |                      |

4. **CFD results and discussion**

The simulations provided the amount of heat that is being transferred from LHe to GHe through the 2K HX. With the known inlet and the calculated outlet temperatures of the fluids by ANSYS CFX®, it was possible to determine the enthalpies at the boundaries. The amount of heat transferred between the fluids was confirmed with the amount of heat transferred by fluids to the heat exchanger, while the enthalpy balance error between fluids was confirmed to be smaller than 1.2%. The amount of heat transferred by fluids can be determined from the relation given below:

\[
\dot{Q}_{\text{LHe}} = \dot{m}\left[ h_{h,i} - h_{h,o} \right] \text{and } \dot{Q}_{\text{GHe}} = \dot{m}\left[ h_{c,o} - h_{c,i} \right] \text{[W].}
\]

The maximum possible heat transfer, \( \dot{Q}_{\text{max}} \), between fluids is expressed as:

\[
\dot{Q}_{\text{max}} = \dot{m}\left[ h_{h,i} - h_{h@c,i} \right] \text{[W].}
\]
where \( h_{h@c,i} \) is the enthalpy of the hot fluid at the cold fluid inlet temperature under the hot fluid pressure condition. Then, the effectiveness of a heat exchanger is determined as:

\[
\varepsilon = \frac{Q_{\text{LHe or GHe}}}{Q_{\text{max}}}, \tag{7}
\]

The flash loss (dryness) during the JT expansion can be obtained by:

\[
\text{Flash loss during JT expansion, } \frac{\dot{m}_v}{\dot{m}} = \frac{[h_{h,o} - h_{h@\text{sat}}]}{h_{fg}}. \quad \tag{8}
\]

where \( h_{h@\text{sat}} \) and \( h_{fg} \) are the enthalpy and the latent heat of He II at saturation pressure and temperature, respectively. The flash loss, \( \dot{m}_v/\dot{m} \), indicates the fraction of vapour produced during the JT expansion.

**Table 5. Summarized results obtained from ANSYS CFX®.**

| Parameters                              | 2K Heat Exchanger |
|-----------------------------------------|-------------------|
| Effectiveness (\( \varepsilon \)-NTU) [%] | 87.3              |
| Effectiveness (CFD) [%]                 | 75.7              |
| Outlet temperature for LHe (CFD) [K]    | 2.59              |
| Outlet temperature for GHe (CFD) [K]    | 3.17              |
| Flash loss for LHe (CFD) [%]            | 13.6              |
| Pressure drop for GHe (CFD) [Pa]        | 2.5               |
| Enthalpy balance error (%)              | 0.9               |

The results of the CFD simulations at different thermal loads, as listed in table 5, showed the effectiveness of the 2K HX at the maximum thermal load of 70 W to be 68%, which is 10% lower than that determined from the effectiveness-NTU relations. The reason for this lower effectiveness of the 2K HX could be the presence of stacked perpendicular fins causing the reduction of heat transfer capability, as suggested in Ref. [2]. Increasing the thermal load to the 2K HX reduces the effectiveness from 76% at 20 W of thermal load (0.855 g/s of mass flow rate) to 68% at 70 W (3 g/s).

As seen in the 2K HX geometry, the fins have holes in them to reduce the GHe pressure drop through the 2K HX, as the drag coefficient for the perpendicular flow over a flat fin can be as high as 2, but it also impacts the ability of the GHe to extract enthalpy from the LHe efficiently. The GHe pressure drop at the maximum thermal load was simulated to be 31 Pa, which is way less than the experimental pressure drop of 123 Pa, as presented in section 6.

### 5. Experimental setup – heat exchanger test stand

The 2K refrigerator coldbox encompasses a He I storage tank, a He II storage tank, a 2K HX and a JT valve for superfluid helium production. The 2K HXs can be tested for their efficiency on reducing the LHe temperature from 4.4 K to subcooled \( > 2.2 \) K via incoming 2 K GHe stream from a tank storing superfluid helium at 2.0 K. A JT valve reduces the LHe pressure from 101 kPa to approximately 3.1 kPa, and also maintains continuous production and level of superfluid helium in the He II tank, hence producing identical mass flow rates for both fluids through the 2K HX. This eliminates the need to measure the mass flow rate for the LHe at low temperatures. The low pressure in the He II tank is maintained by the helium gas pumping system with the maximum thermal capacity of 70 W (3 g/s). The components listed above are protected by two stages of thermal shields, inner one at 80 K and the outer thermal shield at 5 K.
5.1. Flow Control
Flow control for the fluids in the test stand are maintained by control valves placed at specific positions, as seen in figure 4. The control valve CV102 controls the flow rate of LHe flowing through the 5 K thermal shield to the LHe tank, supplied from the LHe storage Dewar (500 L). The control valve CV105 controls the flow of liquid nitrogen (LN₂) through the 80 K thermal shield, supplied from the LN₂ Dewar (200 L). The JT valve CV103 produces superfluid helium continuously and maintains the level of the superfluid helium via feedback from the level sensor of the He II tank. Control valve CV101 controls the bypass line connecting He I to He II tank. The control valve CV20, attached before the helium gas pumping system, controls pressure inside the He II tank. PID controllers (Yokogawa UT32a) are adopted to control the openings and closings of the valves. A 750 W power supply (Kikusui PWX750MHF) generates controlled thermal loads to evaporate superfluid helium in the He II tank. The dry gas meter (Shinagawa DS-65A) measures the flow rate of the helium gas pumping system under atmospheric pressure conditions.

5.2. Temperature and Pressure Sensors
The 2K test stand is equipped with temperature and pressure sensors to monitor the properties of fluids, as shown in figure 4. The platinum-cobalt (PtCo) alloy temperature sensors (Chino R800-6) monitor He I tank and 5 K thermal shield temperatures. T-type thermocouple is used to monitor the 80 K thermal shield temperature. The Cernox® (Lake Shore CX-1050) temperature sensors measure the 2K HX’s inlet and outlet temperatures of LHe and GHe, respectively. Absolute pressure sensors (MKS Instruments Baratron® Type 626C) monitor the fluid pressure conditions in the test stand. Silicon diode temperature sensor (Lake Shore DT670) monitors the temperature of superfluid helium in the He II tank. Pressure sensors PT105 and PT106 are fine range pressure sensors for accurate measurement at 0 - 13.3 kPa range. Superconducting liquid helium level sensors (AMI) monitor the levels of He I and He II in their respective tanks. An electric cartridge heater (100 W) at the bottom of the He II tank varies the flow rate of GHe through the 2K HX for performance measurement at variable thermal loads. The voltage readings from sensors are monitored and recorded via digital multimeter (Keithley 2000 and 6500). Current input (1 μA) to Cernox® sensors is provided with a DC sourcemeter (ADCMT 6243), and 1 mA to PtCo temperature sensors by Lakeshore 120 current source.

![Schematic diagram for the heat exchanger test stand](image)

6. Experimental results and discussions
The 80 K thermal shield was steadily operated at 110 K, and the 5 K thermal shield remained at 11 K during the experiment. The maximum mass flow instability generated by level control on the 2.0 K superfluid helium through the 2K HX was approximately 0.013 g/s. The pressure control on superfluid
helium in the He II tank was performed with the precision of ±10 Pa. The heater inside the He II tank was operated until 70 W (including flash losses) of power, as the helium gas pumping system has the capacity to handle 70 W (3 g/s) of thermal load at 3 kPa.

![Figure 5](image1.png)

**Figure 5.** (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.

The positions of the sensors are shown in the figure 5(b). The temperature data seen in the figure 5(a) is from the operational mode of the 2K HX (level control in the He II tank) with the heater power to He II being varied from 0 to 70 W. From the figure 5(a) it is observed that the inlet temperature of LHe (TI101) to the 2K HX remains constant throughout the experiment at around 4.2 K. The inlet temperature of the GHe (X51202) initially is > 2.0 K (below 20 W), due to the excess thermal load from the level sensor wire (above He II level) in the He II tank, heating the outgoing 2.0 K gas (see figure 4), before it reaches the 2K HX. In the case of thermal load to the 2K HX being more than 20 W, the GHe inlet temperature reduces and remains constant at 2.0 K, and the LHe outlet temperature (TI106) starts to rise with consequent increments in thermal load (20 to 70 W), which is also observed with the CFD results as seen in table 5. The GHe outlet temperature (TI205) of the 2K HX keeps on reducing, as the thermal load to it keeps on increasing.

![Figure 6](image2.png)

**Figure 6.** Experimental effectiveness and GHe pressure drop of 2K HX compared with CFD results.

![Figure 7](image3.png)

**Figure 7.** Flash loss w.r.t 2K HXs’ LHe outlet temperature.
The effectiveness of the 2K HX can be determined from the known temperature and pressure conditions, as shown in figure 5(a) and equations (5-7), and are summarized in figure 6. The actual heat transferred by fluids to each other through the 2K HX has an error of approximately 5% throughout the flow range, showing that the amount of heat removed by GHe is always higher than that given by the LHe. This is in part due to the heat load from surroundings coming to the SS316L casing wall of the 2K HX. The effectiveness (LHe effectiveness) obtained at 70 W of thermal load to the 2K HX was 74% (from figure 6), which provided 2.45 K of subcooled LHe at the outlet of the 2K HX, for GHe inlet temperature of 2.0 K, as seen in figure 5(a). The effectiveness of the 2K HX obtained from experiments is 6% higher than that from the CFD simulations. Also, the predicted effectiveness was higher at lower thermal loads (80% at 20 W) and kept on reducing with higher thermal loads (74% at 70 W), which was also observed in the CFD results (76% at 20 W → 68% at 70 W), as seen in figure 6 and table 5. The reason for such reduction in effectiveness from lower to higher thermal loads, as shown previously in section 2.1, is due to the GHe and LHe heat transfer coefficients, \( h_c \) and \( h_h \), respectively, being directly proportional to \( Re^n \), where \( n < 1 \). This causes the heat transfer coefficients not to rise with the same rate as the mass flow rate (directly proportional to thermal load) of the fluids, causing reduced heat transfer capability at higher flow rates.

The flash loss at 70 W of thermal load to the 2K HX was 14%, as seen in figure 7. The target value for the operational mode of the superfluid helium cryogenic system is 9%, corresponding to the 2K HX’s LHe outlet temperature of 2.2 K. The GHe pressure drop through the 2K HX at 70 W of thermal load was determined to be 123 Pa, which is higher than the required pressure drop of < 100 Pa, but not a priority factor for the superfluid helium cryogenic system at KEK.

7. Conclusion
The effectiveness of the 2K HX was determined experimentally and compared with the results obtained from the CFD simulations. The effectiveness of the 2K HX satisfies the specification only for the thermal loads smaller than 20 W. It was also observed that the heat transfer capability from LHe to GHe was hindered due to the presence of stacked fins perpendicular to the GHe flow and lesser surface area (NTU), hence the deteriorated performance of the 2K HX. The measured flash loss during the JT expansion in experiments was on par with the data obtained at the LHe outlet temperature of the 2K HX. Pressure drop of GHe through the 2K HX is quite large at higher flow rates, so it has to be reduced in the future designs.

8. Future Studies
The current results will act as the benchmark for the optimization of the current design using theoretical and numerical methodologies, and the new design will be tested in the heat exchanger test stand. More effort will be infused in reducing the discrepancies between the CFD simulation and the experimental results. The CFD simulations can act as a good tool to measure and compare the performance of the optimized design to the current design of the 2K HX. Experiments will be continued to determine the heat transfer coefficient of GHe.

9. References
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