氏　　　名	Ashish Kumar
学位（専攻分野）	博士（工学）
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学位論文題目	Study on 2K Heat Exchanger for Superfluid Helium Cryogenic Systems of Superconducting Accelerators
論文審査委員	主　査　　准教授　木村　誠宏 准教授　岡村　崇弘 准教授　中西　功太 助教　清水　洋孝 教授　仲井　浩孝 助教　髙田　卓 核融合科学研究所　ヘリカル研究部装置工学・応用物理研究系

(Form 3)

Summary of Doctoral Thesis

Name in full: Ashish Kumar

Title: Study on 2K Heat Exchanger for Superfluid Helium Cryogenic Systems of Superconducting Accelerators

The superfluid helium cryogenic systems are widely employed for the operation of superconducting magnets and cavities below 2.0 K. At KEK, superconducting radio frequency (SRF) cavities are used for electron beam acceleration at the compact Energy Recovery Linac (cERL) and the Superconducting RF Test Facility (STF) for the International Linear Collider (ILC). The SRF cavities operate at temperatures of 2.0 K or below, due to their higher resonant frequency of 1.3 GHz. To obtain temperature < 2.0 K, SRF cavities are cooled with saturated superfluid helium (He II), which is another phase of liquid helium (LHe or He I) when its temperature is below 2.17 K, under saturation condition. The superfluid helium is produced continuously via a Joule-Thomson (JT) valve in the cryogenic system, which also maintains the level of He II in the helium tanks of the SRF cavities. Also, a 2K heat exchanger (2K HX) is introduced in series with the JT valve to recover the coldness from evaporating saturated 2.0 K gaseous helium (GHe). 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. As such, the vapor flash loss (dryness) is also reduced from 40% to 9.4% during the JT expansion for production of 2.0 K saturated superfluid helium. The saturated vapor pressure (3.13 kPa) on the 2.0 K He II is maintained with the aid of rotary vane vacuum pump in series with roots blower, operating at room temperature and pressure. The capacity of these pumps to maintain 3.13 kPa vapor pressure is limited and will reduce with further lowering of inlet pressure. As such, if the GHe pressure drop through the 2K HX is high, it can reduce the inlet pressure to the vacuum pumps, hence reducing the flow rate through the 2K HX to maintain the level of He II.

At KEK, we have a 2K heat exchanger (2K HX_1) consisting of helically coiled tubes and laminated fins made of oxygen-free copper (OFC), designed by Prof. K. Hosoyama. It was designed to handle mass flow rates of ~3.5 g/s in counterflow arrangement. The laminated fins on the helical tube are to increase the surface area for the 2.0 K GHe and the enthalpy extraction is thus improved from the LHe flowing through the helical tubes. Two 2K HX_1 in series for each 2K refrigerator cold box are employed to obtain 84% effectiveness at the maximum operating flow rate for the cryogenic systems (~4 g/s). The focus of this research will be on determining the performance of the 2K HX_1 and the GHe pressure drop through it. Moreover, its design will be optimized to improve the He II production rate from the superfluid helium cryogenic systems. The performance of a heat exchanger 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, without mixing. The challenge in determining its effectiveness theoretically, is the unknown heat transfer properties of GHe flowing through the unique design of this 2K heat exchanger, hence it needs to be determined experimentally using a heat exchanger test stand. Also, a numerical model based on computational fluid dynamics (CFD) and finite difference methods (FDM) is employed to validate the experimental results and to study the heat exchanger design.

The performance of the 2K HX_1 was determined experimentally with the heat exchanger test stand to be 75% with a GHe pressure drop of 136 Pa at 3 g/s of mass flow rate. The quality of the He II (wetness) obtained at the exit of the JT valve was 86% (vapor flash loss – 14%). CFD simulations were performed with the aid of ANSYS CFX® to determine the heat transfer properties of GHe flowing through the 2K HX_1. The obtained results from the CFD simulations were fed to the numerical model to determine the effectiveness using FDM, performed with the help of Mathematica®. The effectiveness from CFD simulations and FDM was determined to be 73.2% with a GHe pressure drop of 118 Pa at 3 g/s.

A CFD based parametric study was also conducted to optimize the 2K HX_1 design, with the main goal of maximizing the He II production (or cooling capacity) for the cryogenic systems, while keeping the effectiveness of the 2K heat exchanger as high as possible. The current setup of the two 2K HX_1 in series for each cold box, produces 70 W and 80 W of cooling capacity at 2.0 K for STF and cERL cryogenic systems, with 84% effectiveness. The optimized 2K HX (2K HX_3) design has 84% effectiveness with 50% lower GHe pressure drop at 3 g/s, compared to the two 2K HX_1 in series. Due to the lower GHe pressure drop of the 2K HX_3, the cooling capacity of STF and cERL cryogenic system can be improved by up to 10%. From the parametric study, a particular design was manufactured and tested experimentally to prove the reliability of the numerical model for the 2K HXs. It provided higher effectiveness (by 4%) with lower GHe pressure drop (by 40 Pa) at 3 g/s flow rate, compared to the 2K HX_1, and the obtained experimental results were in agreement with its numerical model.

In conclusion, the performance of the 2K HX_1 was determined experimentally and verified with its numerical model. A parametric study of the 2K HX_1 design was conducted and its design was optimized. The optimized design (2K HX_3) improves the cooling capacity of the STF and cERL cryogenic systems. The parametric study was validated experimentally using the heat exchanger test stand at STF.

Form8・Separate Sheet
（様式８・別紙１）

Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏　　名　　Ashish Kumar

Title
論文題目　　Study on 2K Heat Exchanger for Superfluid Helium Cryogenic Systems of Superconducting Accelerators

近年の加速器では超伝導高周波空洞の周波数を上げて空洞の小型化を目指す事例が増え、それに伴って空洞の運転温度を 2 K 以下にする必要がある。超伝導加速器を 2 K 以下に冷却する超流動ヘリウム冷却システムでは、ヘリウム液化機で生成した液体ヘリウムをジュール・トムソン膨張させて、より温度の低い超流動ヘリウムを連続的に生成する。一方、その膨張過程で一部の液体ヘリウムが蒸発し、超流動ヘリウムの生成量が減少してしまう。超流動ヘリウムの生成量の減少を避けるため、ジュール・トムソン膨張させる直前の液体ヘリウム温度をできるだけ下げることにより、超流動ヘリウムの生成量を増加させることができる。これを実現するために 4.4 K の液体ヘリウムを空洞からの発熱によって蒸発した 2 K のヘリウムガスで 2.2 K まで冷却する 2K 熱交換器が導入されている。この熱交換器の最適化は超流動ヘリウムの生成量の増加、すなわち、超流動ヘリウム冷却システムの冷却能力の向上に重要な役割を果たす。

出願者はこの 2K 熱交換器の最適化を目指して、高エネルギー加速器研究機構の STF 棟および ERL 開発棟に設置されている超流動ヘリウム冷却システムの 2K 熱交換器について、ANSYS CFX®を用いて数値流体力学シミュレーションを行った。加えて STF 棟に設置されているテストスタンドで実際に熱交換器の性能を測定し、熱交換器の数値モデルおよび性能評価の妥当性を検証した。

2K 熱交換器の高性能化の為に、"effectiveness"の向上とヘリウムガス中の圧力降下の抑制を目指しつつ、トレードオフの関係にあるこれらのパラメータを超流動ヘリウムの最大生成量というパラメータを導入して適切に評価した。

"effectiveness"を増加させることによって温度の高い液体ヘリウムを温度の低いヘリウムガスで効率良く冷却することができるようになるが、その一方で熱交換器中での圧力降下が大きくなるとヘリウムガスを減圧する真空排気ポンプの実効排気能力が低下し、超流動ヘリウム冷却システムの冷却能力も低下してしまう。従って、"effectiveness"を増加させつつ、熱交換器での圧力降下を小さくするような設計指針が得られれば、超流動ヘリウムの生成量の増加が見込まれ、空洞の冷却を効率良く行う事ができるようになる。

出願者が、実際に稼働している 2K 熱交換器の形状をできるだけ変更しないように、数値流体力学シミュレーションによって 2K 熱交換器の最適化設計を行い、また、その設計による 2K 熱交換器を実際に製作して性能測定を行った結果、"effectiveness"の増加とヘリウムガス中の圧力降下の減少を実現することができた。これにより、出願者の最適化の手法が妥当なものであることが示された。

本審査会を兼ねた公開発表会では、出願者は論文内容を明瞭かつ簡潔に発表し、また、

聴講者を含む審査委員の質疑に対しても的確に回答し、研究内容を十分に理解していた。

また、出願者は現在までに複数の国際会議（peer review 付き）で発表を行っており、そのうちの論文 1 編が Cryogenics 誌への掲載に向けて査読中である。博士論文の執筆、本審査での発表および質疑応答は全て英語で行われ、英語能力は十分であることが確認された。

以上のことから、審査委員全員一致で Kumar 氏の博士論文の本審査を合格と判定した。

以上