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# Plate-fin heat-exchangers for a 10 kW Brayton cryocooler and a 1 km HTS cable

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**Abstract**

Plate-fin heat exchangers (PFHX) are designed and fabricated for a cryogenic cooling system, serving for a 10 kW Brayton cryocooler and a 1 km HTS transmission cable under development in Korea. To achieve compactness and thermal efficiency at the same time, a recuperative HX for Brayton cycle and a sub-cooling HX of liquid nitrogen for HTS cable are designed as integrated parts. A key design feature is focused on the coldest part of sub-cooling HX, where the streams of liquid nitrogen and refrigerant (helium gas) are arranged as two-pass cross-flow so that the risk of freeze-out of liquid nitrogen can be reduced. Details of hardware PFHX design are presented and discussed towards its immediate application to the HTS cable system.

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*Keywords:* Heat exchanger; plate-fin; Brayton cryocooler; superconducing cable; anti-freeaing

## 1. Introduction

A 10 kW Brayton cryocooler is under development in Korea as partial effort of the governmental project for high-temperature superconductor (HTS) power cable [1][2]. The goal of this project is to install and demonstrate the HTS cable and its cryogenic cooling system over 1 km length of transmission line (at 154 kV) in Jeju Island by 2016. The distributed thermal load is carried by a circulating flow of liquid nitrogen (LN) to the Brayton cooler [2]-[4] which is

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operational in a closed cycle with helium (He), as schematically shown in Fig. 1. The cryogenic system requires two different heat exchangers; a recuperative counterflow (He vs. He) heat exchanger (to be called HX-1) and a liquid-subcooling (He vs. LN) heat exchanger (to be called HX-2).

Plate-fin heat exchanger (PFHX) was selected for both HX's, as widely used in cryogenic refrigeration and liquefaction systems because of its compactness [6]. Chang et al. [5] presented a preliminary study on the thermal performance (including the effect of axial conduction through parting and end plates) and pressure drop loss to determine the dimension of HX's. As a result of the study, it was decided to modify the arrangement of HX-1 and HX-2 such that the entire HX body is fabricated into two pieces of nearly the same size, as illustrated in Fig. 1. The warmer HX-A is the major part (about 65~70%) of HX-1, and the colder HX-B is a combination of HX-2 and the remaining part (about 30~35%) of HX-1. It was evaluated with commercial software (Aspen-MUSE) that this modified HX design is a reasonable compromise between thermal performance and compactness, taking into accounts the losses due to pressure drop and axial conduction.

Lately, a crucial design issue has emerged on the possibility of freezing of liquid-nitrogen in a long-length cable [7]. As the distance between cooling stations gets longer, the required temperature of LN supply becomes lower (for example, down to 65 K) in order to maintain the liquid at subcooled state (i.e. well below its boiling temperature) for electrical insulation [8]. Even though the liquid (mean) temperature is above its freezing point (63.3 K), liquid may partially freeze on the HX wall [9], if the temperature of cold refrigerant (He) is lower than 63.3 K. The onset of LN freezing will result in an immediate shrink of flow passages, and may end up with a disastrous blockage of LN circulation. For safety, the cryogenic system should be operational clearly away from the freezing condition under normal load. At the same time, a proper anti-freezing scheme is also important in preparation for any abnormal fluctuation of thermal load.

Chang et al. [9] proposed and experimentally verified that cross-flow HX's are superior in anti-freezing of LN to typical counterflow HX's, because the temperature distribution in a cross-flow HX is basically two-dimensional. As next step, it is intended in this paper to effectively incorporate the proposed anti-freezing schemes into the practical PFHX's for the cryogenic system under development.

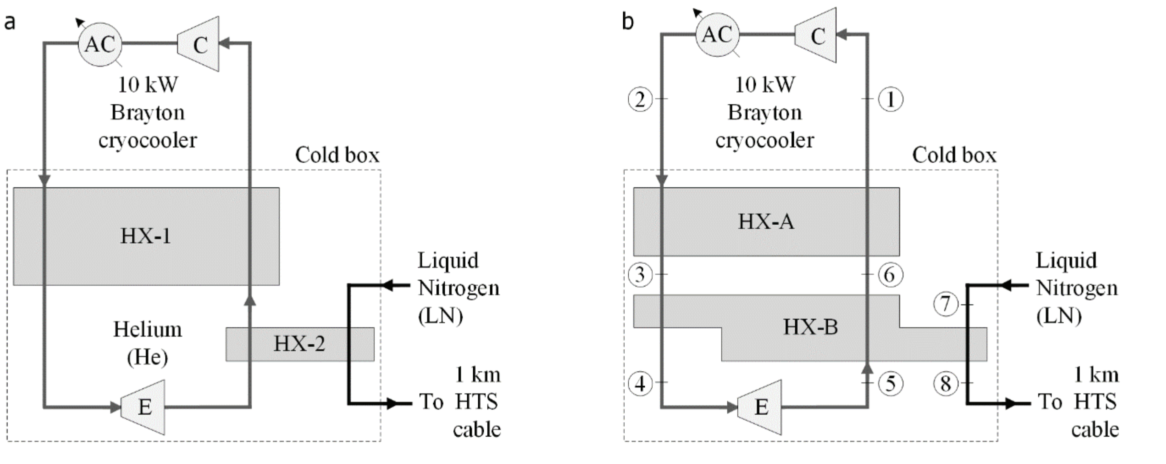


Fig. 1. Schematic flow diagram of cryogenic cooling system for a 10 kW Brayton cryocooler and a 1 km HTS cable (a) basic cycle (b) modified cycle with integrated HX design (C: compressor, AC: after-cooler, E: expander, HX: heat exchanger, He: helium, LN: liquid nitrogen).

## 2. Anti-freezing schemes of liquid nitrogen

Some ideas have been proposed as anti-freezing scheme of liquid nitrogen (LN). Yoshida et al. [7] suggested two different schemes. The first is a tube-in-bath type of HX shown in Fig. 2(a), where the cold gas flows in a cooling coil through LN container. Even though a complete blockage may be avoided under freezing condition, the size of this HX could be excessively large to achieve a reasonable level of effectiveness. The second is a two-stage type of

HX shown in Fig. 2(b), where the cold He gas is warmed-up through parallel flow HX at the first stage, before making a thermal contact with LN at the second stage. Detailed design was presented as plate-fin HX's and tube-in-tube HX's, but the plate-fin type was adopted because of its reliability and compactness. One disadvantage of this HX is that the pressure drop of refrigerant (He) through the winding passage could significantly affect the thermodynamic efficiency of Brayton cryocooler.

Another anti-freezing scheme recently proposed by Chang et al. [9] is to employ a cross-flow HX. In typical counterflow HX's, the temperature distribution of two streams is basically one-dimensional so that all flow passages may be clogged-up simultaneously under freezing condition. In cross-flow HX's, on the contrary, the fluid temperature varies not only along the flow direction, but also along the transverse direction so that some passages may remain open for the liquid flow under freezing condition. It was verified by a rigorous experiment that the two-dimensional nature of temperature distribution makes cross-flow HX's more robust against the freeze-out.

A simple cross-flow HX's, however, is not readily applicable here, mainly because the HX effectiveness is low. Two modifications were suggested to increase the effectiveness, while still taking advantage of anti-freezing [9]. One is to arrange cross-flow HX's as "multi-pass" in the direction of counterflow [6], as schematically shown in Fig. 2(c). As the number of passes increases, the effectiveness gets close asymptotically to that of counterflow HX, but the pressure drop becomes an important design factor. The other is to combine a cross-flow HX (as cold part) and a counterflow HX (as warm part), as shown in Fig. 2(d). This design can be considered as a scheme to take advantage of effective counterflow and anti-freezing cross-flow at the same time.

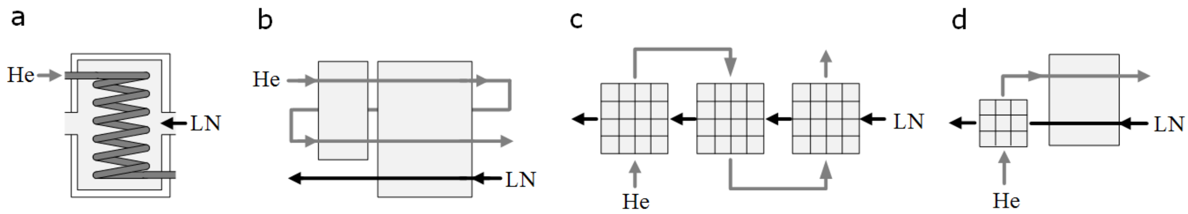


Fig. 2. Schematics of four different anti-freezing schemes proposed by Yoshida et al. [7] and Chang et al. [9] (a) tube-in-bath HX; (b) two-stage HX; (c) multi-pass cross-flow HX; (d) combined cross-flow and counterflow HX.

## 3. Results and discussion

Two PFHX's (HX-A and HX-B) are re-designed with incorporating the anti-freezing schemes presented in the previous section. The design concept is graphically shown as the layer-by-layer arrangement of plate-fins in Fig. 3. It is recalled that the overall size is nearly identical for the two HX's, and the inlets and exits are indicated by the numbers defined in the flow diagram of Fig. 1(b). In the drawings, the left side is the warm end, and the right side is the cold end for both HX's.

HX-A is a simple counterflow of high-pressure He (at warm layer) and low-pressure He (at cold layer), whose inlet and exit ports are installed in perpendicular direction to the main streams for compact assembly, as shown in Fig. 3(a). HX-B is composed of two parts; a counterflow of high-pressure He and low-pressure He (at left) and a two-pass cross-flow of cold He and warm LN (at right), as shown in Fig. 3(b). The cross-flow part is arranged such that the gas flow (He) has two passes in the direction of counterflow with the liquid flow (LN). It may be stated that the anti-freezing schemes shown in Fig. 2(c) and 2(d) are properly adopted here. Since the cryogenic turbo-expander is connected between ④ and ⑤ in Fig. 1(b), the coldest position of this cooling system is the helium exit of expander (⑤). This means that the freeze-out of LN will begin to occur, if any, at the top corner or the warm layer (i.e. the top of LN exit ⑧) of HX-B in Fig. 3(b), which is also the position where an electrical heat should be attached for emergency heating.

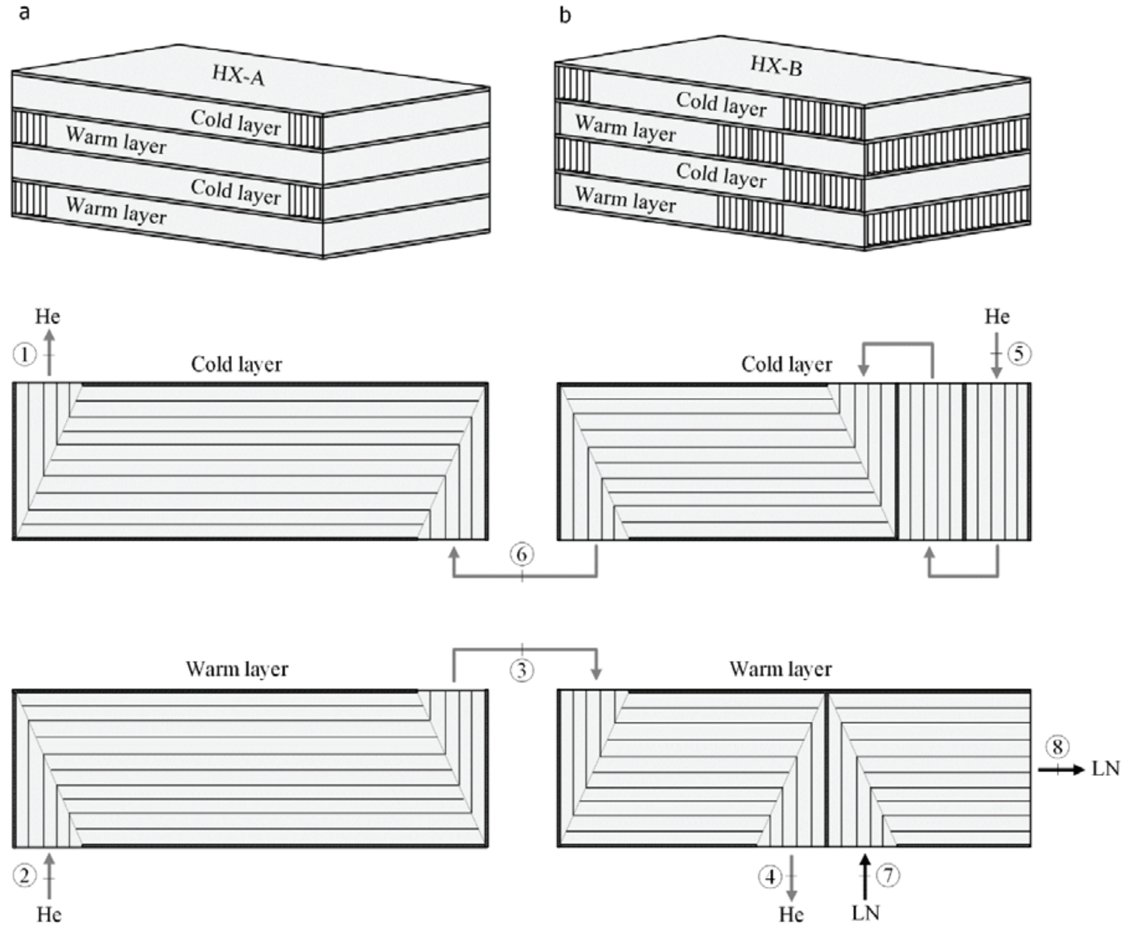


Fig. 3. Graphic representation of plate-fin heat exchanger design (a) HX-A (b) HX-B.

The design values of flow rate, temperature, and pressure at each point of cryogenic cooling system are re-calculated and listed in Table 1. The required heat exchange rate is 141 kW for HX-A, and 66 kW (counterflow) + 10 kW (cross-flow) for HX-B, respectively. As mentioned above, the coldest temperature at ⑤ (65.5 K) is higher than the freezing point of LN (63.3 K) under normal and steady-state condition, but the anti-freezing scheme is needed in preparation for unusual or temporary decrease of thermal load. A dynamic simulation for the transient behavior is also underway in parallel with this heat exchanger development.

The basic geometry and specifications of fins and parting plates are provided by the heat exchanger manufacturer (Donghwa Entec Co. Ltd.), as shown in Fig. 4. Fins are serrated type with a thickness of 0.1 mm, and the cross-section of a flow passage is approximately 1.3 mm x 3 mm. The material of fins and plates is aluminum 3003. The required size of HX-A and HX-B is determined by trail-and-error calculations with commercial software (Aspen-MUSE and HTRI-XPHE) and the results are also indicated in Fig. 4. For compact assembly in a cryostat of vertical cylinder, the warm side of HX-A is at top, but the cold side of HX-B is at top, where the cryogenic turbo-expander is connected. The manufacturer machined, stacked, and brazed the parts, and the final products were leak-tested (according to ASME BPV Code) and pressure-tested (1.5 MPa). Photographs of serrated fins and stacked plate-fins for brazing are shown in Fig. 5. The fabricated HX's are delivered to the KEPCO Research Institute, being ready for immediate assembly with other components of the cryogenic system.

Table 1 Design values of flow rate, temperature and pressure at each point of cryogenic cooling system in Fig. 1

| | Helium | | | | | | Liquid nitrogen | |
|---|---|---|---|---|---|---|---|---|
| | ① | ② | ③ | ④ | ⑤ | ⑥ | ⑦ | ⑧ |
| Flow rate, kg/s | 0.183 | 0.183 | 0.183 | 0.183 | 0.183 | 0.183 | 0.451 | 0.451 |
| Temperature, K | 293 | 298 | 150 | 80.9 | 65.5 | 145 | 78.0 | 67.0 |
| Pressure, MPa | 0.51 | 1.24 | 1.21 | 1.19 | 0.58 | 0.54 | 1.00 | 0.98 |

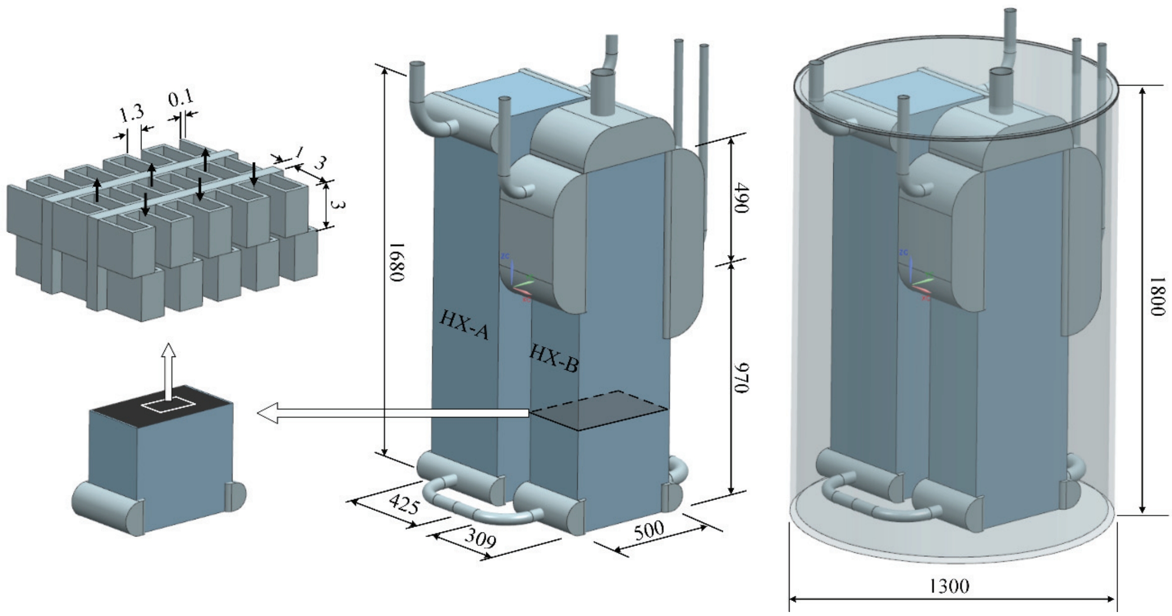


Fig. 4 Three-dimensional drawings of plate-fins and heat exchanger assembly (unit: mm).

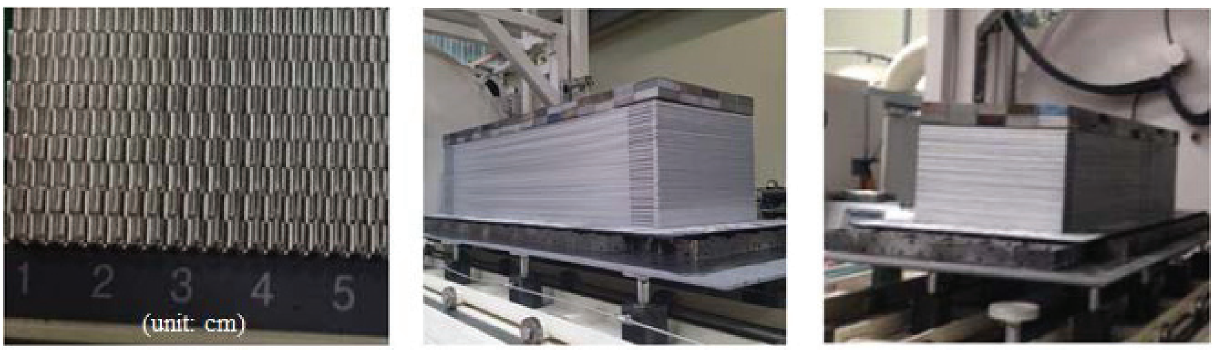


Fig. 5 Photographs of serrated fins and stacked plate-fins for brazing.

## 4. Conclusions

The progress of ongoing Korean HTS cable project is reported towards the cryogenic system for a 10 kW Brayton cryocooler and a 1 km cable that will be installed in transmission grid. As key components, two integrated heat exchangers are designed for the recuperation of helium gas in the Brayton cooler and the sub-cooling of liquid nitrogen supplied to the HTS cable. A special design effort is put into the cold end to reduce the freeze-out risk of liquid nitrogen by employing a two-pass cross-flow, as lately proposed and verified by an experimental study. The designed HX's are successfully fabricated, and now ready for practical application to an efficient, compact, and safe cryogenic system.

## Acknowledgements

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