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Cross-flow heat exchangers for anti-freezing of liquid nitrogen

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ABSTRACT

Cross-flow heat exchangers are proposed and experimentally investigated as an anti-freezing scheme of liquid nitrogen. The possibility of freeze-out of liquid nitrogen is an important design issue in developing long superconducting cables, as the supply temperature of liquid nitrogen is close to its freezing temperature (63.3 K). Plate-fin heat exchangers are fabricated as typical counter-flow and newly proposed two-pass cross-flow in laboratory scale, and tested with cold helium gas at temperatures below 60 K. The experimental results show that the cross-flow heat exchanger is less vulnerable to the freeze-out condition, since the temperature distribution is basically two-dimensional. The cross-flow heat exchangers are effective in avoiding a complete clog-up of all passages and reducing the risk of freeze-out of liquid nitrogen.

1. Introduction

Liquid nitrogen (LN) is an excellent coolant for high-temperature superconductor (HTS) power systems, including the HTS cable. The distributed thermal load is carried to a cryogenic refrigerator by the circulating flow of liquid nitrogen [7,5,6,4,9,3]. In high-voltage applications, it is important to maintain the liquid at sub-cooled state (i.e. well below its boiling temperature) for electrical insulation [8]. Fig. 1 schematically shows a long (1 – 3 km) HTS cable system with a large-capacity (10 kW) Brayton cryocooler under development in Korea [3] and typical liquid-nitrogen cycle on phase diagram. In sub-cooling heat exchanger (HX), liquid nitrogen is cooled from LN1 to LN2 in thermal contact with the cold refrigerant gas such as helium [7,3] or neon [9].

As the cable length between cooling stations increases in practical systems, the supply temperature of liquid is required to be as low as 65 K, and the possibility of freeze-out of liquid nitrogen emerges as a crucial design issue. Liquid nitrogen may freeze in the passage of HX if the wall temperature is lower than the freezing temperature (63.3 K). Fig. 2 illustrates an example of temperature profile of two streams (LN and He) and wall in a counter-flow HX under freezing condition. The dashed curve indicates the wall temperature, which can be determined by thermal resistance model [3]. It is noted that liquid may freeze even though the mean temperature of liquid flow is higher than its freezing temperature. Once liquid begins to freeze on the wall, the flow passages shrink and a disastrous blockage of circulation may occur. For safety, the cryogenic system should be operating certainly away from the freezing condition under normal load. At the same time, anti-freezing schemes are necessary in preparation for any abnormal fluctuation of thermal load.

Lately, Yoshida et al. [9] presented two design ideas to avoid the freeze-out of liquid-nitrogen flow. The first is tube-in-bath type HX, as shown in Fig. 3a. Since the cold gas flows in a cooling coil through liquid container, a complete blockage of liquid flow may be avoided even in case of partial freezing on the coil surface. The size of this system, however, could be enormously large to achieve a reasonable HX effectiveness. The other is two-stage type of plate-fin HX, as shown in Fig. 3b. The cold gas is warmed-up through parallel-flows at the first stage, before making a thermal contact with liquid nitrogen at the second stage. A disadvantage of this HX is that the pressure drop of refrigerant in the winding passage may significantly affect the thermodynamic efficiency of cryocooler.

In this paper, cross-flow heat exchangers are proposed as a simple and useful anti-freezing scheme. In cross-flow HX's, the fluid temperature varies not only along the flow direction, but also along the transverse direction. The two-dimensional nature of temperature distribution is one of the reasons why cross-flow HX's are thermally less effective than counter-flow HX's, but could be helpful in avoiding the complete blockage of liquid nitrogen under freezing condition. This study intends to fabricate a typical counter-flow HX and a newly proposed cross-flow HX in laboratory scale, and experimentally verify their flow and thermal characteristics of liquid nitrogen under freezing condition.

2. Design and fabrication of heat exchangers

Fig. 4a and b show plate-fin configuration and typical temperature distribution of counter-flow and cross-flow HX's, respectively. The isotherms are simply graphical sketches to illustrate the freez-

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Nomenclature

C	heat capacity rate, $\dot{m}c_P$ [W/K]
c_P	specific heat at constant pressure [J/kg K]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
q	heat transfer rate [W]
T	temperature [K]
t	time [s]

Greek letter

ε	heat exchanger effectiveness

Subscripts

1	inlet of heat exchanger
2	exit of heat exchanger
He	helium gas
LN	liquid nitrogen

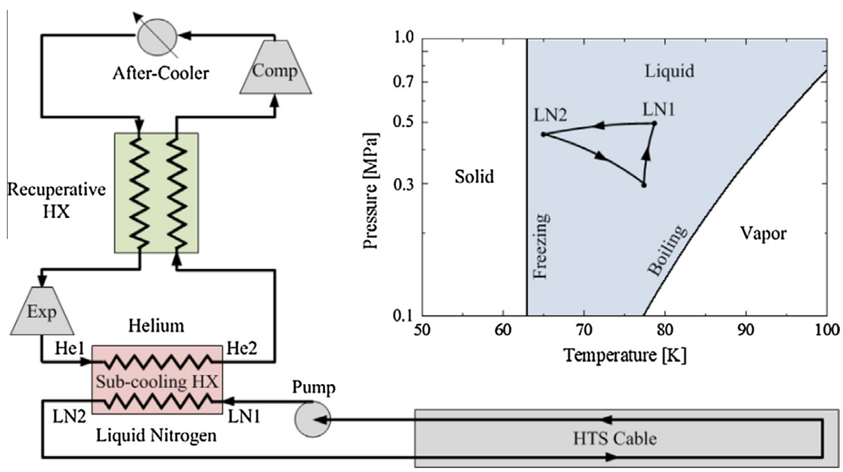

Fig. 1. Cryogenic refrigeration system for HTS power cable and liquid-nitrogen cycle on phase diagram.

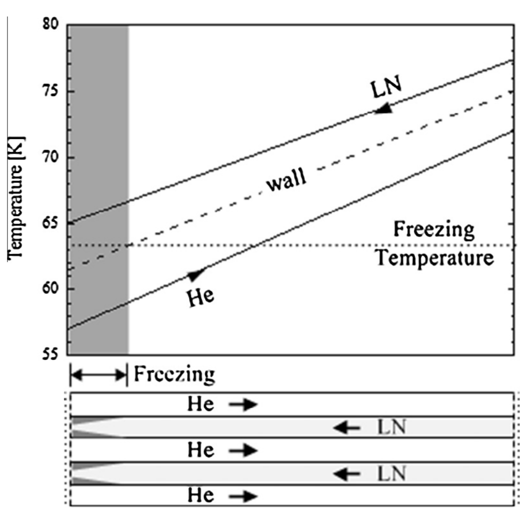

Fig. 2. An example of temperature profile in sub-cooling heat exchanger under freezing condition.

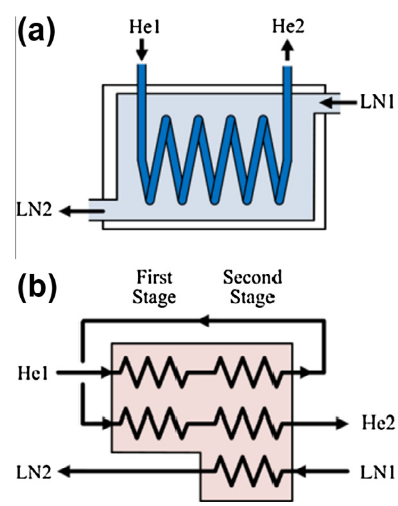

Fig. 3. Anti-freezing schemes presented by Yoshida et al. [9]. (a) Tube-in-bath type. (b) Two-stage type.

ing area. In counter-flow HX, the temperature distribution of two streams is basically one-dimensional so that all flow passages of liquid nitrogen may be clogged-up simultaneously under freezing condition. In cross-flow HX, on the contrary, the temperature distribution is two-dimensional so that some passages may remain open for liquid flow under freezing condition. A simple cross-flow HX, however, is not readily applicable here, because the HX effectiveness is small and there is a possibility of local freezing at normal condition, as illustrated in Fig. 4b.

Two-pass cross-flow HX is a compromise between counter-flow HX and simple cross-flow HX, as shown in Fig. 4c. Since the two passes of cross-flow are arranged in counter-flow direction, the HX effectiveness can be increased and the possibility of local freezing can be reduced. For cryogenic applications, plate-fin HX's are

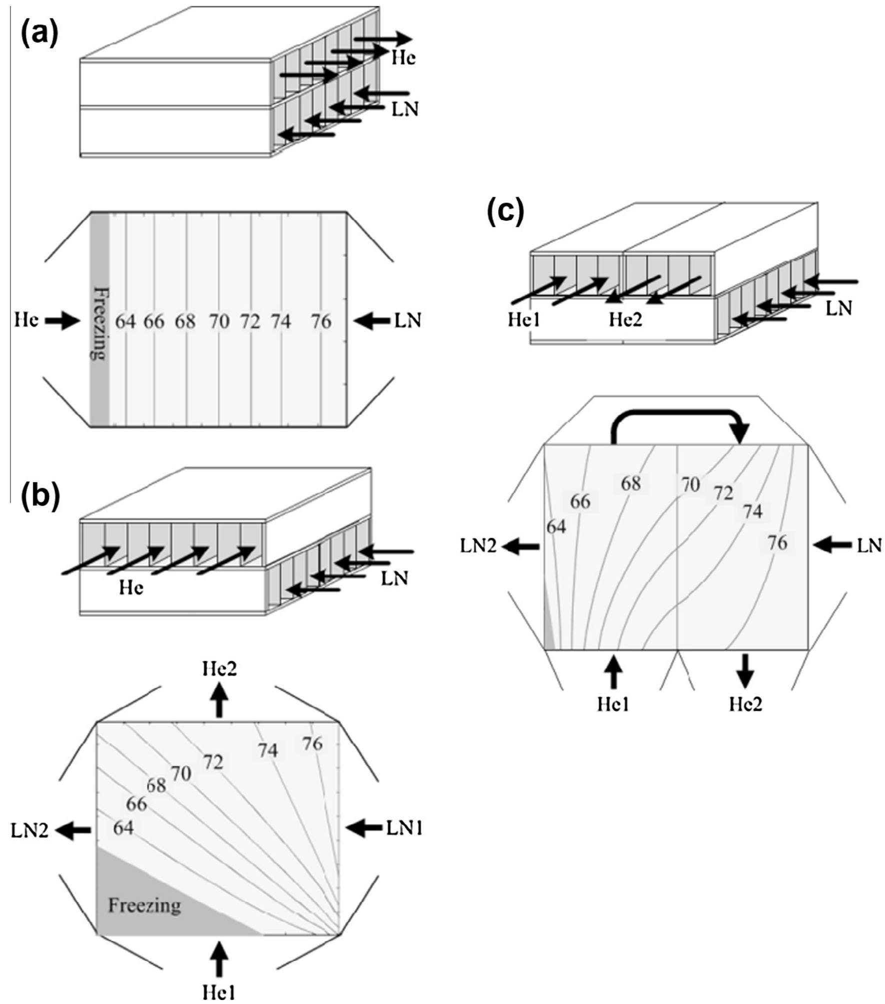

Fig. 4. Configuration of plate-fin heat exchangers and typical isotherms to illustrate the freezing area. (a) Counter-flow heat exchanger. (b) Cross-flow heat exchanger. (c) Two-pass cross-flow heat exchanger.

easily fabricated in multi-pass cross-flow, as widely used for multiple fluid streams in liquefied natural gas (LNG) or air liquefaction systems [1].

For experimental verification, a counter-flow HX and a two-pass cross-flow HX are designed and fabricated as plate-fin type. The size of HX's is determined in consideration of the refrigeration capacity of cryocooler used in experiment, the amount of helium gas consumption, and the space limitation of cryostat. A domestic HX manufacturer in Korea (Donghwa Entec Co. Ltd.) designed plate-fin HX's with commercial software (Aspen MUSE), and fabricated them with wavy fins of 3 mm height. The detailed dimension and specifications are listed in Table 1. Material of all parts including fins, parting sheets, side bars, and in/out ports is aluminum, and the cross-section of a flow passage is approximately 1.3 mm $\times$ 3 mm for both fluids. Fig. 5a and b are the layer-by-layer and assembled photographs of counter-flow and cross-flow HX's, respectively.

Table 1
Dimension and specifications of test heat exchangers.

	Counter-flow HX	Two-pass cross-flow HX
Number of layers	2 (He) + 3 (LN)	4 (He) + 5 (LN)
Total depth	31 mm	47 mm
Effective length	120 mm	120 mm
Total length	158 mm	146 mm
Total width	50 mm	50 mm
Fins	Aluminum, wavy fins, 0.1 mm thickness, 3.0 mm height, 787 fins/m	
Parting sheets	Aluminum, 1.0 mm thickness	
Side bars	Aluminum, 5.0 mm thickness	
In/Out ports	Aluminum, 10 mm outer diameter	

3. Experiment

Fig. 6 is a schematic overview of experimental set-up. A single-stage GM cryocooler (Cryomech Model AL300) is mounted on the top plate of a cryostat in order to provide helium gas to the test HX at temperatures below the freezing point of liquid nitrogen. The cryostat is partially filled with liquid nitrogen for pre-cooling the helium (He) and liquid nitrogen (LN) streams.

Helium gas from a high-pressure tank is cooled by three steps: (1) in a recuperator with the exiting flow of helium, (2) through the liquid-nitrogen pool, and (3) by the cold-head of GM cryocooler. The recuperator is a long (15 m) concentric tube HX made with two brass tubes (12.7 mm OD, 6.4 mm OD). The GM heat exchanger is tube-on-cylinder type, which was developed for previous experiment at Hong Ik University [2]. A copper cylinder (100 mm diameter, 100 mm height) is welded with a circular top plate,

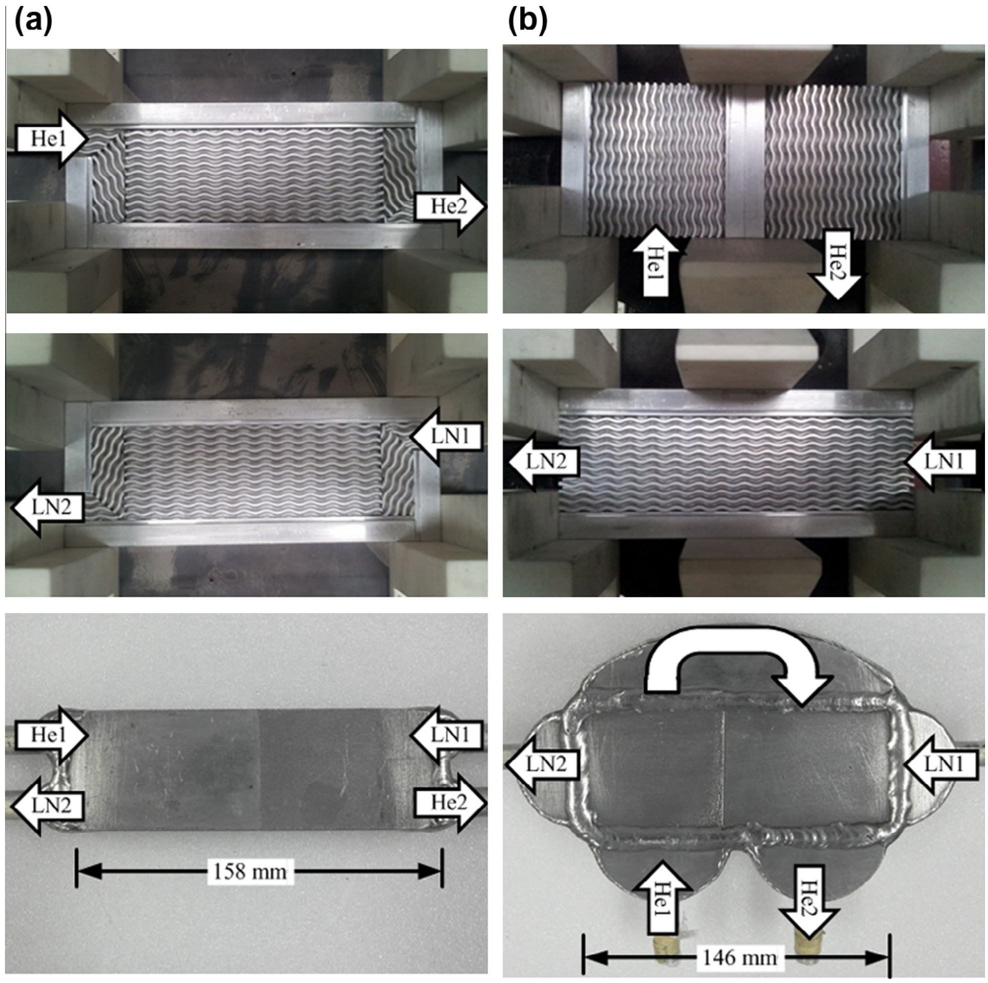

Fig. 5. Layer-by-layer and assembled photographs of test heat exchangers. (a) Counter-flow. (b) Two-pass cross-flow.

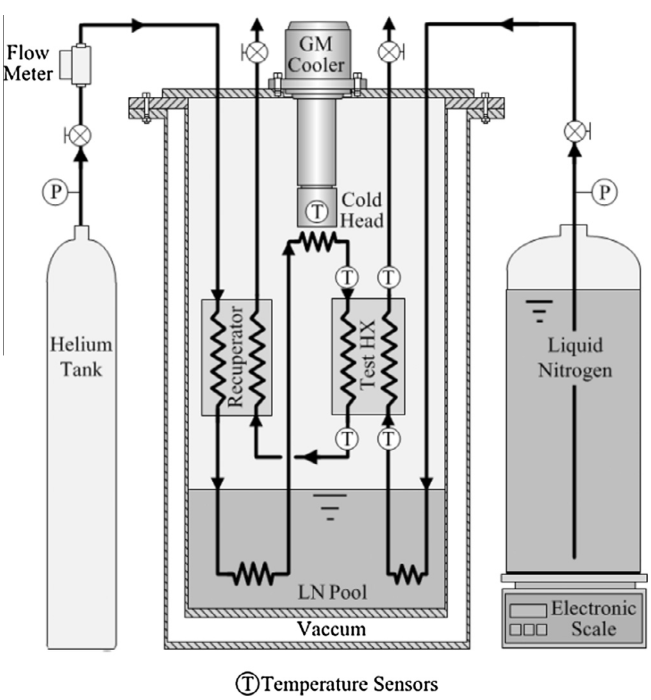

Fig. 6. Schematic overview of experimental set-up.

forming a "cup" shape (upside down) of extended surface. On external surface of the cylinder, a copper tube (6.4 mm OD) is spirally wound and brazed, and the top plate is bolt-jointed to the cold-head of cryocooler. Dimension and (experimentally confirmed) analytical model are fully described in Chang and Ryu [2]. A thermo-foil heater is attached on the cold-head of GM cryocooler to control the actual refrigeration power.

Liquid nitrogen is supplied from a pressurized container to the test HX, after passing through a long (15 m) tube submerged in liquid nitrogen pool. The boil-off gas from the pool can easily escape the cryostat so that the internal pressure is atmospheric and the liquid temperature is 77.3 K at all times. In order to make sure that the vapor fraction is zero and liquid is in sub-cooled state at the inlet (LN1) of test HX, the liquid pressure in the tube and test HX is maintained around 300 kPa, where the boiling temperature is 88 K. Since the cold-head and test HX are placed in a space filled with nitrogen vapor, it is important to insulate the surface to prevent the condensation of vapor. The external surfaces are heavily wrapped with foam insulation and covered with a plastic bag. Fig. 7 is a photograph of the top-plate assembly of cold-head of GM cryocooler, He recuperator, GM heat exchanger, and test HX.

Temperature is measured with silicon diode sensors (Lakeshore DT-670-SD) at the coldhead, the inlets (LN1, He1) and exits (LN2, He2) of test HX, as indicated by Ⓣ in Fig. 6. The subscripts LN and He denote the stream of liquid nitrogen and helium, respectively, and the subscripts 1 and 2 denote the inlet and exit of test

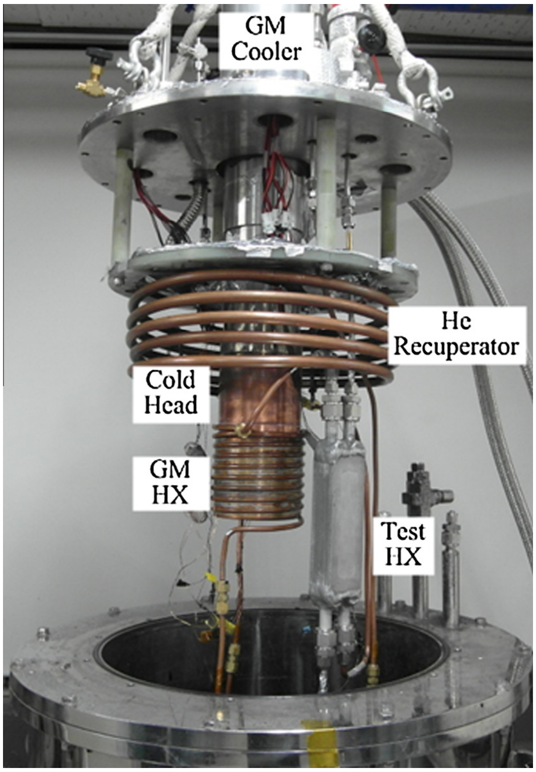

Fig. 7. Photograph of top-plate assembly of cold-head, helium recuperator, GM heat exchanger, and test heat exchanger.

HX, respectively. The sensors are attached tightly with cryogenic varnish on the surface, and temperature is recorded at every second with a data acquisition unit (Lakeshore Temperature Monitor 218).

The flow rate of helium is measured with a mass flow-meter (MK Precision Model TSM-240) at the exit of helium tank. A problem has been encountered in measuring small flow rate of liquid nitrogen, since a suitable LN flow-meter is unavailable or expensive. It was attempted to add a warm-up passage to the outflow of liquid nitrogen and use a gas flow-meter at room temperature, as successfully executed by Chang and Ryu [2]. In this experiment, however, the same method did not work, because the valve control is unstable and difficult in obtaining the steady flow of desired rate over the long piping system. A simple method is taken to directly measure the mass of liquid nitrogen container (m_{LN}) with an electronic scale as shown in Fig. 6 and estimate the flow rate by numerical differentiation.

$$\dot{m}_{LN} = -\frac{dm_{LN}}{dt} \approx \frac{m_{LN}(t-\Delta t) - m_{LN}(t+\Delta t)}{2\Delta t} \tag{1}$$

This estimate is accurate and independent of the sampling time (Δt) for steady flow, but has a limited accuracy on transient behavior, as discussed later. The small flow rate of liquid nitrogen is easily set at desired level, as liquid nitrogen is shortly ejected to atmosphere.

4. Results and discussion

Fig. 8a and b are the plots of measured temperature history to obtain a steady-state for counter-flow HX and two-pass cross-flow HX, respectively. Time is measured from the point of turning on the cryocooler and opening the helium tank, after purging the test HX with liquid nitrogen. The flow rate is 0.27 g/s for He and 0.67 g/s for LN, which are set to be the same in two HX's. The heat capacity rates are calculated as

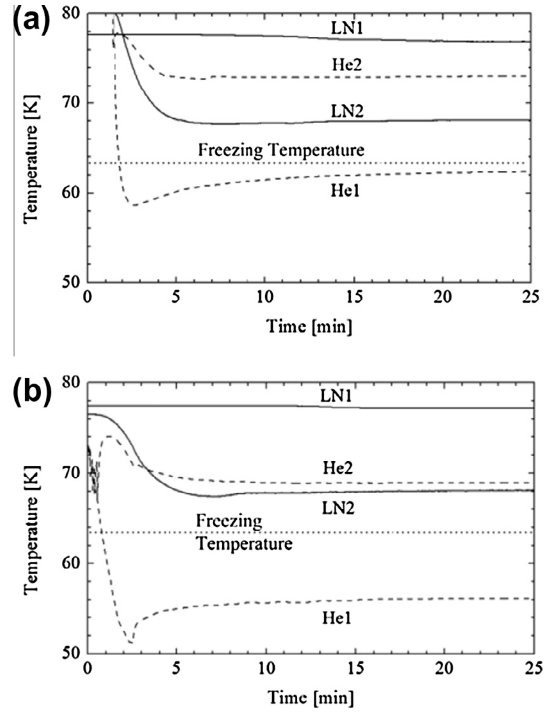

Fig. 8. Measured temperature history to obtain a steady-state for sub-cooling liquid nitrogen from 77.4 to 68.0 K. (a) Counter-flow HX. (b) Two-pass cross-flow HX.

$$C_{He} = \dot{m}_{He} c_{P,He} = 1.40\ \mathrm{W/K} \tag{2}$$

$$C_{LN} = \dot{m}_{LN} c_{P,LN} = 1.36\ \mathrm{W/K} \tag{3}$$

where c_P is the specific heat at constant pressure. In 2–3 min, the inlet temperature of helium (He1) drops below the freezing temperature of liquid nitrogen, and then gradually rises towards steady state. The heater power on the cold-head of cryocooler is 100 W for counter-flow HX and 80 W for two-pass cross-flow HX. These values are determined by trial-and-error such that liquid nitrogen is sub-cooled from 77.4 K (N1) to 68.0 K (N2) for the two HX's. It takes less than 20 min to reach the steady state.

In steady state, the cooling rate of liquid nitrogen is

$$q_{LN} = C_{LN}(T_{LN1} - T_{LN2}) = 12.8\ \mathrm{W} \tag{4}$$

for both HX's. Since C_{LN} is smaller than C_{He}, the HX effectiveness is defined as

$$\varepsilon = \frac{T_{LN1} - T_{LN2}}{T_{LN1} - T_{He1}} \tag{5}$$

The effectiveness is 63.1% for counter-flow HX and 43.9% for two-pass cross-flow HX. The first reason for these low values is that the HX areas are not large enough. In addition, the axial heat conduction through parting sheets and side bars is another reason for the low effectiveness. The heat leak due to conduction is more serious in two-pass cross-flow HX. From the energy balance, the ineffectiveness due to the heat leak is estimated to be 14.8% for counter-flow HX and 36.7% for two-pass cross-flow HX. In practical systems, the effectiveness could be significantly increased with a larger size of HX and with proper modifications of HX arrangement as discussed later, but the effectiveness itself is not a major issue of this study.

The main issue is the flow and thermal characteristics of two HX's under freezing condition. Fig. 9a and b show the transient behavior followed by stepwise variations of heater power to the

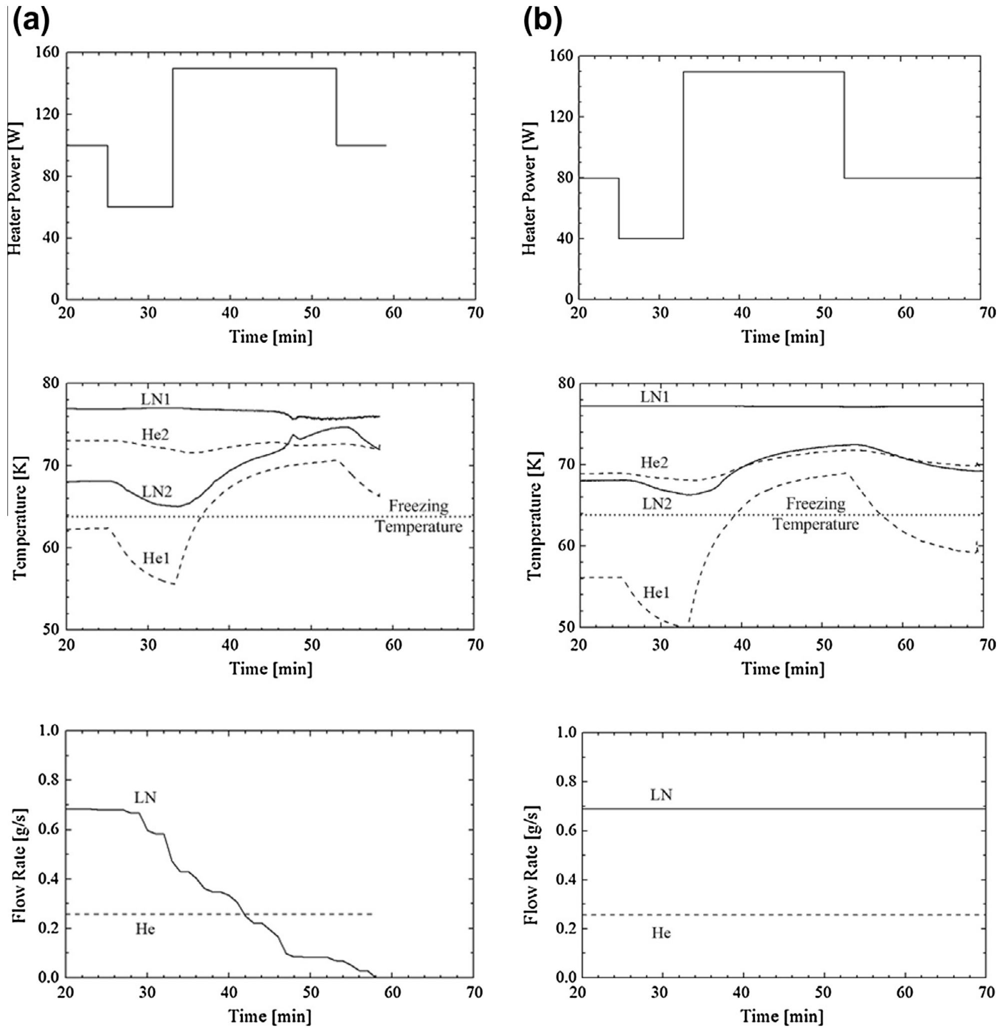

Fig. 9. Stepwise variation of heater power to cold-head of cryocooler, and measured history of temperature and flow rate. (a) Counter-flow HX. (b) Two-pass cross-flow HX.

cold-head of cryocooler. As shown in the top graphs, the heater power is reduced by 40 W for 8 min (as temporary freezing condition), then increased up to 150 W for 20 min (as warm-up condition), and finally returns to the original power (as recovery condition). The measured history of temperature (LN1, LN2, He1, He2) and flow rate (LN, He) is plotted in the graphs below over the entire process.

In case of counter-flow HX, the LN flow rate decreases shortly after the heater power is reduced. This means that liquid nitrogen begins to freeze on the passage wall, even though the mean temperature of liquid is well above the freezing temperature. The erratic decrease is more or less due to the error of numerical differentiation of Eq. (1). The LN flow continues to decrease and ends up with complete clog-up, no matter how high the helium temperature rises during the warm-up period. The key point in this experimental result is that the lowest bulk LN temperature is around 65 K at the beginning of the warm-up period, and then rises to a temperature above 70 K with a nonzero LN flow followed by a freeze-out process that eventually blocks the flow.

In case of two-pass cross-flow HX, the LN flow rate keeps constant over the entire process, which means that there is no noticeable change in flow resistance. The lowest helium temperature drops below 50 K, therefore liquid nitrogen must be at least under "local" freezing condition. A reason for the survival of LN flow in spite of the freezing condition is clearly the effect of two-dimensional temperature distribution in cross-flow HX. After the warm-up period, the test HX tends to gradually recover the steady state. Of course, the cross-flow HX cannot avoid the freezing of LN, if the helium temperature is decreased even lower. It is observed in other experiments that the surviving time before complete blockage is longer in cross-flow HX.

A quantitative criterion for anti-freezing condition is not easy to develop only with the presented results. On the other hand, it may be generally stated that cross-flow HX's are able to tolerate the freezing condition better than counter-flow HX's. The improved tolerability is an obvious merit in practical operation of the cryogenic cooling system, especially for power and utility services.

As mentioned above, a drawback of cross-flow HX's is low HX effectiveness. A variety of ideas are feasible to increase the effectiveness, while still taking advantages of anti-freezing. One way is to increase the number of passes in cross-flow such that the multi-pass cross-flow HX gets close asymptotically to a counter-flow HX [1], as shown in Fig. 10a. The other is to combine the cross-flow HX (at cold part) and the counter-flow HX (at warm part), as shown in Fig. 10b. Detailed heat-exchanger design is underway for application to the full-scale refrigeration system in the Korean HTS cable program.

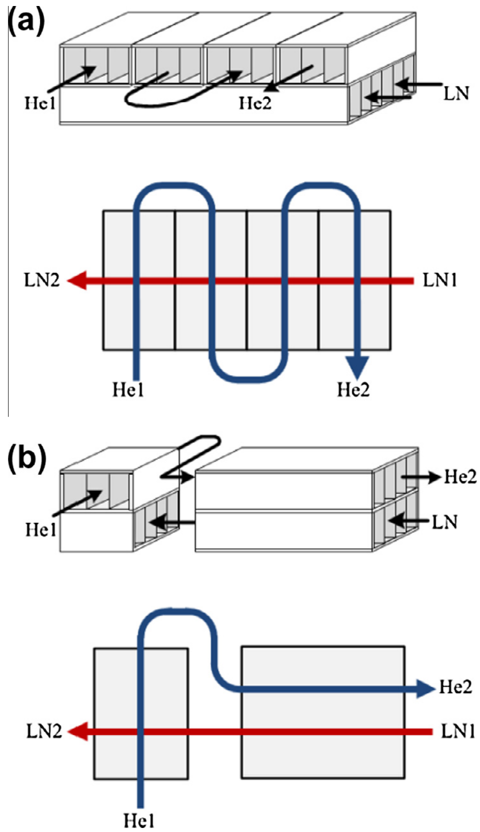

Fig. 10. Ideas to improve the effectiveness of cross-flow heat exchangers. (a) Multi-pass cross-flow HX. (b) Combined cross-flow and counter-flow HX.

5. Conclusions

Anti-freezing schemes of liquid nitrogen are investigated as partial efforts to develop a cryogenic cooling system of long HTS power cables in Korea. In order to verify the proposal to employ cross-flow heat exchangers for sub-cooling liquid nitrogen to 65 K, an experiment is designed and successfully executed in laboratory scale. Plate-fin heat exchangers are fabricated as a typical counter-flow HX and a newly proposed two-pass cross-flow HX, and their flow and thermal characteristics of liquid nitrogen are compared under freezing condition. It is demonstrated that the two-pass cross-flow HX is superior in anti-freezing to the counter-flow HX, mainly because the temperature distribution is two-dimensional. Two-pass or properly modified cross-flow heat exchangers are readily applicable to any cryogenic cooling system for effectively reducing the risk of freeze-out of liquid nitrogen.

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