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New application of plate–fin heat exchanger with regenerative cryocoolers

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ABSTRACT

A design idea is newly proposed and investigated for the application of plate–fin heat exchanger (PFHX) with regenerative cryocoolers. The role of this heat exchanger is to effectively absorb heat from the stream of coolant and deliver it to the cold-head of a cryocooler. While various types of tubular HX's have been developed so far, a small PFHX could be more useful for this purpose by taking advantage of compactness and design flexibility. In order to confirm the feasibility and effectiveness, a prototype of aluminum-brazed PFHX is designed, fabricated, and tested with a single-stage GM cryocooler in experiments for subcooling liquid nitrogen from 78 K to 65–70 K. The results show that the PFHX is 30–50% more effective in cooling rate than the tubular HX's. Several potential applications of PFHX are presented and discussed with specific design concepts.

1. Introduction

Regenerative cryocoolers are conveniently used in many cryogenic systems, where the refrigeration load is relatively small. A number of cryocooler models are available in market as Stirling, GM (Gifford–McMahon), or pulse tube cycle. Even though the operating principle of the refrigeration cycles is different each other [1,2], every regenerative cryocooler has the coldest cooling part in common as a cylindrical head surface called "cold-head". Since the diameter of cold-head is small (typically less than 120 mm), the effective cooling area is quite limited, which often becomes a major constraint in efficient thermal design.

A heat exchanger (HX) is employed to effectively absorb heat from a stream of coolant (such as liquid nitrogen or gaseous helium) and deliver the thermal load to the cold-head. Various types of tubular HX's have been developed for different applications so far. Yoshida et al. [3] and Suzuki et al. [4] used "tube-on-cylinder" HX's for HTS power systems as illustrated in Fig. 1(a). Liquid nitrogen is pumped and subcooled from 78 K to 65–70 K through two HX's attached to two units of GM coolers. The HX is composed of a thick cylindrical cup (upside down) as extended surface, on which a tube is spirally wound and brazed. Recently, Chang and Ryu [5] performed an experiment with different sizes of tubular HX's and also presented an analytical model to show that there exists an optimal size to maximize the cooling rate for a given unit of cryocooler.

A similar type of tubular HX was used also in GM–JT (Gifford–McMahon/Joule–Thomson) systems [6–9] for 4.2 K refrigeration, as shown in Fig. 1(b). The high-pressure helium stream of JT circuit is pre-cooled through spirally wound tubes at the cold-heads of two-stage GM cooler. In some cases, a finned-tube has been used in order to augment the external heat transfer. Similar HX's were used with GM cryocoolers for the cooling of HTS rotating machinery and superconducting magnetic energy storage (SMES) application. Since compactness is a major design factor in HTS motors for shipboard application [10], the cooling temperature of HTS windings is as low as 20–30 K [11], and a tubular HX was used as thermal interface between multiple units of GM coolers and circulating helium gas. In a recently developed SMES system [12], HTS windings were also cooled at 20 K by circular aluminum plates, having an internal hole through which gaseous helium is forced to flow. The thermal load is carried by helium to the cold-head of cryocooler, where a tubular HX was used as well.

Plate–fin heat exchanger (PFHX) is another (far different) type of heat exchanger, being also widely used in large-scale cryogenic refrigeration and liquefaction systems. It is made with multiple layers of corrugated aluminum sheets separated by flat plates to create a series of finned chambers. The primary advantage of PFHX is compactness and design flexibility. The surface area per unit volume is much greater (over ten times) than that of conventional shell-and-tube heat exchangers [13]. PFHX is easily designed in a variety of configurations, such as counter-flow, parallel flow,

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Nomenclature

C_P	specific heat of liquid nitrogen
d	hydraulic diameter
H	heat exchanger effective height
h	heat transfer coefficient
k	thermal conductivity
L	heat exchanger length
l	fin height
$\dot{m}$	mass flow rate
m_{LN}	mass of liquid nitrogen container
Nu	Nusselt number
q	cooling rate
T	temperature
t	time
w	fin pitch
z	vertical distance from bottom

Greek letters

δ	thickness of fin or plate
η_f	fin efficiency

Subscripts

1, 2, 3, ...	layer number of PFHX
e	exit
i	inlet
j	summation index of multi-stream
PFHX	plate–fin heat exchanger
w	side wall

cross flow, multi-pass or multi-stream HX's. [14,15]. On the other hand, the axial conduction through the aluminum plates could be an obstacle, if a large temperature gradient is required for compact cryogenic design.

In this study, it is proposed to apply a PFHX to various cryogenic systems where regenerative cryocoolers are used. This idea is motivated by an intuition that the axial conduction could be positively utilized, while still taking advantage of compactness and design flexibility. The direct combination of PFHX and regenerative cryocooler has never been reported, as far as the authors are aware. In order to confirm the feasibility of the proposed idea, it is intended to design, fabricate, and experimentally test a prototype of PFHX with a commercial GM cryocooler. In addition, a variety of potential application schemes of PFHX's are pursued.

2. Design and fabrication of PFHX

A plate–fin HX is designed for use with a single-stage GM cryocooler (Sumitomo Heavy Industry model RDK-500B [16,17]), as graphically shown in Fig. 2. The top portion of two rectangular side plates is bent by 90° so that the "wing-shaped" flanges can be served for bolt-joint with the cold-head. Out of 8 threaded holes evenly spaced on the bottom circle (108 mm diameter) of cold-head, 6 holes (3 holes with each plate) are used for assembly. The contact area between the cold-head and the PFHX is approximately 5500 mm^2 (61% area of the circle), which is the sum of two "D-shaped" circular segments. The top surface of flanges is machined and polished for a good thermal contact. The side plates will play an important role of thermal conductor that delivers heat from the streams in PFHX to the cold-head of cryocooler.

The number of layers between two side plates is seven, which is determined by the geometric constraint of cold-head. The seven layers are classified as two groups: odd-numbered (1, 3, 5, 7) and even-numbered (2, 4, 6) layers, which will be called "O-layers" and "E-layers", respectively. As shown in Fig. 3, the inlet/exit ports are located at left-top and right-bottom for O-layers and at right-top and left-bottom for E-layers. The two groups of layers can be used in parallel flow or counter-flow, as necessary. The custom-ordered PFHX is fabricated by a manufacturer in Korea. The specifications of prototype PHHX are listed in Table 1. Material of all parts including corrugated fins, sheets/plates, and inlet/exit ports is aluminum, and the cross-section of a flow channel is 1.3 mm × 3 mm ($w \times l$). Fig. 3 is the photographs of layer-by-layer views, stacked layers, and final product of the prototype PFHX.

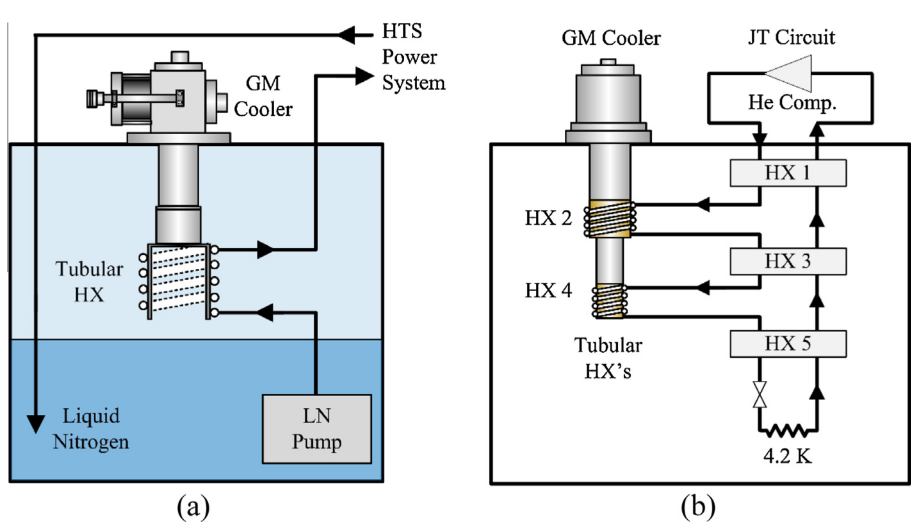

Fig. 1. Existing applications of tubular HX's with regenerative cryocoolers. (a) Liquid-nitrogen HX with single-stage GM cooler. (b) Helium HX for GM–JT refrigeration at 4.2 K.