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High-effectiveness miniature cryogenic recuperator

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Abstract

The performance of cryogenic refrigerator greatly depends on the effectiveness of heat exchanger, which generates major entropy at low temperature. There are numerous types of heat exchanger available, but it is not easy to apply most of them to cryogenic application because the cryogenic heat exchanger must have high effectiveness value as well as small conduction loss in the environment of considerable temperature difference. In this paper, two kinds of heat exchanger are noticeably introduced for high-effectiveness miniature cryogenic recuperator (recuperative heat exchanger). Also, the flow mal-distribution problem, which is a critical issue of performance deterioration in a high-effectiveness recuperator, is addressed with simplified model, and its alleviation method is discussed.

Key words: Cryogenic, Heat exchanger, Recuperator

Nomenclature

C_R : Heat capacity ratio
D_h : Hydraulic diameter [m]
h : Heat transfer coefficient $[\mathrm{W/m^2 \cdot K}]$
k : Thermal conductivity $[\mathrm{W/m \cdot K}]$
Nu : Nusselt number, $[hD_h/k]$
T : Temperature [K]
x : Flow mal-distribution parameter

Greeks

ε : Recuperator effectiveness

Subscript

c : Cold fluid
h : Hot fluid
i : Inlet of recuperator
o : Outlet of recuperator
I : Recuperator I
II : Recuperator II

1. Introduction

Cryogenic refrigeration is distinguished from conventional refrigeration by regeneration process either thermal or mechanical, which means the working medium must be reutilized to precool itself. A regeneration process is sometimes neglected in most room temperature conventional refrigeration cycles like a vapor compression cycle because the performance of the cycle is hardly changed with the existence of a regeneration process. The performance of cryogenic refrigeration, however, is essentially influenced by the efficiency of regeneration process. The heat exchanger for regeneration process is treated as a very important component in a cryogenic refrigerator.

An example of simple cryogenic refrigerator is shown in Fig. 1. This kind of cryogenic refrigerator, categorized as a simple recuperative cryogenic refrigerator, generally adopted as the fundamental essence in a large-scale cryogenic refrigerator like a gas liquefaction system. In the actual application, a

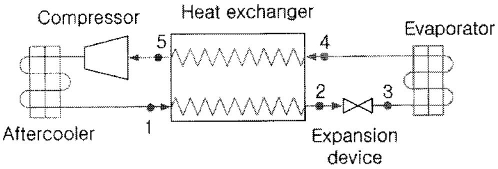

Fig. 1. Schematic diagram of cryogenic refrigerator (J-T cryocooler).

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spiral tube heat exchanger or a plate-fin heat exchanger is typically used as a high- effectiveness recuperator, but those are rarely adapted in small-scale cryogenic refrigerator.(1) Moreover, there is little study on miniature cryogenic recuperator.(2-5) We focus on highly effective recuperative cryogenic heat exchanger for the purpose of miniaturization. In this paper, several subjects on high-effectiveness recuperator for small-scale cryogenic refrigerator are addressed with practical issues including its fabrication and the performance.

2. Compact cryogenic recuperator

In general, miniature cryogenic recuperator requires small thermal mass and large heat transfer area for its high-effectiveness. Hence, the high-density compact structure is essentially needed. It can be realized by two kinds of compact configuration. One is a perforated plate heat exchanger(6), and the other is a PCHE (Printed Circuit Heat Exchanger)(7). The flow path of those recuperators can be extremely miniaturized by chemical etching process, while the other heat exchangers (plate-fin heat exchanger, spiral tube heat exchanger, etc.) may have limitation of flow path size owing to manufacturing process.

2.1 Perforated plate heat exchanger

A perforated plate heat exchanger is fabricated by stacking thin plates with perforated holes and spacers as shown in Fig. 2. The perforated plates are generally made of copper for excellent thermal conductivity in radial direction, and the spacers are made of material whose thermal conductivity is poor to reduce axial conduction loss. Therefore, it shows excellent thermal performance for high- effectiveness cryogenic miniature recuperator in a small-scale application, which requires large temperature difference with considerably short length.(8-9)

The thermal performance of a perforated plate heat exchanger is enhanced with increasing number of stacking plates or decreasing size of hole to be perforated. The more plates are stacked, the more heat transfer area is created, and the performance of heat exchanger is increased. If the hole size decreases, the heat transfer coefficient increases since Nusselt number defined as Eq. (1) is nearly constant value when the flow is laminar, which is generally observed flow in a perforated plate heat exchanger.

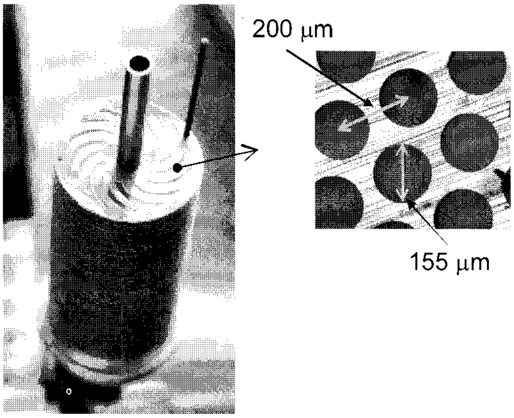


Fig. 2. Perforated plate heat exchanger(4).

$$\mathrm{Nu} = \frac{hD_h}{k} \tag{1}$$

The minimum size of holes, however, has the limitation of larger than two times plate thickness due to restraint in etching process. In the case that a smaller hole is required to enhance the performance of recuperator, the thickness of plate should be reduced, and it makes the number of stacking plates increase. Generally, the stacking direction of perforated plate heat exchanger is the same with flow direction of heat exchanger. Therefore, increasing number of stacking plates makes the fabrication process costly. In addition to that, the leakage between the plates becomes more serious as the number of stacking plates increases.

The spacer can be made of poor thermal conductivity material like stainless steel or polymer. It is preferred to use stainless steel spacers, which are to be bonded with perforated plates by vacuum brazing or diffusion bonding since it provides more reliable leakproof design. On the other hand, polymer spacers require an auxiliary pressing device to prevent leakage by thermal contraction in cryogenic environment even though polymer spacers have lower thermal conductivity than stainless steel.

2.2 PCHE (Printed Circuit Heat Exchanger)

PCHE has a similar but little different flow structure to that of an usual plate heat exchanger. The flow path of PCHE is created by etching process, while that of plate heat exchanger is by stamping process. Also, there is no gasket-sealed structure in PCHE structure. The photo of finely etched plate is depicted in Fig. 3. The etched plates are stacked and bonded by vacuum brazing or diffusion bonding. In the case that the flow path is very fine (hydraulic diameter is less than about 200 ㎛), diffusion bonding is preferred. The reason is that the flow path can be clogged by the filler metal in vacuum brazing process. PCHE fabricated by diffusion bonding is shown in Fig. 4.

The stacking direction of PCHE is perpendicular to flow direction, so the number of stacking plates is much smaller than that of perforated plate heat exchanger. However, the bonding area of plate is much larger than that of perforated plate heat exchanger. Thus, it is very difficult to achieve leakproof bonding. Especially, pressure condition in the diffusion bonding process becomes a critical parameter besides temperature and bonding time condition. If the pressure is not uniformly distributed along the plates, the incomplete bonding point is created due to pressure deficiency, then, the leakage occurs at the point. Therefore, the etching flow pattern of PCHE should be carefully designed with consideration of pressure distribution as well as thermal and hydraulic performance.

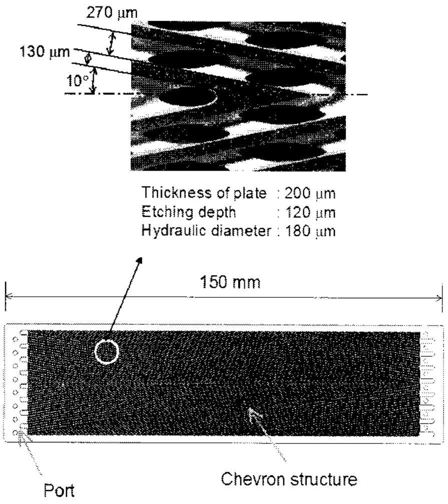


Fig. 3. Etched flow pattern in PCHE(3).

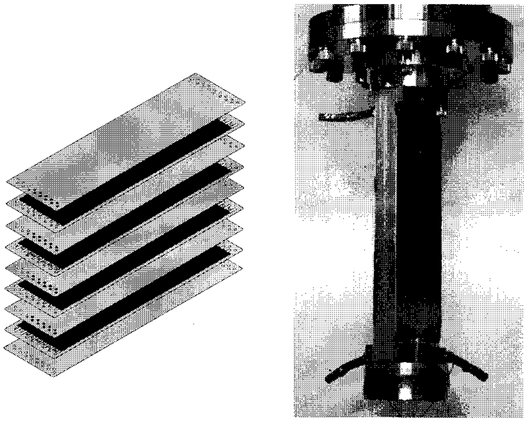


Fig. 4. Fabricated PCHE(3).

3. Flow mal-distribution

The perforated plate heat exchanger and the PCHE usually have multiple channels because thermal performance is improved with multiple small channels rather than a single large channel. In designing a multi-channel heat exchanger, it is generally presumed that the flow is uniformly distributed through the channels. However, the performance degradation by flow mal-distribution is always observed, and it becomes crucial in the case of high-effectiveness recuperator (NTU>20). Flow mal-distribution can be caused by a poor header design, blockage in channels, temperature-dependent viscosity effect, two-phase instability, fouling, and so on.(11-13) Especially, when we treat a small channel, it is difficult to control precisely the dimension of channel size. Therefore, the tolerance of fabrication, which is difficult to specify, results in the critical cause of flow mal-distribution.

3.1 Modeling of flow mal-distribution

Considering a simple two single-channel recuperator as shown in Fig. 5, the cold fluid outlet temperature of each recuperator can be expressed in Eq. (2) with respect to mal-distribution parameter x.(14) Here, the cold stream is assumed to be evenly distributed by 0.5 or 50%, but the hot stream is mal- distributed by x and 1-x.

For Heat exchanger Part I,

$$(T_{\mathrm{h,o}})_{\mathrm{I}} = T_{\mathrm{h,i}} - \frac{1-\exp^{-\mathrm{NTU}(1-C_{\mathrm{R,I}})/2}}{1-C_{\mathrm{R,I}}\exp^{-\mathrm{NTU}(1-C_{\mathrm{R,I}})/2}}(T_{\mathrm{h,i}}-T_{\mathrm{c,i}})$$

where $C_{\mathrm{R,I}} = x/0.5$

For heat exchanger Part II,

$$(T_{\mathrm{h,o}})_{\mathrm{II}} = T_{\mathrm{h,i}} - C_{\mathrm{R,II}}\frac{1-\exp^{-\mathrm{NTU}(1-C_{\mathrm{R,II}})/2}}{1-C_{\mathrm{R,II}}\exp^{-\mathrm{NTU}(1-C_{\mathrm{R,II}})/2}}(T_{\mathrm{h,i}}-T_{\mathrm{c,i}})$$

where $C_{\mathrm{R,II}} = 0.5/(1-x)$

(2)

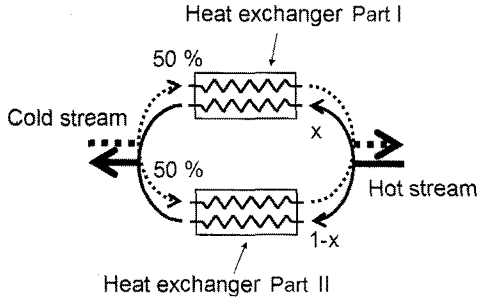


Fig. 5. Two single-channel recuperator model.

The ineffectiveness of the recuperator is then finally calculated as Eq. (3).

$$1-\varepsilon=\frac{x(T_{\mathrm{h,o}})_{\mathrm{I}}+(1-x)(T_{\mathrm{h,o}})_{\mathrm{II}}-T_{\mathrm{c,i}}}{T_{\mathrm{h,i}}-T_{\mathrm{c,i}}} \tag{3}$$

As shown in Fig. 6, the ineffectiveness has the designed value at x=0.5, but severe degradation is observed as mal-distribution parameter x deviates from 0.5. In addition to that, the amount of degradation effect becomes much critical as NTU increases, which means the mal-distribution effect is very important in designing a high-effectiveness recuperator.

3.2 Flow mal-distribution alleviation method

The effect of flow mal-distribution is possibly alleviated by several methods. It can be alleviated by controlling the pressure drop characteristic of channel using viscosity change induced by fluid temperature variation,(10) but it accompanies severe pressure drop. Another method is to construct bypass structure between flow passages like Fig. 7. The transverse bypass holes are implemented in this structure so that the interlayer mixing of each hot stream or cold stream is possible. The flow can be forcibly mixed through bypass structure, so the flow can be redistributed even if the flow is mal- distributed by inhomogeneity of channels. The experimentally measured ineffectiveness of PCHE with and without bypass structure are shown in Fig. 8. As shown in Fig. 8(a), the ineffectiveness of PCHE without bypass structure is larger than the estimation, and it even increases as mass flow rate goes higher. The fact shows that the performance degradation is due to the deficiency of the overall heat transfer coefficient which is driven by flow mal-distribution, not the conduction loss.(14) If the overall heat transfer coefficient

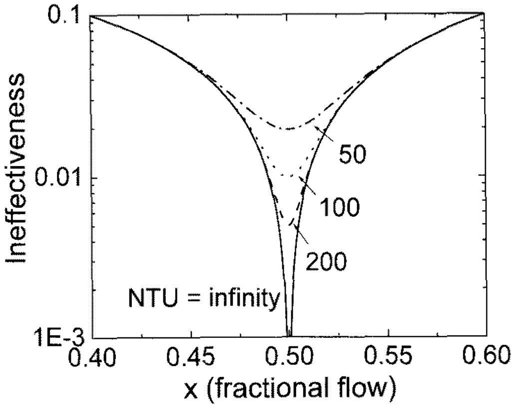
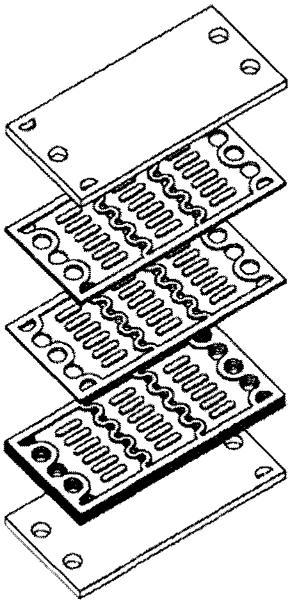
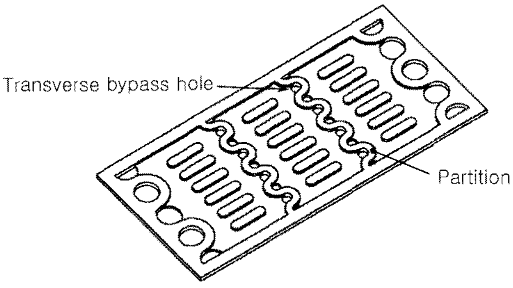


Fig. 6. Thermal ineffectiveness with respect to flow in two channel heat exchanger model.

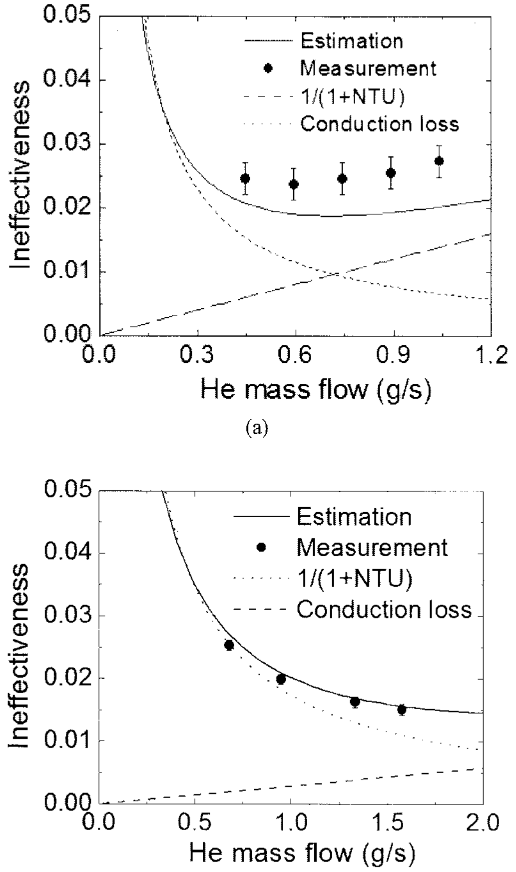


(a)



(b)

Fig. 7. Schematic diagram of transverse bypass PCHE; (a) overview and (b) specific structure(14).



(a)

(b)

Fig. 8. Ineffectiveness of PCHE; (a) without bypass structure and (b) with bypass structure(3,15).

is assumed to be reduced by 35%, the measured value agrees well with the estimated value. The flow mal-distribution effect can be eliminated by adopting the bypass structure in multi-channel recuperator design. The estimation and the measured value agree well as shown in Fig. 8(b). This shows that the bypass structure alleviates flow mal- distribution effectively.

4. Conclusion

Two kinds of recuperator, a perforated plate heat exchanger and a PCHE (Printed Circuit Heat Exchanger), are introduced for high-effectiveness miniature cryogenic recuperator. They can be fabricated to have very small flow path by chemical etching process. Advanced bonding methods (vacuum brazing or diffusion bonding) are applied for small flow path. The performance deterioration owing to flow maldistribution problem is treated with a simplified model, which shows that it becomes critical in high-effectiveness recuperator. The degradation effect can be alleviated by a smart structure adopting flow bypass scheme in the design of the recuperator.

Acknowledgement

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