# Miniature PCHE-Type Recuperator with Transverse Bypass

**J. Jung, S. Jeong, G. Hwang**

Korea Advanced Institute of Science and Technology
Daejeon, Republic of Korea

## ABSTRACT

A high effectiveness multi-channel heat exchanger may have a flow distribution problem. Even slightly mal-distributed flow, in such a heat exchanger, causes a severe thermal performance reduction, but what is worse is that the complete elimination of flow maldistribution is practically impossible. No matter how good the design or the manufacture of the heat exchanger will be, the flow is slightly mal-distributed (the only way of avoiding it is to make a single-channel heat exchanger). During the investigation of a miniature PCHE-type (Printed Circuit Heat Exchanger) recuperator, the performance reduction due to flow maldistribution is observed. One of the methods to alleviate it needs to be adapted.

In this paper, the transverse bypass structure is combined with a conventional PCHE. In a conventional PCHE, hot stream layer and cold stream layer stacked alternately with the fluid in each layer, and they are completely separated. On the other hand, in the transverse bypass PCHE, the layers of hot or cold stream are joined to each other through the transverse bypass. Hence, internal flow redistribution and partial flow mixing are allowed. The performance reduction which was observed in the conventional PCHE is alleviated in the transverse bypass PCHE.

## INTRODUCTION

A regeneration process is an essential part of a cryogenic refrigeration cycle. A thermodynamic device in which the regeneration process takes place is either a regenerator or a recuperator. A regenerator is adopted in a periodic cycle and a recuperator is adopted in a steady operation cycle. Most of small-scale cryogenic refrigerators operate in a periodic cycle, and accordingly many regenerators are needed. People have great interest in them and a variety of analytic and experimental results are available. Moreover, there are still some on-going studies.

However, the circumstances are very different for recuperator. They are not used widely in small-scale cryogenic refrigerators. People have little interest in them, and the studies are very rare. The authors had the specific application of a recuperative pulse tube refrigerator[1], especially for such a miniature recuperator, but there was not an appropriate one for the application. Hence, the decision was made to develop the required one. The recent results of this effort are presented in this paper.

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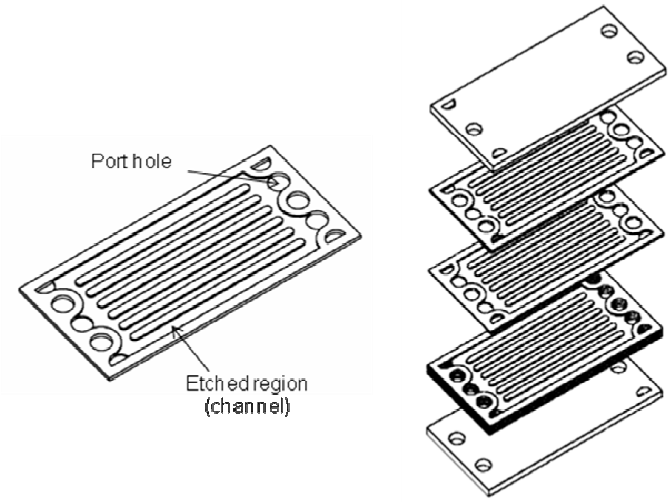



**Figure 1.** Schematic diagram of PCHE.

## CORE FOR MINIATURE RECUPERATOR

The most important factor in a miniature recuperator is the heat transfer area. Sufficiently large heat transfer area leads to a high effectiveness and, accordingly, to a small recuperator loss. Large heat transfer area, typically, requires a huge size. Thus, we have to consider the compactness of a heat exchanger as well. The most compact heat exchanger among various types of heat exchanger is a mesh-type regenerator which is commonly applied in small-scale cryogenic refrigerators.[2]

Conventional tube-bundle-cored heat exchangers (such as coil-wound heat exchangers) have far lower compactness. Even compact-cored heat exchangers (such as plate heat exchangers and plate-fin heat exchangers) are not comparable to mesh-type regenerators in compactness. Those types of heat exchanger cannot be adopted as a miniature recuperator. Instead, perforated plate heat exchangers with mini or micro perforations are preferred. They can be manufactured as compactly as mesh-type regenerators, introducing advanced machining technology for small perforations. It is found that an etching-cored heat exchanger[3] (PCHE) can also be well miniaturized so compactly as mesh-type regenerators.

The typical structure of a PCHE is shown in Fig. 1. It looks like a plate heat exchanger with each plate having etched channels. Reducing etching width and depth of channels in a PCHE, mini or micro channels can be easily formed. The etched plates are, then, stacked and bonded to form a complete heat exchanger. Two bonding methods are applicable to PCHE: vacuum brazing and diffusion bonding. Vacuum brazing is restrained to bonding of less finely etched plates (hydraulic diameter of channel > ~ 200 μm). Otherwise, molten filler metal which appears during brazing process may fill the channels, so an entire or a portion of the channels may be clogged. Applying vacuum brazing, bonding failure is easily encountered due to plate wrinkle. It is caused by thermal distortion of stacked plates. In general, such a bulky object like stacked plates does not have uniform temperature distribution during the heating process. This causes some wrinkled plates. The best way to prevent the wrinkle problem is to press the stacked plates with a force force during the brazing process. Then, wrinkle is effectively suppressed.

Diffusion bonding, on the other hand, does not have any restraint in channel size. It is applicable to fine channels, because no liquid phase appears during bonding process. Contact pressure between bonding surfaces is of the utmost importance in this case. Unless the contact

pressure reaches its minimum requirement, the surfaces in contact do not bond. Moreover, a huge pressing force does not always guarantee successful bonding. In the vicinity of etching-generated void, local contact pressure may not reach the requirement of contact pressure even with huge pressing force. Thus, structural analysis for pressure transmission has to be accompanied for successful diffusion bonding.

## THERMAL PERFORMANCE MODEL

A well-established ε (effectiveness) - NTU relation[4] including axial conduction effect is applied to a PCHE-type recuperator as a thermal performance model. It is given by Equation (1).

$$1-\varepsilon=\frac{1}{1+\mathrm{NTU}\left\{\dfrac{1+\lambda\left[\lambda\mathrm{NTU}/\left(1+\lambda\mathrm{NTU}\right)\right]^{1/2}}{1+\lambda\mathrm{NTU}}\right\}} \tag{1}$$

where $\lambda=\dfrac{kA_{\mathrm{cond}}/L}{\left(\dot{m}c_{\mathrm{p}}\right)_{\min}}$.

Heat transfer coefficient for PCHE core is available from Heatric company.[5] This simple model enables us to estimate the recuperator performance quickly and easily, but temperature-dependent property effect is not included in the model.

## FLOW MAL-DISTRIBUTION EFFECT

Performance deficiency has been reported in a multi-channel cryogenic recuperator.[6-9] The deviation between the estimated performance and the measured performance are sometimes too large to be regarded as just simple error like round-off error or instrumental error. In the case of a single-channel recuperator, however, difference between estimation and measurement is not so severe.[10] People have inferred that performance deficiency in a multi-channel heat exchanger is originated from mal-distributed flow (not evenly distributed flow). In fact, it was indirectly verified by Cowans.[6] He experienced the performance deficiency in his multi-channel recuperator. Introducing flow compensating mechanism to his recuperator, he could obtain design performance with significantly reduced performance deficiency. This indirectly reveals that the performance deficiency is due to flow mal-distribution. Performance deficiency, hence, has to be presumed in a multi-channel recuperator, and we need to avoid it for high-effectiveness heat exchanger.

The authors summarized some methods for alleviating flow mal-distribution problem.[11] Those methods can be classified into two categories. The first category handles the flow itself (flow regulation or flow re-distribution) to reduce performance deficiency, and the second one makes a heat exchanger resistant to flow mal-distribution (small performance deficiency even under severe flow mal-distribution). For example, temperature-controlled flow compensating mechanism of Cowans belongs to the first category. Also, a baffle installed at a header of a plate-fin heat exchanger for uniform flow distribution belongs to the first one. The flow itself changes as a result of the applied methods, and performance deficiency is reduced. As the second method, if we enhance transverse conduction through a recuperator body without enhancement of axial conduction, performance deficiency would be reduced.[12] In this case, the flow does not change. The recuperator gets resistant to flow mal-distribution. However, the methods for mitigating flow mal-distribution effect have their own demerits. The flow compensation of Cowans requires a large pressure drop, and enhanced transverse conduction usually accompanies the enhanced axial conduction.

In this paper, the transverse bypass structure is proposed as an optimal method for mitigating flow mal-distribution effect.[13] It does not sacrifice other favorable characteristics of a recuperator but does make the recuperator a little harder to manufacture. Transverse bypass is a passage

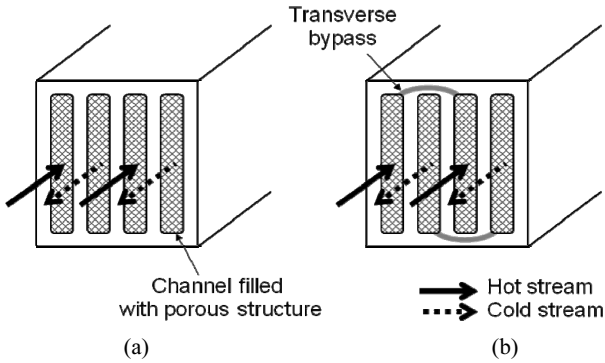



**Figure 2.** (a) Conventional recuperator and (b) recuperator with transverse bypass.

between channels of the same fluid in a recuperator as shown in Fig. 2. It is not confined to the local section of channels but distributed throughout the channels. Thus, the fluid can move freely between the channels through the transverse bypass at any position. Even if a recuperator had a geometric inhomogeneity in the core, flow could be re-distributed, which leads to reduction of performance deficiency.

## TRANSVERSE BYPASS PCHE

The transverse bypass structure is applied to manufacturing a PCHE core. The etching pattern is modified so that the transverse bypass is formed. It is shown in Fig. 3. In this configuration, the fluid does not pass through a single layer only, but it is compiled at transverse bypass holes and re-distributed to the other layers several times. Flow configuration can be depicted like Fig. 4. While flow distribution does not change throughout in a conventional PCHE-type recuperator, flow distribution can be re-arranged in a transverse bypass PCHE-type recuperator. This feature makes the transverse bypass PCHE-type recuperator superior to a

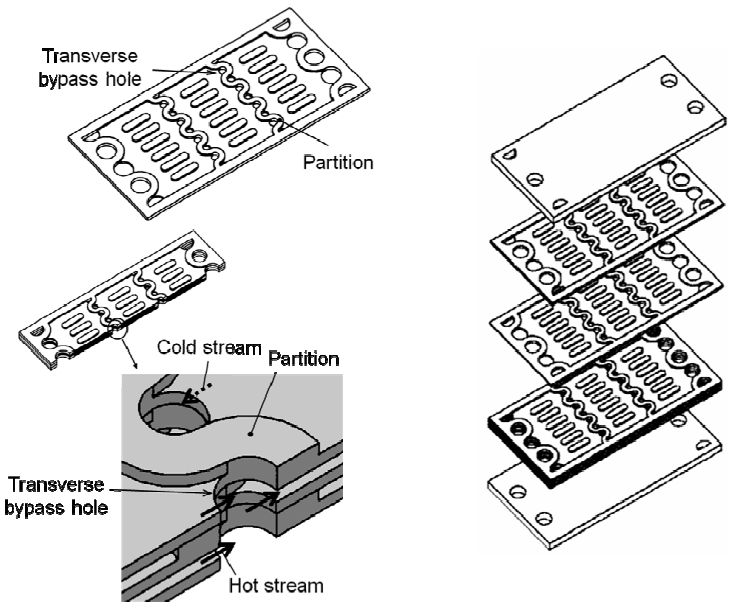
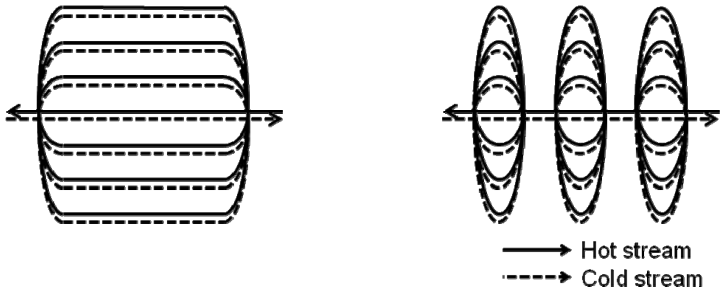



**Figure 3.** Schematic diagram of transverse bypass PCHE core.




(a) (b)

**Figure 4.** Flow configuration in (a) conventional PCHE core and (b) transverse bypass PCHE core.

conventional one.

The transverse bypass PCHE-type recuperator was designed and fabricated to experimentally verify the effectiveness of the adapted transverse bypass structure. The detailed etching pattern is presented in Fig. 5. 100 μm thick stainless steel plates were used. The actual etching depth was less than half of the plate thickness in this case although the depth was expected to be deeper than that. 400 layers of etched plates were stacked (200 layers per each stream) and diffusion-bonded to form a complete recuperator as shown in Fig. 6. The geometric factors of the recuperator are presented in Table 1. The performance of the recuperator was estimated based on the values in Table 1. In the estimation, the conduction shape factor between channels was evaluated in a numerical way; at first, conduction shape factor was calculated in a unit cell, and, then, the calculation result was extended to the entire recuperator. The definition of conduction shape factor is given by

$$S = \frac{q}{k\Delta T} \tag{2}$$

where $q$ is heat transfer rate between channels and $\Delta T$ is temperature difference between cold channel surface and hot channel surface. Thus, transverse conduction resistance is given by Equation (3).

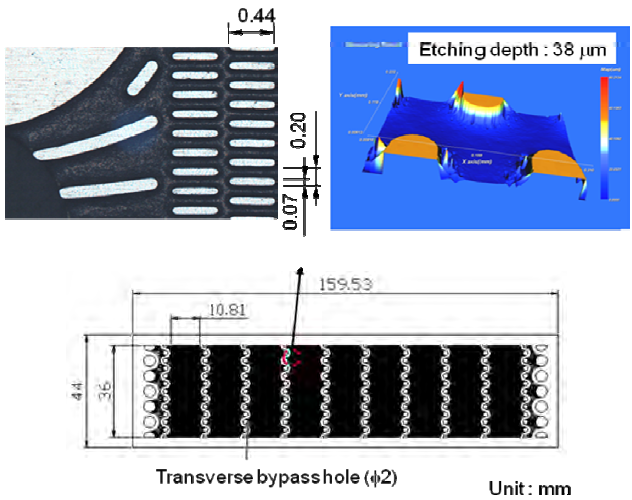



**Figure 5.** Internal structure and layout of transverse bypass PCHE-type recuperator.

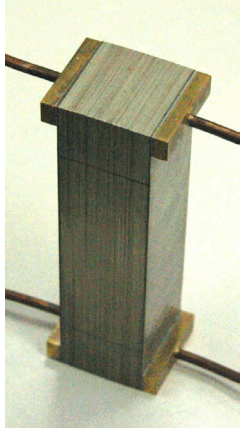


**Figure 6.** Fabricated recuperator.

$$R_{\text{cond}} = \frac{1}{kS} \tag{3}$$

The calculated overall conduction shape factor and the corresponding transverse conduction resistance are presented in Table 2, and the estimated performance is depicted in Fig. 7. At low mass flow rate, the ineffectiveness component from axial conduction is predominant. As mass flow rate increases, ineffectiveness component from stream-to-stream heat transfer gets larger. Flow mal-distribution mainly influences ineffectiveness component from stream-to-stream heat transfer.

**Table 1.** Geometric factors of fabricated recuperator.

| | |
|---|---|
| Hydraulic diameter | $48\times10^{-6}$ m |
| Heat transfer area (single layer) | $5.1\times10^{-3}$ m$^2$ |
| Heat transfer area (200 layers) | 1.0 m$^2$ |
| Flow area (single layer) | $0.63\times10^{-6}$ m$^2$ |
| Flow area (200 layers) | $126\times10^{-6}$ m$^2$ |
| Axial conduction area (single layer) | $3.8\times10^{-6}$ m$^2$ |
| Axial conduction area (400 layers) | $1.6\times10^{-3}$ m$^2$ |
| Axial conduction length | 0.131 m |

**Table 2.** Transverse conduction resistance of fabricated recuperator.

| | |
|---|---|
| Conduction shape factor ( $S$ ) | 8040 m |
| <77 ~ 300 K> | |
| Mean thermal conductivity of SS304 | 12.3 W/m·K |
| Conduction resistance | $10\times10^{-6}$ K/W |
| <30 ~ 80 K> | |
| Mean thermal conductivity of SS304 | 6.1 W/m·K |
| Conduction resistance | $142\times10^{-6}$ K/W |

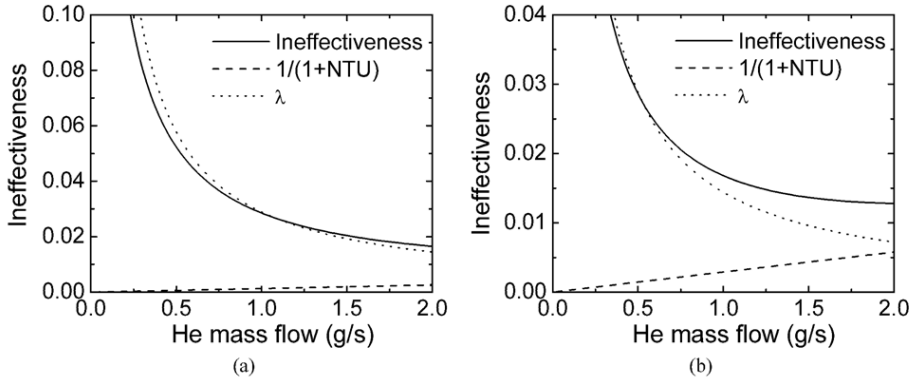



**Figure 7.** Estimated performance of fabricated recuperator (a) at 80 ~ 300 K and (b) at 30 ~ 80 K.

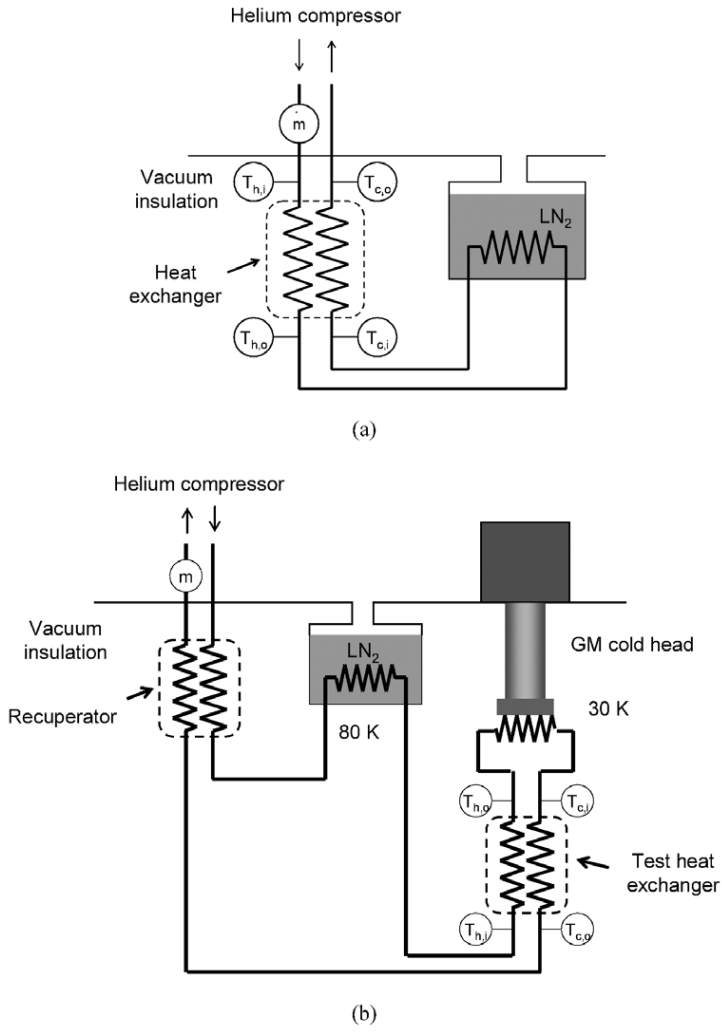



**Figure 8.** Performance test facility (a) for 80 ~ 300 K and (b) for 30 ~ 80 K.

## PERFORMANCE MEASUREMENT

The recuperator performance is measured with the test facility shown in Fig. 8. Four temperatures (inlet and outlet temperatures of each stream) are measured with respect to various mass flow rates. From the measured temperatures, the ineffectiveness is calculated and the result is shown in Fig. 9. The estimation and the measurement agree well from 80 ~ 300 K operation. Since the ineffectiveness component from the axial conduction is predominant in the 80 ~ 300 K operation, overall ineffectiveness is not influenced by flow mal-distribution effect. Effect of transverse bypass is not verifiable in this operation range.

As operating temperature goes down in the recuperator, axial conduction decreases due to the reduction of the thermal conductivity of SS304 and the stream-to-stream heat transfer coefficient decreases. That is, the ineffectiveness component from the axial conduction decreases and that from stream-to-stream heat transfer increases, so the overall ineffectiveness gets sensitive to flow mal-distribution. In the 30 ~ 80 K operation, estimation and measurement data show some deviation. Nevertheless, this deviation is different from that due to flow mal-distribution effect. If the deviation was originated from flow mal-distribution effect, it would have been very small at low mass flow rate and it get larger as mass flow rate increases. Contrarily, the deviation is large at low mass flow rate and gets smaller as mass flow rate increases. As an example, performance deficiency due to flow mal-distribution in the actual case is shown in Fig. 10. It is the measured ineffectiveness of PCHE-type recuperator which was

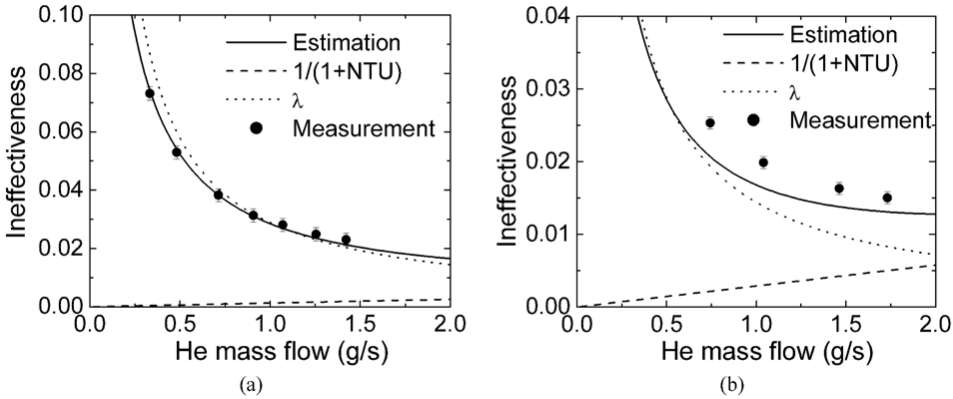



**Figure 9.** Measured performance of fabricated recuperator (a) at 80 ~ 300 K and (b) at 30 ~ 80 K.

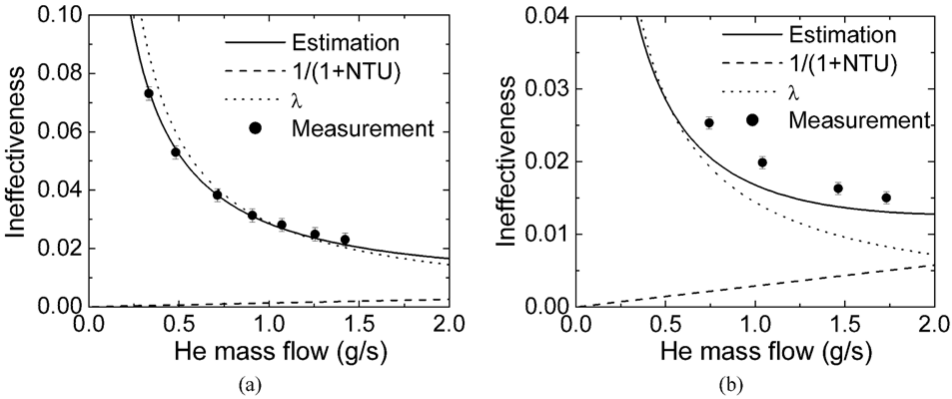



**Figure 10.** Measured performance of conventional PCHE-type recuperator.

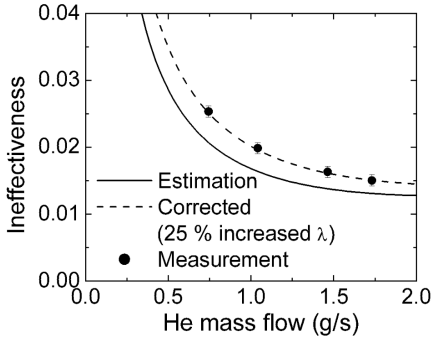



**Figure 11.** Corrected ineffectiveness in fabricated recuperator.

designed and fabricated formerly by the authors without transverse bypass. In this case, the difference between estimation and measurement gets larger as mass flow rate increases. It is noted that the tendencies of Fig. 9 (b) and in Fig. 10 are completely different. The difference between estimation and measurement is not originated from flow mal-distribution in the transverse bypass recuperator. It is rather simple error from axial conduction estimation. If we increase axial conduction by 25 %, the estimation and the measurement data agree quite well as shown in Fig. 11. Finally, we reach the conclusion that the transverse bypass PCHE-type recuperator does not show performance deficiency due to flow mal-distribution, so the transverse bypass structure clearly mitigates flow mal-distribution effect in a PCHE-type recuperator.

## SUMMARY

A PCHE-type recuperator is investigated as a miniature recuperator. A PCHE-type recuperator has etched core and, thus, can provide compact structure required for a miniature recuperator. Performance deficiency problem is commonly encountered in a multi-channel cryogenic recuperator, such as a PCHE-type recuperator. It is due to flow mal-distribution. There are several practical methods for mitigating flow mal-distribution effect. In this paper, the transverse bypass structure is applied to the PCHE core. Transverse bypass is a transverse passage among the channels of the same fluid through which fluid can move freely, so internal flow re-distribution is allowed in a transverse bypass recuperator. The ineffectiveness of the recuperator is measured at different temperature region, which are 80 ~ 300 K and at 30 ~ 80 K. The effect of the transverse bypass structure is verifiable at the 30 ~ 80 K operation. Measurement did not show any appreciable performance deficiency due to flow mal-distribution, so it is concluded that the transverse bypass structure mitigated the flow mal-distribution effect.

## ACKNOWLEDGMENT

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