Novel regenerator design and its experimental characteristics

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This paper discusses a new regenerator with parallel wires and its experimental characteristics. Pressure drop characteristics of the parallel wire regenerator were compared to that of the screen mesh regenerator. It was found that the friction factor of the parallel wire type was three to five times smaller than that of the screen mesh type. Ineffectiveness was determined by measuring the instantaneous pressure, the flow rate and the gas temperature at the warm and cold sides of the regenerator. Parallel wire regenerator made of stainless steel showed poor thermal performance due to its excessive axial conduction loss. To reduce the axial conduction loss, segmentation of the regenerator was suggested and the ineffectiveness result was presented for the segmented regenerator.

INTRODUCTION

A regenerator with parallel heat transfer components to the oscillating flow theoretically has a better performance than screen mesh or random wire type regenerators that are commonly used in cryocoolers. Advantages of the parallel geometry are the small friction factor and the low void fraction. In reality, however, parallel geometry regenerators have been easily suffered from flow maldistribution and axial conduction. Several previous researchers have attempted to realize the parallel geometry type regenerators [1], [2], [3], [4]. Some of them failed to obtain a desired performance and most of the previous studies showed the refrigerator performance, which is an indirect method to measure the regenerator characteristics. In this paper, parallel wire geometry which is similar to the parallel plate or tube was suggested for a regenerator and series of experiments were carried out to characterize the regenerator directly. Figure 1 shows a conceptual diagram of the parallel wire regenerator. Bundle of fine wires are tightly fixed in a housing and gas flows through the void space formed by wires. This paper describes the detailed fabrication process and the direct measurement results of the parallel wire regenerator.

FABRICATION PROCEDURE

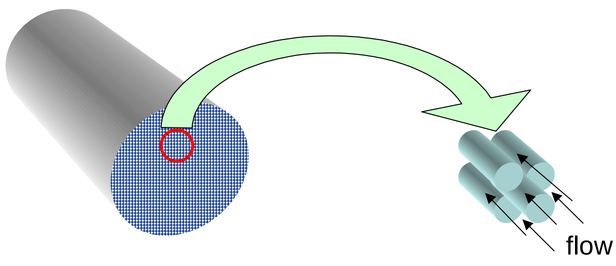

Figure 1 Schematic diagram of parallel wire regenerator

Figure 2 shows the fabrication procedure of the regenerator with parallel wire bundle. The detailed description for each fabrication step is as follows.

(a) : Fine stainless steel wire was wound around in a house-made reel. Wire

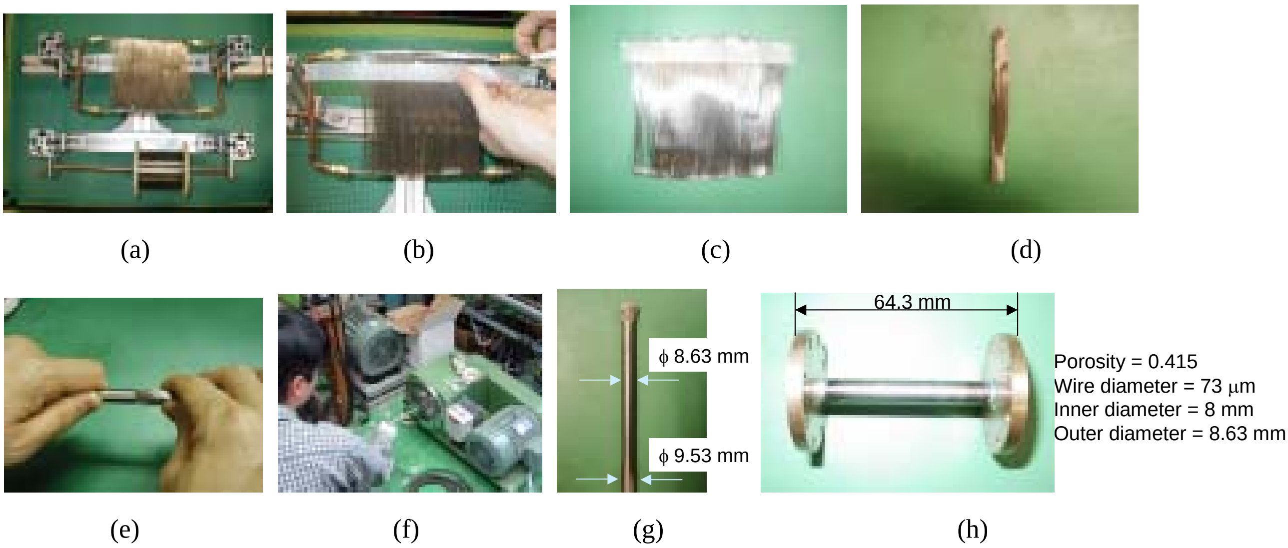

Figure 2 Fabrication procedure for the parallel wire regenerator

diameter was equal to 73 μm. It was not necessary to align wires each other but it was better to wind all wires tightly.

(b) : After the wire bundle was fixed with a sticky tape, the wire bundle was cut off with scissors.

(c) and (d) : Flat bundle was rolled round and the end of the bundle was fixed with the tape.

(e) : Round bundle was inserted into the tube.

(f) and (g) : The tube with the wire bundle was put into a swaging machine in order to reduce the diameter of the tube. This process made the porosity become small and the wire bundle be stuck in the tube.

(h) : The ends of the swaged tube were cut away with a wire-EDM(Electro Discharge Machine). Then, the wire bundle inside the tube was cleaned up carefully. Finally, flanges were attached at the ends of the regenerator to connect the sample with the experimental setup.

EXPERIMENTAL RESULTS

Friction factor

After a prototype regenerator was fabricated, the friction factor was measured at steady flow condition. The Fanning friction factor is defined as follows.

$$f_F \triangleq \frac{\Delta P d_h}{2\rho u^2 L_r}, \quad u = \frac{\dot{m}}{\rho A_g}, \quad d_h = \frac{e_v d_w}{1-e_v} \qquad (1)$$

where A_g : free flow cross sectional area of the regenerator, e_v : porosity, d_w : wire diameter, L_r : regenerator length. Pressure drop and flow rate were measured by a variable reluctance type sensor (Validyne model DP-10) and a mass flow controller (Bronkhorst model F-113AC), respectively. Screen regenerators were also tested to be compared with the parallel wire regenerator. Tested samples were made of #200, #250 and #400 mesh. Weave style was a twill type and the porosity was about 0.68. The friction factor of the

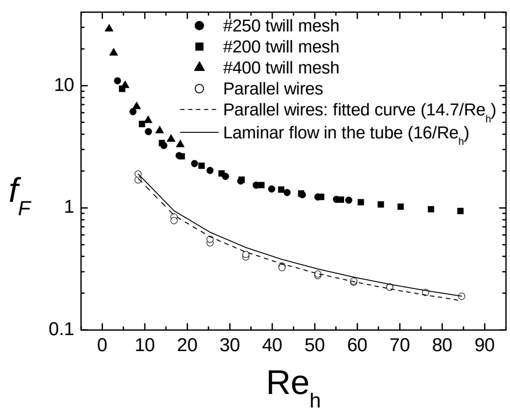

Figure 3 Steady flow friction factor

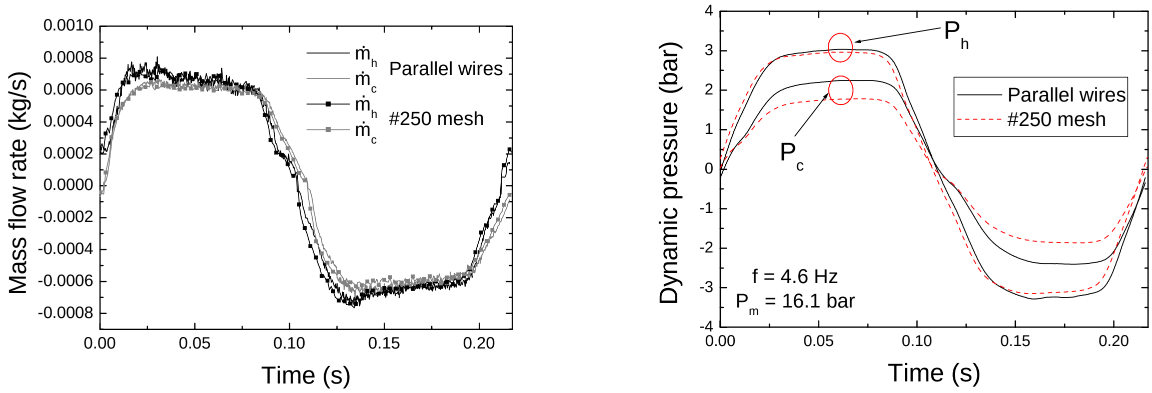

Figure 4 Operating conditions for ineffectiveness measurement (T_h = 277.1 K, T_c = 106.9 K for the parallel wire regenerator and T_h = 287.9 K, T_c = 93.3 K for the #250 mesh regenerator)

parallel wire regenerator was three to five times smaller than those of the screen regenerators as shown in Figure 3. Furthermore, the friction factor of the parallel wire geometry was very similar to the simple analytical result calculated for fully developed laminar flow in a tube [5].

<u>Ineffectiveness</u>

Ineffectiveness is a quantitative performance factor for thermal efficiency of cryocooler regenerator. It is defined as the following equation [6].

$$\lambda \triangleq \left(\int_0^{\tau} \dot{m}hdt\right)_{cold-end} \Bigg/ \left(\left(\int_0^{\tau_1} \dot{m}hdt\right)_{warm-end} + \left(\int_{\tau_1}^{\tau} \dot{m}hdt\right)_{cold-end}\right) \qquad (2)$$

where h : enthalpy of gas, the time interval from 0 to τ_1 : the duration of warm gas flow period, the time interval from τ_1 to τ : the duration of cold gas flow period. The instantaneous mass flow and the gas temperature were measured to calculate the ineffectiveness under actual operating conditions of cryocooler. Full explanation of the experimental setup was presented elsewhere [7]. Testing conditions of regenerators are shown in Figure 4. The #250 mesh regenerator was also tested and its total heat transfer area was the same as that of the parallel wire regenerator. The geometric properties and the experimental results are summarized in Table 1. It was revealed that the ineffectiveness of the parallel wire regenerator was larger than that of the screen regenerator in the operating condition of the experiment. This phenomenon was mainly due to excessive axial conduction in the parallel wire regenerator. Estimated conduction loss was approximately 0.74 W for the parallel wire type and about 0.04 W for the #250 screen. It was assumed that the conduction degradation factor for the packed screens was 0.1. From the ineffectiveness measurement result, we concluded that it was absolutely necessary to reduce the axial conduction loss of the parallel wire regenerator. One of the simplest methods is to segment the regenerator as described in the next section.

Table 1 Geometric properties and experimental results for the screen and the parallel wire regenerator

	Parallel wires	#250 twill
Inner diameter (mm)	8	8
Length (mm)	64.3	64.3
Wire diameter (mm)	0.073	0.038
Porosity	0.415	0.68
Heat transfer area (m^2)	**0.108**	**0.108**
Max. pressure drop (bar)	**0.99**	**1.41**
λ (%)	**3.1**	**1.4**

SEGMENTATION

Figure 5 shows the schematic of the segmented regenerator. The parallel wire regenerator was

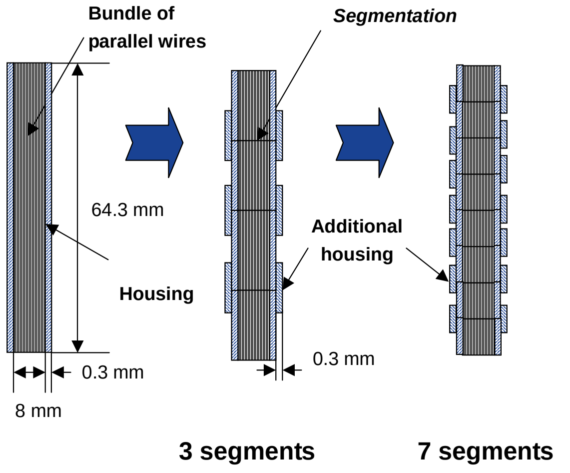

Figure 5 Schematic diagram of the segmented parallel wire regenerator

configured into three and seven-segmented regenerator using a wire-EDM cut. The segmentation of the wire bundle results in thermal contact resistance in axial direction, which presumably reduces the axial conduction thermal loss of regenerator. Ineffectiveness was measured for two types of the segmented regenerators. Operating conditions were similar to the case of the non-segmented regenerator (Figure 4). Ineffectiveness of the three-segmented and the seven-segmented regenerator are 2.7% and 2.2%, respectively. This experimental result indicates that the segmentation clearly improves the thermal performance of the parallel wire regenerator.

SUMMARY

A parallel wire regenerator was conceived and its tested performance data was presented. The friction factor of the parallel wire regenerator was only 20 to 30 % of that of screen mesh regenerator, but the ineffectiveness was more than doubled in a typical operating condition of cryocooler. The poor thermal characteristic of the parallel wire regenerator was alleviated by segmentation to decrease axial conduction loss.

ACKNOWLEDGEMENTS

This research was supported by a grant from Center for Applied Superconductivity Technology of the 21st Century Frontier R&D program funded by the Ministry of Science and Technology and Brain Korea 21 project, Republic of Korea.

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