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Development of parallel wire regenerator for cryocoolers

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Abstract

This paper describes development of a novel regenerator geometry for cryocoolers. Parallel wire type is a wire bundle stacked in parallel with the flow in the housing, which is similar to a conventional parallel plate or tube. Simple and unique fabrication procedure is developed and fully depicted in this paper. Hydrodynamic and thermal experiments are performed to demonstrate the feasibility of the parallel wire regenerator. First, pressure drop characteristic of the parallel wire regenerator is compared to that of the screen mesh regenerator. Experimental result shows that the steady flow friction factor of the parallel wire type is three to five times smaller than that of the screen mesh type. Second, thermal ineffectiveness is determined by measuring the instantaneous pressure, the flow rate and the gas temperature at the warm and cold ends of the regenerator. The measured ineffectiveness of the parallel wire regenerator is larger than that of the screen regenerator due to the excessive axial conduction loss. To alleviate the intrinsic axial conduction loss of the parallel wire regenerator, segmentation is introduced and the experimental results reveal the favorable effect of the segmentation. Entropy generation calculation is adopted to compare the total losses between the screen regenerator and the parallel wire regenerator for various operating ranges. Simulation results show that the parallel wire regenerator can be an attractive candidate to improve cryocooler performance especially for the case of smaller NTU and lower cold-end temperature.

Keywords: Parallel geometry; Oscillating flow; Friction factor; Ineffectiveness; Regenerator; Segmentation; Entropy generation

1. Introduction

A regenerator with parallel heat transfer components to oscillating flow has a better performance theoretically than screen mesh or random wire type regenerators that are commonly used in cryocoolers [1]. Advantages of the parallel geometry are the small friction factor and the low void fraction. In reality, however, the parallel geometry regenerator has been easily suffered from the flow maldistribution and it also has a large intrinsic axial conduction. Several previous researchers have attempted to realize the parallel geometry type regenerators [2–5]. Some of them failed to obtain a desired performance and most of the previous studies showed the overall 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 is suggested for a regenerator and series of experiments are carried out to directly characterize the regenerator performance. This paper presents the detailed fabrication process and the direct measurement results of the parallel wire regenerator test. Analysis of total entropy generation is performed to validate the feasibility of the parallel wire regenerator.

2. Basic concept and fabrication procedure

Fig. 1 shows the conceptual diagram of the parallel wire regenerator. Bundle of fine wires are tightly fixed and

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Nomenclature

A	total heat transfer area of regenerator matrix
A_g	free flow cross sectional area of regenerator
A_m	cross sectional area of regenerator matrix
C_m	heat capacity of regenerative matrix
C_p	specific heat of gas at constant pressure
C_v	specific heat of gas at constant volume
D_r	diameter of regenerator
d_h	hydraulic diameter
d_w	wire diameter of screen
e_v	porosity
f_F	steady flow friction factor
h	enthalpy of gas
h_t	interstitial heat transfer coefficient between matrix and gas
k_m	effective thermal conductivity of regenerator matrix
k_o	thermal conductivity of non-segmented regenerator matrix
L_r	length of regenerator
$\dot{m}$	mass flow rate
P	pressure
R	gas constant
Re_h	Reynolds number $(= \dot{m}d_h/(A_g\mu))$
$\dot{S}_{cm}$	entropy generation due to axial conduction through matrix
$\dot{S}_{gen}$	entropy generation rate
$\dot{S}_{\Delta P}$	entropy generation due to pressure drop
$\dot{S}_{\Delta T}$	entropy generation due to heat exchange between gas and matrix
T	gas temperature
$\overline{T}$	mean gas temperature
T_m	matrix temperature
t	time
u	Darcian velocity
X	amplitude
x	axial direction

Greek symbols

ΔP	pressure drop
λ	ineffectiveness
μ	viscosity
ρ	gas density
ρ_m	matrix density

Subscripts

1	warm-end of regenerator
2	cold-end of regenerator

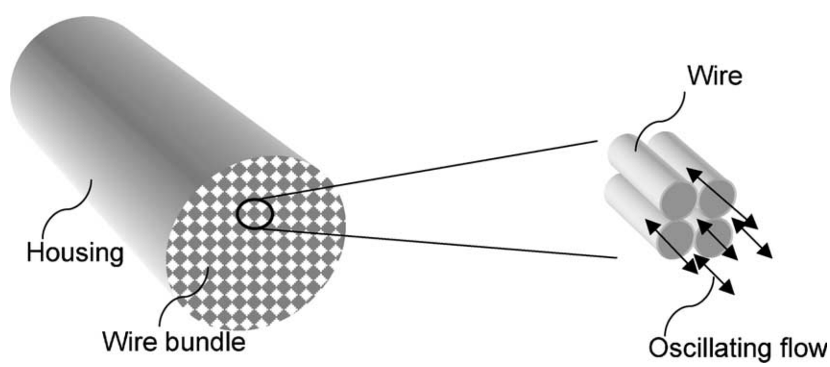

Fig. 1. Schematic diagram of the parallel wire regenerator (diameter of each wire is exaggerated for clear view).

parallel to the flow direction in the housing. Gas flows through the void space that is formed by wires. There is no well-defined existing technology for fabrication of the parallel wire regenerator in literature. Therefore, we suggest a new fabrication method in this paper. Fig. 2 shows the series of photos for 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 is wound around in a house-made reel. Wire diameter is 73 μm. It is not necessary to perfectly align wires each other but it is better to wind all wires tightly.
(b) After the wire bundle is fixed with a sticky tape, the wire bundle is cut off with scissors.
(c) Flat bundle is rolled round and the end of the bundle is fixed with the tape.
(d) Round bundle is inserted into the tube.
(e) The tube with the wire bundle is put into a swaging machine in order to reduce the diameter of the tube. This process makes the porosity become small and the wire bundle be stuck in the tube.