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Anisotropic steady-flow hydrodynamic parameters of microporous media applied to pulse tube and Stirling cryocooler regenerators

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Abstract

The hydrodynamic parameters associated with steady longitudinal and lateral (radial) flow of helium in several widely-used pulse tube and Stirling cryocooler regenerator fillers were measured and correlated in this investigation. Pressure drops in test sections packed with regenerator fillers were experimentally measured. Computational fluid dynamics (CFD) models of the regenerator test sections and their vicinities were developed and simulations were performed in which the regenerator test sections were modeled as porous media. By iterative repetition of the simulations, the longitudinal and radial permeability and Forchheimer inertial coefficients were determined such that they would lead to agreement between experimental measurements and the simulations. The regenerator fillers included 325 and 400 mesh stainless steel screens, stainless steel metal foam, sintered 400 mesh stainless steel screens, and a stack of micromachined perforated plates. The hydrodynamic response of the regenerator fillers were also correlated as friction factors. The results confirm that the aforementioned regenerator fillers are anisotropic.

Keywords: Cryocoolers; Regenerator; Permeability; Inertial coefficient; Steady flow

1. Introduction

The crucial role of the regenerator in pulse tube and Stirling cryocoolers is well recognized and improving the performance of the various types of cryocoolers is of great interest. For pulse tube refrigerators (PTRs) there are several sources of irreversibility [1]. The regenerator in a PTR is a porous metallic structure which is typically the largest source of loss in cryocoolers [2]. Axial heat conduction, thermal saturation, and frictional losses all cause irreversibility. However, it is difficult to accurately predict the impact of these and other solid–fluid interactions within the porous media for periodic flow. To simplify the analysis of these periodic systems, isotropic hydrodynamic parameters associated with steady flow have sometimes been used [3]. It has recently been shown that CFD tools can simulate the entire cryocooler devices under steady and steady-periodic conditions [4–6]. However, the accuracy of these CFD predictions depend strongly on the accuracy of the closure relations they use. The hydrodynamic and heat transfer parameters associated with the interaction between the coolant fluid and the porous regenerator are thus among the most important closure relations, and are relatively poorly understood. This is particularly true about the hydrodynamic and thermal transport parameters associated with periodic flow in microporous structures.

Rigorous analysis of flow in porous media is in principle possible by pore-level simulations. However, such simulations are impractical for design purposes, and microscopic governing equations and boundary conditions are instead transformed into macroscopic governing equations and

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Nomenclature

$\overline{\overline{C}}$	inertial resistance coefficient tensor (m^{-1})
$\overline{\overline{c_f}}$	Forchheimer inertial coefficient tensor (–)
$c_{f,i}$	directional Forchheimer inertial coefficient (–)
E	fluid total specific energy (J/kg)
$\vec{F}_{bf}$	body force (N)
f	friction factor
g	gravitational constant (=9.81 m/s^2)
$\vec{g}$	gravitational acceleration (m/s^2)
h	specific enthalpy (J/kg)
$\overline{\overline{I}}$	identity tensor
$\overline{\overline{K}}$	Darcy permeability tensors (m^2)
K_i	directional Darcy permeability (m^2)
k	thermal conductivity (W/m K)
m	mass (kg)
T	temperature (K)
t	time (s)
$\vec{u}$	volume-average intrinsic velocity (m/s)
P_c	inlet pressure for annular test section (Pa)
P_1	regenerator inlet pressure (Pa)
P_2	regenerator exit pressure (Pa)
Re	Reynolds number (–)

Greek symbols

$\overline{\overline{\beta}}$	viscous resistance coefficient matrix (m^2)
ε	porosity (–)
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
$\overline{\overline{\tau}}$	stress tensor (N/m^2)

Subscripts

f	fluid
r	radial
s	solid
t	turbulent
x	axial

Superscript

T	transpose

boundary conditions by applying volume averaging [7–12]. Volume averaging and other similar methods lead to macroscopic and tractable governing equations which are consistent with micro-scale conservation principles, although they often mask much of the details related to pore-level processes. They also introduce constitutive relations that are needed for closure of macroscopic conservation equations. Without pore-level direct simulation, these macroscopic relations need to be specified empirically. Included among these relations are the Darcy permeability and Forchheimer's inertial coefficient tensors which need to be defined for the closure of the macroscopic momentum conservation equation.

Several investigator have measured and correlated the regenerator friction factors in steady-state or steady-periodic flow [13–16]. However, the present investigation is novel in its rigorous CFD-based determination of the hydrodynamic parameters.

In this paper, the hydrodynamic parameters associated with steady flow of helium in several common pulse tube and Stirling cryocooler fillers are measured and correlated. The hydrodynamic parameters associated with oscillatory flow of helium in the same regenerator fillers will be addressed in a separate forthcoming article [17].

2. Experiments

2.1. Regenerator fillers

Table 1 summarizes the geometric and structural characteristics of the regenerator fillers that were investigated. The common approach for constructing a regenerator is to fill its housing with a stack of microscreen sheets, micromachined perforated plates, or metal foam pellets, etc., and adjust its porosity by proper packing. It is therefore reasonable to assume that these porous regenerators are axisymmetric.

Table 1
Characteristics of the tested porous structures

Porous matrix type	Length/diameter (mm)	Wire diameter/pore diameter	Porosity (%)	Material
Tested regenerators for axial flow tests				
325 Mesh screen	38.1/7.94	35.6 μm	69.2	Stainless steel
400 Mesh screen	38.1/7.94	25.4 μm	69.2	Stainless steel
Sintered 400 mesh	38.1/7.94	Sintered	62	Stainless steel
Foam metal	38.1/7.94	Sintered	55.47	Stainless steel
Micro-machined disks[a]	31.4/15	36–40 μm	26.8	Nickel
	OD/ID/length (mm)	Wire diameter		
Tested regenerator for radial flow test				
325 Mesh screen/annular geometry	20/4/11.43	35.6 μm	69.6	Stainless steel

[a] Provided by International Mezzo Technologies Inc. Baton Rouge, Louisiana.