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Oscillatory flow in microporous media applied in pulse – tube and Stirling – cycle cryocooler regenerators

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Abstract

Pulse tube and Stirling cryocoolers are widely used in aerospace and other high-demand application. A key component in these systems is the regenerator, which is typically a microporous metallic structure that is subject to periodic flow of a cryogenic fluid. The thermal and hydrodynamic irreversibilities in the regenerator, which play crucial roles with respect to the efficiency of the aforementioned cycles, are poorly understood, however.

In this investigation experiments were performed where pressure drop associated with steady-periodic (axial and lateral (radial)) flows of helium in test sections packed with several widely used pulse tube and Stirling cryocooler regenerator fillers were measured under ambient temperature conditions. A computational fluid dynamic (CFD) – assisted method was developed for the analysis and interpretation of the experimental data, whereby the permeability and inertial coefficients that lead to agreement between the data and the predictions of CFD simulations were iteratively obtained. The directional permeability and Forchheimer inertial coefficients were thus obtained for the tested regenerator fillers, and were found to be independent of the frequency of flow oscillations for the frequency range 5–60 Hz. The results also show that the oscillatory flow hydrodynamic parameters are different than steady-flow parameters representing similar flow conditions.

Keywords: Regenerators; Porous media; Directional; Oscillatory flow; Permeability; Forchheimer coefficient

1. Introduction

Pulse tube cryocoolers (PTCs) are a class of rugged and high-endurance refrigeration systems that operate without a moving part at their cold ends, and are capable of easily reaching 120 K or lower. PTCs also can be configured in multiple stages to reach temperatures below 10 K. PTCs are particularly suitable for applications in space, missile guiding systems cryosurgery, superconducting electronics, magnetic resonance imaging, liquefaction of nitrogen, and liquid nitrogen transportation. PTCs utilize the oscillatory compression and expansion of a gas (usually helium) within a closed volume to achieve refrigeration. Useful reviews of PTCs can be found in [1–4], among others. Despite extensive research in the past, some aspects of PTC performance are not fully understood, and consequently systematic modeling of PTC systems has been difficult. Early models as well as recent models that are suitable for scoping and design calculations have primarily been lumped parameter-type [5–7], and semi-mechanistic models based on the numerical solution of relevant differential conservation equations, which have been reported only in the past several years [8–10]. Very recently, some computational fluid mechanics (CFD) analyses of entire PTC systems have been successfully performed and demonstrated [11–13].

A key component of all PTCs, as well as Stirling refrigeration cycles, is the regenerator. The regenerator in these systems is typically a microporous metallic structure that is subject to periodic flow of the working fluid. The porous

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Nomenclature

$\overline{\overline{C}}$	Fluent's inertial resistance coefficient tensors (m^{-1})
$\overline{\overline{c_f}}$	Forchheimer inertial coefficient tensors (–)
$c_{f,j}$	directional Forchheimer inertial coefficient (–)
f	friction factor
freq	frequency (Hz)
h	enthalpy (J/kg)
$\overline{\overline{I}}$	unit identity tensor (–)
k	thermal conductivity (W/m K)
$\overline{\overline{K}}$	Darcy permeability tensors (m^2)
K_j	directional Darcy permeability (m^2)
P	static fluid pressure (N/m^2)
T	local instantaneous temperature, volume average temperature in porous media (K)
t	time (s)
$\vec{u}$	local instantaneous velocity vector, volume average intrinsic velocity (m/s)
‖	magnitude of quantity

Notation

D	diameter
HWA	hot wire anemometer
ID	inner diameter
L	length
OD	outer diameter
P_1	regenerator inlet pressure measurement location
P_2	regenerator exit pressure measurement location
P_3	buffer volume pressure measurement location
RTS1	axial test apparatus regenerator housing module
RTS2	axial test apparatus regenerator housing module for micro-machined disks
V_1	regenerator inlet velocity measurement location

Greek symbols

$\overline{\overline{\beta}}$	Fluent's viscous resistance permeability tensors (m^2)
ε	porosity tensors (–)
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
$\overline{\overline{\tau}}$	stress tensors (N/m^2)
∇	gradient operator
Γ_n	pressure amplitude (N/m^2)
Δ_n	pressure phase angle (°)

Subscripts

f	fluid
osc	oscillating flow conditions
r, x	radial and axial coordinate directions
s	solid
steady	steady-flow condition

Superscript

T	transpose

solid structure absorbs heat from the working fluid during one-half of a period, and releases the absorbed heat to the working fluid in the remaining one-half period. The frequency of the flow oscillations vary from 1 to 100 Hz in conventional PTCs, but is expected to be much higher in future miniature PTCs. The design parameters of the regenerator such as its aspect ratios (length-to-diameter ratios), physical dimensions, pore structure, and regenerator materials are known to have a significant impact on the coolers' overall performance. In the past the selection and/or optimization of these design parameters have been either empirical, or based on relatively crude lumped parameter or one-dimensional semi-mechanistic models. Recent CFD analyses, although still limited in scope and depth, have shown that much improvement can be achieved with respect to the design and optimization of PTCs [11–13]. However, an important deficiency with respect to the state of art models dealing with PTCs, which applies to well-established as well as novel and forthcoming designs, is the poor understanding about the hydrodynamic and thermal transport parameters associated with periodic flow in microporous structures. This is particularly troubling with regards to the regenerator, where friction and thermal non – equilibrium between the fluid and the structure play crucial roles. Little attention has been paid to this issue primarily because of the difficulty of experimental measurements, and friction factors for some regenerators have been measured only recently [14–15].

This investigation is aimed at the measurement and correlation of the anisotropic hydrodynamic parameters associated with steady-periodic gas flow in several widely applied PTC regenerator fillers. A novel, CFD assisted method has been developed for the analysis and interpretation of the experimental data, whereby the permeability and Forchheimer inertial coefficients that lead to agreement between experimental measurements and the results of detailed CFD are rigorously determined.

2. Experiments

2.1. Regenerator fillers

Table 1 summarizes the regenerator fillers that were studied, and their important geometric and structural characteristics. Five regenerator fillers were used in the experiments. The micro-machined disks are novel, and will be discussed shortly. The common approach for constructing a regenerator is to load it with a stack of screen sheets or other filler material, and adjust its porosity by properly packing the stack. As a result of the stacking, the hydraulic resistance of the porous structure in axial and lateral direction will