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Hydrodynamic parameters for ErPr cryocooler regenerator fillers under steady and periodic flow conditions

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ABSTRACT

The regenerator, typically a microporous structure that is subject to periodic flow of a cryogenic fluid, is the most critical component of Pulse Tube or Stirling cryocoolers, which are widely used for high-demand defense and aerospace applications. Despite the critical impact of hydrodynamic irreversibilities in the regenerator on the overall cycle efficiency, the impact of the parameters that influence these losses are poorly understood.

In this investigation, experiments were conducted in which steady and oscillatory flows of helium were imposed on $Er_{50}Pr_{50}$ rare-earth regenerator filler material and mass flow and pressure drop data were recorded under ambient temperature conditions. A filler material composed of 63–75 μm diameter $Er_{50}Pr_{50}$ spheres was selected based on current commercially available particle geometries. The flow parameters in the experiments were in the laminar flow range. A computational fluid dynamic (CFD)-assisted method was applied for the analysis and interpretation of the experimental data, with sinusoidal time variations of inlet and exit boundary conditions for the periodic flow case. The permeability and inertial coefficients that led to agreement between the experimental data and computational simulations were iteratively obtained. The resulting Darcy permeability and Forchheimer inertial coefficients are reported herein. A constant Darcy permeability value for all steady and periodic flow tests was found to correlate well to experimental data. The Forchheimer inertial coefficients were correlated and found to be functions of the system charge pressure and the pore-based Reynolds number. The results also show that the periodic flow inertial coefficients are different than the steady flow parameters typically used.

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 reaching cryogenic temperatures. PTCs also can be configured in multiple stages to reach temperatures below 4 K. PTCs are particularly suitable for applications in space technology, missile guiding systems, cryosurgery, superconducting electronics, magnetic resonance imaging, and liquid nitrogen transportation. Stirling-type PTCs utilize the oscillatory compression and expansion of a cryogenic 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. Previous models that are suitable for design calculations have primarily been lumped parameter-type [5–7], and semi-mechanistic models based on the numerical solution of relevant differential conservation equations [8–10]. Very recently, some computational fluid dynamics (CFD) analyses of entire PTC systems have been successfully performed and demonstrated [11–13].

The most critical component of all PTCs and Stirling cryocoolers is the regenerator. The regenerator in these systems is typically a porous metallic or rare-earth structure that is subject to periodic flow of the working fluid. The design parameters of the regenerator including its aspect ratio (length-to-diameter ratio), physical dimensions, pore structure, and regenerator filler materials are known to have a significant impact on the cryocooler's 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 the art models dealing with PTCs, which applies to current

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Nomenclature

A	area (m^2)
$\bar{\bar{C}}$	fluent's inertial resistance coefficient tensors (1/m)
c_f	Forchheimer inertial coefficient (–)
f	frequency (Hz)
h	enthalpy (J/kg)
$\bar{\bar{I}}$	unit identity tensor (–)
K	darcy permeability (m^2)
k	thermal conductivity (W/m K)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
P	static fluid pressure (N/m^2)
P^*	non-dimensional charge pressure (–)
Re_K	pore based Reynolds number (–)
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)

Notation

P_1	regenerator inlet pressure measurement location
P_2	regenerator outlet pressure measurement location

Greek Symbols

$\bar{\bar{\beta}}$	fluent's viscous resistance permeability tensors (m^2)
ε	porosity tensors (–)
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
σ	uncertainty (%)
τ	stress tensors (–)
φ	phase angle (rad)
ω	angular frequency (rad/s)
∇	gradient operator

Subscripts

f	fluid
in	inlet location
out	outlet location
s	solid

Superscript

T'	transpose

and forthcoming designs, is a poor understanding of the hydrodynamic and thermal transport parameters associated with periodic flow in these porous structures. This is particularly troubling with regards to the regenerator, where friction and thermal non-equilibrium between the fluid and the solid structure play crucial roles, adversely impacting their performance and in some cases rendering them inapplicable. An understanding of the hydrodynamics and thermal transport phenomena in porous media during periodic flow is thus necessary for the development of reliable analytical or numerical design tools for these cryogenic systems. Little attention has been previously paid to this issue primarily because of the difficulty associated with experimental measurements.

Hydrodynamic parameters have been measured and published for some regenerator fillers [14–18] commonly used in higher temperature cryocooler applications. Cha et al. [19], for example, measured and correlated anisotropic hydrodynamic parameters associated with steady-periodic gas flow in several widely used PTC regenerator fillers including – 325 SS mesh screens (69.2% porosity), 400 SS mesh screens (69.2% porosity), sintered 400 SS mesh (62% porosity), foam metal (55.47% porosity), and micro-machined disks (26.8% porosity).

Furthermore, Kim and Ghiaasiaan [20]; Pathak and Ghiaasiaan [21]; and Pathak et al. [22,23] conducted pore-level direct numerical studies to derive the hydrodynamic and thermal resistance parameters associated with laminar unidirectional-steady and periodic flow through generic porous media [20–24]. Extensive steady-state pore level investigations have been reported elsewhere [25–30]. The aforementioned investigations, however, have not addressed the poorly-understood periodic flow in porous media. This investigation is aimed at the measurement and correlation of the hydrodynamic parameters associated with steady and periodic gas flows in spherical $Er_{50}Pr_{50}$ rare Earth regenerator fillers. $Er_{50}Pr_{50}$ fillers are most appropriate as regenerator fillers for approximately 18–80 K temperature range, and are finding extensive applications. The $Er_{50}Pr_{50}$ powder investigated here is the primary form of this filler material that is currently available. A CFD-assisted method has been employed for the analysis and interpretation of the experimental data, whereby the Darcy permeability and Forchheimer inertial coefficients that lead to agreement between experimental measurements and the results of detailed CFD simulations are determined.

2. Experiments

2.1. Regenerator filler

Fig. 1 shows the $Er_{50}Pr_{50}$ rare Earth regenerator filler that was studied in this investigation along with the regenerator test section. The filler was made of near-spherical pellets with an average diameter of 69 μm and a porosity of 38%. These particles cover a size range of 63–75 μm diameter. The $Er_{50}Pr_{50}$ powder filled a cylindrical regenerator space of 2.3 cm in diameter and 5.08 cm in length. This regenerator test section was used for both the steady and periodic flow experiments.

The common approach for constructing a regenerator is to load it with a stack of screen sheets or other filler material (spherical pellets, foam metal, etc.), 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 vary. In light of the randomness of the stacking process for various fillers, and the average spherical diameter in the pellets, the porous structures can be assumed to be isotropic. The $Er_{50}Pr_{50}$ pellets were provided by Atlas Scientific (San Jose, CA) and the construction of the regenerator was done at NASA Ames Research Center (Moffett Field, CA).

2.2. Steady flow experiments

The steady flow test apparatus is schematically displayed in Fig. 2, and includes, a mass flow meter, two Omega PX94 pressure transducers, an Omega FMA 1700/1800 mass flow meter, and a specially designed module that houses the porous structure sample.

The working fluid in all the tests was research grade Helium with a nominal purity of 99.9999%. The regenerator test section was designed and fabricated at NASA Ames Research Center. It includes a specially designed regenerator housing module that has flange type end-connections, O-ring seals, and flange type