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

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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

Keywords: Regenerators, Porous media, Periodic flow, Steady flow, Oscillatory flow, Darcy permeability, Forchheimer coefficient, CFD, ErPr, rare earth, Hydrodynamics

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 Er50Pr50 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 Er50Pr50 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.

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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 Er50Pr50 rare Earth regenerator fillers. Er50Pr50 fillers are most appropriate as regenerator fillers for approximately 18–80 K temperature range, and are finding extensive applications. The Er50Pr50 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 Er50Pr50 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 Er50Pr50 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 Er50Pr50 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
connecting components. The test section had an inner diameter of 2.3 cm and length of 5.08 cm. The regenerator module was used for all of the tests.

Two PX94 pressure transducers (from Omega, 0-300 psi model) measured the local instantaneous pressures. A mass flow meter (from Omega, model FMA 1700/1800) was used to measure the local instantaneous velocities at the inlet of the regenerator.

A total of fifty-nine steady flow tests were conducted, covering a mass flow rate range of $4.3 \times 10^{-5}$ to $8.7 \times 10^{-4}$ kg/s at a charge pressure range of 0.345–1.724 MPa. In each test, the local pressures at the inlet and exit of the regenerator and the regenerator inlet velocity were measured. The steady-state pressures at $P_1$ and $P_2$, and the mass flow rate (see Fig. 2) were recorded. All the tests were performed at ambient room temperature.

### 2.3. Periodic flow experiments

The oscillatory flow test apparatus is schematically displayed in Fig. 3, and includes a compressor, a dynamic mass flow meter, several pressure transducers, a buffer volume, and a specially designed module that houses the porous structure sample. A 4 kW CFIC compressor is used to impose oscillatory flow. The aforementioned regenerator module and research grade helium as the working fluid were used for all of the tests. Three PCB piezo transducers (model 401A, from PCB Piezotronics) and one PX94 (mentioned above) pressure transducer measured the local instantaneous pressures. An in-house (developed at NASA Ames Research Center) built dynamic mass flow meter was used to measure the mass flow rate at the inlet of the regenerator.

A total of 24 periodic flow tests were conducted, covering the frequency range 30–70 Hz at charge pressures of 1.034 MPa and 1.724 MPa. In each test, the time histories of local instantaneous pressures at the inlet and exit of the regenerator and the buffer volume were recorded under steady-periodic conditions. The time variation of regenerator inlet mass flow rate was also measured along with the piston displacement in the compressor. In all of the tests, the peak-to-peak sinusoidal voltage amplitude was first increased until either the maximum compressor piston displacement or the maximum current limit was reached. The voltage amplitude was then maintained constant and the
steady-periodic pressures at \( P_1 \) and \( P_2 \) and the mass flow rate (see Fig. 3) were recorded. All the tests were performed at ambient temperature.

3. Data analysis and interpretation

3.1. CFD modeling and governing equations

The CFD code ANSYS Fluent [31] was used to model the test sections, shown in Figs. 2 and 3. Mesh generation was performed using GAMBIT [32]. Axi-symmetric, two-dimensional flow was assumed everywhere, and this assumption was justified in view of the axi-symmetric test apparatus and boundary conditions. The two simulated systems evidently each have two different types of fluid zones: open flow channels and porous media. For the open components, the transient mass, momentum, and energy conservation equations solved by Fluent are:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]

(1)

\[
\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) + \nabla P - \nabla \cdot (\tilde{\eta}) = 0
\]

(2)

\[
\nabla \cdot (k \nabla T + \tilde{\eta} \mathbf{u}) - \nabla \cdot (c_\rho E + P) = 0
\]

(3)

where

\[
E = \frac{P}{\rho} + \frac{\mathbf{u}^2}{2}
\]

(4)

and

\[
\tilde{\eta} = \mu \left( \nabla \mathbf{u} + \nabla \mathbf{u}^T \right) - \frac{2}{3} \nabla \cdot \mathbf{u} \mathbf{u}^T
\]

(5)

These equations apply to all sections except for the regenerator filler. The latter region is modeled as a porous medium with local solid–fluid thermal equilibrium assumption. The time dependent mass, momentum, and energy equations for this region can be represented as:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = 0
\]

(6)

\[
\frac{\partial (\rho \mathbf{u} \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u} \mathbf{u}) + \nabla P + \nabla \cdot (\tilde{\eta} \mathbf{u}) = - \left( \frac{\mu \mathbf{u} + \tilde{\eta}}{2} \cdot \mathbf{u} \mathbf{u}^T \right)
\]

(7)

\[
\nabla \cdot \left( (ck + (1 - \varepsilon) k_s) \nabla T + (\tilde{\eta} \cdot \mathbf{u}) \right) = - \frac{\partial}{\partial t} (\varepsilon \rho E_f + (1 - \varepsilon) \rho E) + \nabla \cdot \left( \mathbf{u} (\varepsilon \rho E_f + P) \right)
\]

(8)

where \( \varepsilon \) is the porosity and \( \tilde{\eta} \) (m²) and \( \tilde{\eta} \) (m⁻¹) appearing in Eq. (7) are the viscous and inertial resistance coefficient tensors according to Fluent’s notations. The velocity \( \mathbf{u} \) in Eqs. (6)-(8), represent the volume-averaged intrinsic (physical) fluid velocity in the porous structure.

The porous regenerator is homogeneous and isotropic, and therefore the viscous and inertial resistance coefficients are both scalars. The coefficients in the last two terms of Eq. (7) can thus be shown to be related to Darcy permeability, \( K \), and Forchheimer’s inertial coefficient, \( c_f \) by Eqs. (9) and (10), respectively.

\[
K = \frac{\varepsilon^2 \beta}{2}
\]

(9)

\[
c_f = \frac{CR^5}{2\varepsilon^3}
\]

(10)

The Reynolds number used in this study was the pore-based Reynolds number, shown in the following equation:

\[
Re_K = \frac{m R^5}{\mu A}
\]

(11)

3.2. Applied inlet and boundary conditions

In each test, following the establishment of steady or steady-periodic conditions, measurements were performed, including the pressures at location \( P_1 \) in Figs. 2 and 3. Time dependent (periodic) mass flow rate condition was imposed at the inlet and time dependent static pressure boundary condition was imposed at...
were first transformed into the frequency domain and represented as Fourier Sine Series.

<table>
<thead>
<tr>
<th>Component index</th>
<th>Radius, ( r ) (cm)</th>
<th>Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (regenerator test section)</td>
<td>1.15</td>
<td>5.08</td>
</tr>
<tr>
<td>B (transfer line)</td>
<td>0.23</td>
<td>6.35</td>
</tr>
</tbody>
</table>

To simplify the data analysis, the periodic pressure variations at \( P_2 \) were also transformed into the frequency domain using FFT. The boundary steady-periodic pressures for the simulated system could thus be represented as:

\[
P_i(t) = \sum_{n=1}^{\infty} P_n \sin(n \omega t + \varphi_n), \quad \omega = 2\pi f, \quad i = 1, 2
\]  

\[
\tilde{m}_n(t) = \sum_{n=1}^{\infty} \tilde{m}_n \sin(n \omega t + \varphi_n), \quad \omega = 2\pi f, \quad i = 1
\]
where \( i = 1 \) and 2 represent locations \( m_1 \), \( P_1 \), and \( P_2 \) in Figs. 2 and 3, respectively, and \( m_n \), \( P_n \), and \( \phi_n \) represent the \( n \)th harmonic mass flow and pressure magnitudes and phases of the Fourier sine series. It was also observed that the magnitudes at higher fundamental frequencies were negligibly small compared to the magnitudes of the first fundamental harmonics at the compressor driving frequency, and therefore only the first fundamental harmonic of magnitudes and phases were needed to accurately replicate the actual measured waveform. Table 1 is a summary of all the parameters in Eqs. (12) and (13) for the tested regenerator filler. Thus, in a periodic flow simulation, Eq. (12) with \( i = 2 \) represented the outlet conditions to the system, while the same equation with \( i = 1 \) represented experimental measurements that would be compared with simulation predictions. A similar list of parameters representing other previously-studied regenerator fillers can be found in Cha [12].

A user defined function (UDF) feature in Fluent provides the capability of imposing various time-dependent flow and heat transport properties, at any desired boundary of the model. A UDF is a special function written in C++, which can be dynamically loaded with the FLUENT solver to enhance the default features of the code. E.g. UDFs can be used to define arbitrary boundary conditions, material properties, and source terms, as well as specify customized model parameters. In this investigation for periodic flow, a transient pressure and mass flow rate UDF was developed according to Eqs. (12) and (13) and applied in order to impose time-dependent pressure and mass flow boundary conditions.
For the steady-flow simulations, the experimentally collected mass flow rate and outlet pressure were applied at the inlet and outlet of the regenerator domain, respectively. Table 2 is a summary of all the parameters associated with the steady flow tests. Therefore, in a steady-flow simulation, the experimentally measured inlet pressure to the regenerator was compared with the simulation’s resulting predictions.

For all simulations, the investigation assumed laminar flow conditions. This was based on the criteria developed by Pedras and De Lemos [33], where they found the critical pore-based Reynolds number for the laminar to turbulent transition to be approximately 350. For the entire set of steady and periodic flow simulations, the pore-based Reynolds number held the assumption of laminar flow.

3.3. CFD model for steady and periodic flow

The physical dimensions of the model and component indices for the steady and periodic flow tests are shown in Table 3 and Fig. 4. Note that Figs. 4 and 5 are shown in the cylindrical coordinate system. Fig. 5 depicts the details of the regenerator component, which was simulated using approximately 12,000 nodes for steady flow simulations and 9600 nodes for the periodic flow simulations.

The third-order MUSCL discretization scheme and pressure-velocity coupling scheme were used in all the simulations. A normalized residual convergence criterion of $1.0 \times 10^{-6}$ for the mass, $x$-velocity, and $r$-velocity, and $1.0 \times 10^{-8}$ for the energy, were used with under relaxation factors of 0.2 for density, body forces, and energy, and explicit relaxation factors of 0.5 for momentum and pressure. The energy equation was solved for each time step as an additional CFD validation step. The isothermal condition of 300 K was applied to the walls of the simulated models. For periodic flow, constant time steps of $1.5 \times 10^{-5}$ s were used for all of the simulations to ensure accurate results and ease of data analysis, with a flow Courant number of 200. The number of max iterations per time step used was 250 with 10,000 total time steps. All simulations were run on a commercially available core i7 PC.

3.4. Determination of hydrodynamic parameters

The following procedure, originally developed by Cha [19], was employed for the tested regenerator filler. For periodic flow, first, the case of 30 Hz at the lowest charge pressure and piston amplitude, was simulated by iteratively adjusting the viscous resistance coefficient $\beta$ without including the inertial effect ($C = 0$) until the simulation predictions at $P_1$ matched the experimental data. Since the effect of the inertial coefficient is nearly negligible at low velocities, the lowest flow case was chosen to determine the viscous resistance. Subsequently the 70 Hz case, which had the largest piston amplitude and charge pressure, was simulated. This time however, only the inertial coefficient $C$ was iteratively adjusted while $\beta$ was kept constant until good agreement was obtained between the $P_1$ predictions and experimental data. Using the determined value of $C$ and $\beta$ was again iteratively adjusted to determine a new $\beta$ for
the 30 Hz, lowest piston amplitude case. This was done in order to
determine a valid $C$ for the lowest flow case. Simulations were then
performed for all the measured frequencies. If good agreement was
obtained for all frequencies then iterative simulations would end,
otherwise $\beta$ and $C$ would be further adjusted iteratively to match
the experiment data, specifically the $P_\text{r}$ simulation and experimen-
tal data. A similar procedure was employed for steady flow where
the lowest charge pressure, lowest flow rate case was tested to
determine the viscous resistance coefficient, without including
the inertial effect. Then the largest charge pressure, largest flow
rate case was used to determine the corresponding inertia resis-
tance coefficient while borrowing the viscous resistance term from
the aforementioned low flow case. Once determined, the low flow
case was iteratively adjusted to find a valid $C$, and then $\beta$ term was
further adjusted to better match the experiment data and simula-
tion results. It should be mentioned, however, that at this point in
both steady flow and periodic flow cases, only minor adjustments
to $C$ were needed to match all the experiment data and simulation
results to reasonable accuracy, while $\beta$ was found to be constant
for both steady flow and periodic flow cases. All the iterative
adjustments were performed manually.

4. Results and discussion

4.1. Steady flow

For steady flow a total of 59 tests were conducted, with each
test representing a fixed charge pressure and mass flow rate. CFD
simulations were performed for all the measured data using the
methodology described in the previous section. Excellent agree-
ment between data and simulation results were obtained using
the $K$ and $c_f$ values summarized in Table 2.

CFD simulations using the aforementioned parameters led to
excellent agreement with measurements. The Darcy permeability
was found to be $K = 1.93 \times 10^{-11} \text{ m}^2$, corresponding to $\beta = 1.33 \times 10^{-10} \text{ m}^2$, for all the cases. The simulated results for the Er50
Pr50 regenerator filler are depicted in Fig. 6, where $c_f$ is shown as a
function of $Re_K$.

4.2. Periodic flow

A total of 24 oscillatory flow tests were conducted, with each
test representing a fixed compressor frequency, charge pressure,
and piston stroke. The tests covered the frequency range 30–
70 Hz. CFD simulations were performed for all the measured data using
the methodology described in the previous section. Excellent agree-
ment between data and simulation results were obtained using
the $K$ and $c_f$ values summarized in Table 1.

Fig. 10. Effect of uncertainty on $c_f$ values.
values found for steady flow tests. Fig. 7 shows the resulting $c_f$'s as a function of $Re_p$.

Typical simulated results for the $Er_{50}Pr_{50}$ regenerator filler under periodic flow conditions are depicted in Fig. 8. These figures display the measured and predicted inlet pressure, and measured mass flow rate and outlet pressures for the different operating frequencies, piston strokes, and charge pressures associated with the periodic flow simulations. Careful review of these and other simulation results indicated that the flow field in the entire tested regenerator was predominantly one-dimensional, as expected. The figures also show that while there is near-perfect agreement between simulations and measurements with respect to the magnitude of pressure at inlet, a slight discrepancy between measurements and simulations with respect to the oscillation phase shift angles.

### 4.3. Correlations and comparison between steady and periodic hydrodynamic parameters

As mentioned earlier, for both the steady flow and periodic flow results, $K = 193 \times 10^{-11}$ $m^2$ was a constant. The function describing $c_f$ was well approximated by a power correlation (found using MATLAB [34]) as a function of the Reynolds number, of the form shown in Eq. (14), with the determined coefficients presented in Table 4.

$$c_f = a \cdot Re_p^b + c$$  \hspace{1cm} (14)

For the periodic flow cases and certain steady flow cases, where $P$ (which is defined as the system charge pressure divided by a reference pressure of 1 MPa) was greater than 0.7 and $Re_p$ was greater than 0.2, the exponent $b$ in Eq. (14) was a constant value of $-1.4$. The values of $a$ and $c$, for these cases, are shown in Table 4.

The remaining steady flow cases also followed a power function relationship, however, each curve was independently fit with unique constants as shown in Table 5.

A comparison between the actual $c_f$ values and those predicted based on the derived correlations are presented in Fig. 9.

### 5. Uncertainty in results

The uncertainty in the results stems from the accuracy of the sensors associated with the experimental flow tests. To calculated uncertainty, the steady-flow Forchheimer Equation, which is an extension of Darcy's Law, was used along with error propagation analysis, represented by,

$$\frac{\Delta P}{L} = \frac{\mu}{K \rho A \bar{m}} + \frac{c_f}{\sqrt{K \rho A \bar{m}^2}}$$  \hspace{1cm} (15)

$$\sigma_{c_f}^2 = \sigma_{f_{\bar{m}}}^2 + \sigma_{f_{\bar{U}_{\bar{m}}}}^2 + \sigma_{f_{\bar{U}_{\bar{P}_{\bar{m}}}}}^2 + \left(\frac{\partial c_f}{\partial \bar{U}_{\bar{m}}} \bar{U}_{\bar{m}}\right)^2 + \left(\frac{\partial c_f}{\partial \bar{U}_{\bar{P}_{\bar{m}}}} \bar{U}_{\bar{P}_{\bar{m}}}\right)^2$$  \hspace{1cm} (16)

where $U$ is the associated uncertainty of the corresponding sensor. A sample plot to show the effect of uncertainty on the derived $c_f$ values is shown in Fig. 10.

### 6. Concluding remarks

A systematic experimental and CFD-based study for the quantification of Darcy permeability and Forchheimer's coefficients for porous structures under steady and periodic flow conditions was carried out. In the investigation reported here, the hydrodynamic resistance flow parameters for $Er_{50}Pr_{50}$ rare-earth powder regenerator filler material which is useful for pulse tube and Stirling cryocoolers. The porous regenerator filler was made of spherical particles with an average diameter of 69 $\mu m$ and a porosity of 38%. In the periodic flow tests the time variations of pressures were measured in an apparatus that consisted of a modular regenerator housing containing a porous regenerator, for inlet pressure oscillations with 30~70 Hz frequencies at various charge pressures and piston strokes. Also, the pressure drop across the regenerator was collected for steady flow tests for a variety of charge pressures and mass flow rates. By systematic and iterative CFD simulations, the aforementioned hydrodynamic parameters were optimized leading to excellent agreement between simulations and measurements for the tested regenerator filler, yielding useful correlations. The results showed that the Darcy permeability term was constant for both steady flow and periodic flow cases and with the exception of low flow rate, low charge pressure steady-flow cases, the Forchheimer coefficient followed a consistent power model correlation as a function of the pore based Reynolds number.

### Acknowledgement

This work was supported by a NASA Office of the Chief Technologist's Space Technology Research Fellowship.

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