Alexandria Engineering Journal (2015) 54, 787–794

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ORIGINAL ARTICLE

# Characterization of the frictional losses and heat transfer of oscillatory viscous flow through wire-mesh regenerators

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Received 17 December 2014; revised 1 May 2015; accepted 6 June 2015
Available online 23 June 2015

**KEYWORDS**

Oscillatory flow;
Numerical model;
Pulse tube;
Wire-mesh regenerator;
Darcy effect;
Forchheimer's effect

**Abstract** In this paper, new relations for calculating heat transfer and pressure drop characteristics of oscillatory flow through wire-mesh screen regenerator such as Darcy permeability, Forchheimer's inertial coefficient, and heat transfer area per unit volume, as a function of the wire diameter are presented. According to the derived relations, thinner wires have higher pressure drop and higher heat transfer rate. The relations are applicable for all regenerative cryocoolers. Embedding the new relations into a numerical model, three Stirling-type orifice pulse tube cryocoolers with three regenerators different in length and diameter but same volume in a variety of wire diameters, have been modeled. The results achieved by the model reveal that the local heat transfer coefficient decreases with increase of the wire diameter and the length-to-diameter ratio. In addition, it was shown that the mean absolute gas–solid wire temperature difference is a linear function of wire diameter in the range investigated. The results show that for larger length-to-diameter ratios, Forchheimer's effect will dominate frictional losses, and the variations of the frictional losses are proportional to the inverse of the wire diameter. Wire diameter has been optimized to maximize the coefficient of performance of the cryocooler. Shorter regenerators have thinner optimum wires.


## 1. Introduction

The key role of the regenerator in the regenerative cryocoolers such as pulse tube and Stirling cryocoolers is well recognized, and improving the performance of various types of regenerators is of great importance. The regenerator in a regenerative cryocoolers has a micro-porous metallic structure which is typically the largest source of power loss in cryocoolers. Axial heat conduction, imperfect gas–solid heat transfer, and frictional losses are the main origins of irreversibility. The results presented in the works done by Radebaugh [1], Flakes and Razani [2], Cha et al. [3], demonstrated that the numerical models can be used to simulate cryocoolers as an acceptable design and analysis tool. However, the accuracy

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Peer review under responsibility of Faculty of Engineering, Alexandria University.

http://dx.doi.org/10.1016/j.aej.2015.06.001
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**Nomenclature**

| | |
|---|---|
| $A$ | cross sectional area |
| $c_F$ | Forchheimer's inertial coefficient |
| $C_P$ | specific heat at constant pressure |
| $C_V$ | specific heat at constant volume |
| $C_d$ | flow coefficient of orifice |
| COP | coefficient of performance |
| $d_h$ | hydraulic diameter |
| $d_w$ | wire diameter |
| $d_{Reg}$ | regenerator diameter |
| $f$ | friction factor |
| $h$ | heat transfer coefficient |
| $k$ | thermal conductivity |
| $K$ | Darcy permeability |
| $L_{Reg}$ | regenerator length |
| $l$ | mesh distance |
| $\dot{m}_{or}$ | mass flow rate through orifice |
| $N$ | number of packed screens |
| $n$ | number of packed screens per unit length |
| $p$ | pressure |
| $V$ | volume |
| $V_{Com}$ | compressor total volume |
| $Pr$ | Prandtl number |
| $R$ | ideal gas constant |
| $Re_h$ | hydraulic Reynolds number |
| $t$ | time |
| $T$ | temperature |
| $u$ | velocity |
| $V_d$ | dead volume of compressor |
| $V_S$ | swept volume of compressor |
| $x$ | longitude coordinate |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | heat transfer area per unit volume |
| $\beta$ | opening area ratio of the screen |
| $\gamma$ | specific heat ratio |
| $\varepsilon$ | porosity |
| $\Gamma$ | dimensionless parameter |
| $\lambda$ | matrix conductivity factor |
| $\mu$ | viscosity |
| $\rho$ | density |
| $\omega$ | angular frequency of operation |
| $\sigma$ | pitch |

of these numerical predictions depends on the accuracy of the closure relations they used. The dependence of the hydrodynamic parameters (such as Forchheimer's inertial coefficient and Darcy permeability) and heat transfer parameters (such as heat transfer area) on geometry is thus among the most important closure relations. An efficient regenerator must have: (1) a large heat transfer area to result in high gas–solid heat transfer rate to make it tend to gas–solid thermal equilibrium; (2) a large thermal inertia to decrease temperature oscillations; and (3) small pressure drop to decrease power consumption. Meeting all these goals is of great importance, and optimization and compromise are often needed.

In a regenerator as a porous medium, larger solid particles result in larger heat transfer area and hence, better thermal performance of the regenerator. Consequently, the enthalpy flow from the hot end to the cold end of the regenerator as a loss mechanism will decrease and cooling power will be increased. But, increase of size of solid particles causes a higher pressure drop through the regenerator, so that the mechanical performance of regenerator will be disrupted. A part of compressor work is consumed to overcome the resistance forces of the packing material of the regenerator. Thus, for a regenerator with specified dimensions, increase of size of particles, increases both cooling power and compressor power. Apparently, there is an optimum size that maximizes COP of the cryocooler. Some of the common solid matrixes for regenerators are wire-mesh screens, perforated disks, spherical powders, and foam metal. Most of regenerators are constructed by wire-mesh screens (Fig. 1). Wire-mesh screens are categorized into two types: plain and twill.

A one-dimensional theoretical analysis of the regenerator of a typical pulse tube refrigerator has been carried out by Roach et al. [4] based on assuming simple sinusoidal oscillation. In their study, by using the numerical solution of the derived equation along with boundary conditions, optimum regenerator length to diameter ratio ($L/D$) for two different regenerators with 150-mesh screens and 250-mesh screens has been achieved. Qiu et al. [5] investigated theoretically and experimentally the effect of mesh size of woven wire screens of a three-layer regenerator on the performance of the single-stage G–M (Gifford–McMahon) type pulse tube cryocooler and obtained a lowest no-load refrigeration temperature of 11.1 K with an input power of 6 kW.

*In this paper*, new relations are derived for characterization of a wire mesh screen regenerator by using geometrical and empirical relations. Then, all parts of a pulse tube cryocooler have been modeled numerically, and optimization of the regenerator has been performed based on the derived relations.

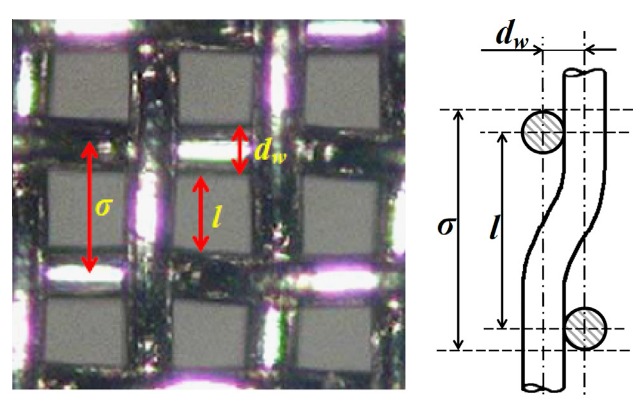


**Figure 1** Photo of wire-mesh screen and the schematic of its lateral view.