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# Review on Friction Factor Correlations for Porous Media of Stirling Cryocooler

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**Abstract**: Cryocoolers are used for achieving temperature below 150 K. Regenerator is an essential part of cryocooler. Regenerators are made up of metallic wire meshes. The application of proper hydrodynamic and heat transfer parameters is very much important in the analysis of wire mesh regenerator using CFD. In this paper, a review on various friction factor correlations proposed for flow through regenerators under steady and steady oscillatory flow are presented. The effect of geometric and operating parameters of the flow through porous media on the friction factor correlations is discussed. The effects of porosity, frequency, charge pressure etc are discussed in detail. Selection of suitable friction factor correlation is important for determining the Darcy and Forchheimers inertial coefficients of porous media. Thus this review will help the designer to select the proper correlation for the porous media and to decide the values of above coefficients for the analysis of the regenerator using CFD.

**Keywords**: Cryocooler, Regenerator, wire mesh, Porous media.

## I. INTRODUCTION

Cryogenics is the study of the production and behaviour of materials at very low temperatures. Cryocoolers are used to produce temperatures ranging from 120 K to near absolute zero through single and multistage configurations. Their applications span a wide array of platforms including superconductors, biological preservation as well as thermal management of various sensory devices. Most of these applications are reserved for high-end military and space operations but the industry is evolving towards commercial uses. Regenerator is an important part of cryocoolers. Wire meshes are stacked in the regenerator. Wire meshes are micro porous structures. In this paper, a review on the different friction factor correlations applicable to porous media is presented. These friction factors depend only on the geometric parameters of wire mesh.

## II. REVIEW ON FRICTION FACTOR CORRELATIONS

E.C.Landrum[1] did an Experimental investigation in which the test section is modeled in CFD and hydrodynamic parameters are iteratively adjusted to match the experimental result. Here the experiments in both axial and radial directions under steady and oscillatory flows were conducted. From this, it was possible to determine viscous resistance coefficient (D) and inertial coefficient (C). By using a Computational Fluid Dynamics (CFD) assisted method directional permeability and Forchheimer inertial coefficients are obtained. This paper describes the measurements of the directional hydrodynamic parameters of steady and oscillatory flow of helium through stacked screens of #635 stainless steel and #325 phosphor bronze mesh fillers using a CFD-assisted methodology ie, with aid of Fluent software. Directional hydrodynamic resistance parameters are determined through measurements of fluid mass flow rate and pressure drop across the porous media. By simulating the experimental test setup and conditions using CFD model viscous and inertial resistances are iteratively adjusted until agreement is reached between experimental results and simulated results. This method of determining the hydrodynamic characteristics under steady and periodic flow conditions, namely the quantification of hydrodynamic parameters that would lead to agreement between experimental data and the predictions of detailed numerical simulations, was proposed by Clearman [2].

W.M Clearman[2] did an experiment, in which helium was passed through regenerator for different mass flow rates and corresponding pressure drop was obtained. During the flow of helium, wire mesh absorbs the heat and offers pressure drop to the flow due to the presence of wire mesh arrangement. The hydrodynamic response of the regenerator fillers were also correlated as friction factors. CFD simulation is done for analysis of experimental data. Pressure drop depends on the geometric parameter of the mesh and hydrodynamic parameters. In this investigation, experiments were conducted for the measurement, and correlation for axial viscous, radial viscous and inertial resistance parameters, associated with steady flow of helium in some common cryocooler regenerator structures. The data analysis was performed using a CFD-assisted method.

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Friction factor is defined as,

$$f = \frac{2}{Re} + 2C_f$$

where,

Reynolds Number $Re = \frac{\rho u\sqrt{K}}{\mu}$

Darcy permeability $K = \frac{\epsilon^2}{D}$

Forchheimer's coefficient $C_f = \frac{C\sqrt{K}}{2\epsilon^2}$

Where,

ρ density of fluid

u is velocity

D is diameter

C is inertial resistance ∈

is porosity

The structures studied for axial flow resistance parameters were stacked 325 mesh screens, stacked 400 mesh screens, sintered 400 mesh screens, metal foam, and aligned micro machined nickel disks with 36–40 µm diameter holes. Radial flow resistance parameters were also measured for stacked 325 mesh screens. A CFD-assisted method was applied for the analysis and interpretation of the experimental data. The test sections and their vicinity were modeled with the regenerator filler represented as a porous zone and the viscous and inertial coefficients (or, equivalently, the permeability and Forchheimer's inertial coefficient) were iteratively adjusted to bring about agreement between the measured pressure drop and the simulated results. Accordingly, the permeability and inertial coefficients were reported for the aforementioned porous structures. The results confirm the importance of anisotropy and average pressure in the porous structures of the tested regenerator fillers.

Choi et al. [3] proposes a new flow model of the pressure drop in oscillating flow through regenerator under pulsating pressure. This paper mainly describes about twill and plain screen regenerators. The schematic diagram of the experimental set up is shown in Fig 1. Two correlations are obtained from the experiments for the twill square screen regenerators under various operating frequencies and inlet mass flow rates. The accurate prediction of the pressure drop through the regenerator is very much important for the optimal design of the system. In this paper, a new pressure drop model is proposed to represent the pressure drop with two variables, i.e. the amplitude and the phase angle with respect to the one side mass flow rate.

i.e, $\Delta P = A_{\Delta P} \exp(i\emptyset_{\Delta P}) \frac{m}{M}$

where, $\Delta P$ pressure drop

$A_{\Delta P}$ amplitude of pressure drop

$\emptyset$ phase angle

M amplitude of mass flow rate

M mass flow rate

The dimensionless parameters are derived from a capillary tube model of regenerator and experiments are performed to obtain functional forms of the parameters.

Friction factor, $f = \frac{A_{\Delta P} d_h}{2\rho_m U^2 L}$

Where,

$d_h$ hydraulic diameter of screen

$\rho_m$ mean density value

U axial velocity

$A_{\Delta P}$ amplitude of pressure drop

L length of regenerator

Here friction factor is function of Re, Va and $\frac{d_h}{L}$

Expansion parameter $e = Re * \frac{d_c}{L} * \frac{1}{Va}$

Valensi number $Va = \frac{{d_c}^2 \omega}{v}$

Hydraulic diameter $d_h = d_w * \frac{e}{1-e}$

A new model is presented for accurate description of oscillating flow characteristic through regenerator under pulsating pressure conditions. The non dimensionalized correlations of the model are derived from the experimental results of twill screen regenerators

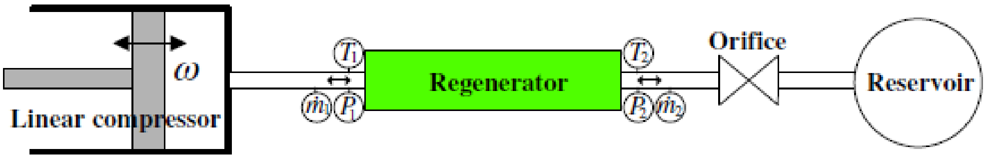


Fig 1: Schematic diagram of experimental apparatus

Kwanwoo Nam[4] did an experiment to obtain the friction factor under cryogenic temperature. Nitrogen gas at room temperature is utilized to make an equivalent cryogenic situation of helium gas that is a common working fluid of cryocooler. Based on the experimental results, the proper correlations are proposed with several non dimensional parameters. The paper present an experimental method and correlations for the friction factor under cryogenic environment. Finally, the improvement of the proposed friction factor is demonstrated from the comparison between the numerical analysis results and the real cryogenic operational data. To obtain the proper friction factor for cryogenic temperature range, the entire regenerator sample can be cooled down to low temperature and the pressure drop can be measured. Even though it is a straight forward way, such an experimental preparation requires excessive painstaking efforts, especially in instrumentation. Therefore, an alternative method can be attempted under room temperature condition to avoid inherent difficulties of cryogenic experiment. The friction factor is correlated in terms of the Valensi number and the expansion parameter, which show substantial change with respect to temperature variation.

$$f = \frac{1}{Va^{0.65}}\left(\frac{0.65}{e} + 0.092\right)$$

Expansion parameter (e) is described in terms of Reynolds number, Valensi number and the gas domain length ratio. The revised friction factor is proposed to improve the oscillating flow model of regenerator at cryogenic temperature. The model based with the room temperature friction factor is found to be incorrect when the cold-end of the regenerator is maintained at cryogenic condition. A.A. Boroujerdi [5] derived new correlations for calculating heat transfer and pressure drop characteristics of oscillatory flow through wire-mesh screen regenerators. The Darcy permeability, Forchheimer’s inertial coefficient, and heat transfer area per unit volume etc are presented as a function of the wire diameter of the mesh screens. The relations are applicable for all regenerative cryocoolers. Here new relations are derived for characterization of a wire mesh screen regenerator by using geometrical and empirical relations.

$$f = \frac{n\epsilon {d_h}^2}{4l\beta} * \frac{33.6}{Re_h} + 0.337\frac{n\epsilon^2 {d_h}^2}{4\beta^2}$$

where,

- n number of packed screen per unit length
- l mesh distance
- $\beta$ opening area ratio of screen
- $d_h$ hydraulic diameter
- Re Reynolds number

Reynolds number $Re = \frac{\rho u\, d_h}{\mu}$

Darcy permeability and Forchheimer’s inertial coefficient are,

$$K = \frac{4}{33.6} {d_w}^2 \left(\frac{1-\gamma}{\gamma}\right) \qquad d_w \text{ is wire diameter}$$

$$C_f = \frac{0.337}{2\sqrt{33.6}} * \frac{1}{\sqrt{\gamma(1-\gamma)^5}}$$ where, $\gamma$ *is* ratio of the wire diameter to the pitch of wire mesh

Heat transfer coefficient,

$$h = \frac{K[1+0.99(RePr)^{0.66}]\epsilon^{1.79}}{d_h}$$ Pr is Prandtl number

In a regenerator as a porous medium, larger solid particles result in larger heat transfer area and hence, better thermal performance of the regenerator. 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 and investigated. Geometrical parameters must be expressed in terms of two main parameters of wire diameter and pitch. In packing wire-mesh screens, the actual porosity can vary by several percent based on the degree of nesting. The half thickness of one screen is very close to the wire diameter suggesting that the screens were not nesting.
S.C. Costa and I.Barreno[6] applied different numerical methods for analysis of the flow through the Stirling engine regenerator. For analysis they found flow resistance coefficients and thermal non equilibrium heat transfer coefficient. Here characterization of wound woven wire matrices shown better overall performance in terms of pressure drop and heat transfer. The recent Stirling engine studies mainly focus on the multidimensional analysis, which is based on full Stirling engine modeling, and can reproduce useful Stirling engine performance results in a time-frame short enough to impact design decisions. In the multidimensional analysis, the regenerator is a difficult component to be modeled because any numerical inaccuracies will influence the full scale Stirling simulation.

Specific correlation equation for stacked matrix configuration S110–63% is

$$f = \frac{111.8}{Re} + 1.85$$

Specific friction factor correlation equation for wound matrix configuration W110–63% is

$$f = \frac{165.5}{Re} + 2.04$$

Nusselt correlation equation for S110–63% and W110-63% are

$Nu = 1.91 + 0.17Re^{0.80}$ and $Nu = 2.15 + 0.07Re^{0.88}$ respectively.

The heat transfer coefficient is defined as

$h = (Nu * k_f)/d_h$ $k_f$ working gas thermal conductivity

In the modeling of a regenerator, an important factor is the internal geometry of the matrix and most of the regenerator models do not assume precise geometrical shape for the elements of the regenerator. In the Stirling engine's analysis the regenerator is usually modeled as a macro-scale porous medium, the porous media model requires the input of a friction factor and heat transfer coefficient which mostly are empirically obtained.
Y.B. Tao[8] used different types of meshes for the analysis of regenerators in cryocooler. Here both hydrodynamic and heat transfer parameters were used for the analysis under steady and oscillatory flow. They also describe the optimization of regenerator mesh. Optimization of regenerator mesh depends upon the Performance of cryocooler. FLUENT CFD codes are used for the Numerical analysis under different mesh geometric parameters and material properties. The mesh regenerator is a typical porous media and the flow in it is oscillating flow. Due to the lack of friction factor correlation for the oscillating flow in porous media, in the past decades, it was difficult to perform accurate numerical calculation and optimization design for the mesh regenerator. In recent years, Nam and Jeong [7] presented a new model for the oscillating flow combined with pulsating pressure in mesh regenerators to overcome the inaccuracy of conventional flow model based on steady flow friction factor and the empirical correlations were derived for the screen regenerators.

Friction factor correlation under oscillating flow in porous media

$$f = \frac{1}{Va^{0.65}}\left(\frac{0.065}{e} + 0.092\right)$$

Expansion parameter, $e = \frac{Re}{Va}\frac{d_p}{L_r}$

Reynolds number, $Re = \frac{\rho X_u d_p}{\mu}$

Amplitude of velocity $X_u = \frac{X_{u1}+X_{u2}}{2}$

Darcy Permeability K and Forchheimer inertia coefficient $C_f$ in oscillating flow is

$$K = \frac{\epsilon d_p^{\,3}}{0.065\,Va^{0.35}L_r}\frac{X_{u1}+X_{u2}}{\beta X_{u1}}$$

$$Va = \frac{\rho\omega d_p^{\,2}}{\mu}$$

They numerically and experimentally investigated the effects of mesh material and mesh size of woven wire screens on the performance of the single-stage pulse tube cooler. Cha et al. [2] performed numerical and experimental studies on the pressure drop characteristics of pulse -tube and Stirling cycle cryocooler regenerators. The directional permeability and Forchheimer inertial coefficients were obtained for the tested regenerator fillers and the hydrodynamic response of the regenerator fillers were correlated as friction factors. A numerical investigation of solid fluid heat transfer and thermal dispersion in porous media was conducted in the investigation by M.G Pathak[9]. The Nusselt number and Thermal dispersion were found by simulation with inputs porosity, Reynolds number, and pulsation frequency. Here the correlation for Nusselt number and thermal dispersion are derived based on obtained numerical data. Frictional losses and other types of irreversibility in the regenerators and heat exchangers of Stirling and pulse tube cryocoolers adversely affect their performance. An understanding of the transport phenomena in porous media during periodic flow is thus essential for the development of reliable analytical or numerical design tools for these cryocooler systems. Heat transfer coefficient monotonically increases as the frequency increases for all unit cell porosities and Reynolds numbers. For each porosity, the higher the Reynolds number, the higher the average heat transfer coefficient. Finally, within the tested range of porosities the magnitude of the average convection heat transfer coefficient increases as the porosity decreases. The detailed numerical data were used for the calculation of unit cell and cycle-average Nusselt number, and the thermal dispersion term that appears in the standard volume-average thermal energy equation for flow in porous media. The Nusselt number and the thermal dispersion term were sensitive to porosity, Reynolds number, and pulsation frequency, and were significantly larger than their counterparts that represented steady flow. Empirical correlations were derived for the Nusselt number and the thermal dispersion term. Kwanwoo Nam[7] experimentally investigated thermal and hydrodynamic characteristics of a regenerator at cryogenic temperature under oscillating flow and pulsating pressure conditions. Here pulsating pressure and mass flow rate are measured at both ends of the regenerator. Thermal characteristics of the regenerator are usually determined from the ineffectiveness. These friction factor correlations were based on the maximum pressure drop and the maximum flow rate for low frequency (less than10 Hz). Second, the pressure drop experiments were performed under oscillating flow combined with pulsating pressure. Helvensteijn et al. [10] presented a friction factor of the regenerator for the oscillation frequency of 30–70 Hz, but the mass flow rate at the regenerator was not directly measured but indirectly calculated from the pressure data and their computational model. In this paper, a novel flow model for the regenerator is developed to improve the accuracy of the numerical model result. The conventional steady flow model turns out to be incorrect when compared to the experimental data under oscillating flow combined with pulsating pressure.

## III.CONCLUSION

This review shows that number of studies had undergone in the field of wire mesh regenerators. The CFD modelling of regenerator as porous media requires hydrodynamic parameters inertial resistance and viscous resistance as input. But it is very difficult to find the input parameters due to the complex nature of the experiment setup and the experiment cost. Therefore the correlation based method to calculate the hydrodynamic parameters is a feasible method for solving this complexity. The version of this template is V2. Most of the formatting instructions in this document have been compiled by Causal.

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