Review on Hydraulic Resistance Parameters of Stirling Cryocooler Regenerator

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Abstract— The regenerator is one of the crucial component of cryocooler. Pressure drop across the regenerator is one of the parameter which determines the performance of the cryocooler. Thus, effect of average pressure on porous medium hydrodynamic closure on steady axial and radial flow for different mesh sizes, different material is considered in this paper. In this paper, the first section shows the work done on regenerator for steady flow, both for axial and radial direction. The second section highlights the complexity of flow in porous media and thus the need of more tedious oscillatory flow. The permeability and Forchheimer inertial coefficient which defines the momentum loss of the porous media is obtained using repetitive iteration using CFD assisted method. The same parameters are also determined for the Oscillatory flow through regenerator, have been discussed, and comparison for steady and oscillatory flow is made.

Key words: Pressure Drop, Steady Flow, Oscillatory Flow, Permeability, Forchheimer Inertia Coefficient

I. Introduction

The regenerator is the temporary heat storage unit, which stores the thermal heat from the fluid in it only to return it back at later stage of cycle. Functionally there is a requirement for a good heat exchange from hot fluid to the cold regenerator material in the first of the cycle and in the latter half, the hot regenerator material should exchange the heat to the cold fluid flowing in reverse direction.

The hydrodynamic and heat transfer parameters associated with the interaction between the coolant fluid and the porous regenerator are thus among the most important closure relations, and are relatively poorly understood. This is particularly true about the hydrodynamic and thermal transport parameters associated with periodic flow in microporous structures. An accurate prediction of the pressure drop across a regenerator is crucial to the design of a Stirling engine, a cryocooler, or a catalytic converter. Various pressure drop correlation for regenerator has been studied by many researchers like London, Miyabe et al., etc. Since the Stirling-cycle machines are operated under the condition of periodically reversing flow, it becomes questionable if the steady flow correlation remains applicable in predicting the pressure-drop in the regenerator of these machines.

All the above-mentioned points thus, motivate the present review on hydraulic resistance parameters on Stirling cryocooler regenerator. The first section in this literature review states about steady flow analysis in axial and radial direction. Followed by second section consisting of discussion on analysis of regenerator at oscillatory flow condition.

II. Steady Flow Analysis of Regenerator

Many researchers have studied flow in porous media, trying to analyse the fluid and thermal behaviour of a flow through it. The analysis of flow considering the flow as steady is the simplest way to start.

A. *Axial Flow*

W.M. Clearman, J.S. Cha et al., [1] (2008) experimentally measured pressure drops in test sections packed with regenerator fillers. The hydrodynamic parameters associated with steady axial and lateral (radial) flow of helium in various widely-used pulse tube and Stirling cryocooler regenerator fillers were measured and correlated in their investigation. E.C. Landrum, T.J. Conrad et al., [2] (2009) had carried out experiments to measure the effect of average pressure on the porous media hydrodynamic closure relations relevant to steady axial flow through several regenerator fillers. Computational fluid dynamics (CFD) models of the regenerator test sections and their vicinities were developed and simulations were performed in which the regenerator test sections were modelled as porous media. By iterative repetition of the simulations, the longitudinal permeability and Forchheimer inertial coefficients were determined such that they would lead to agreement between experimental measurements and the simulations. The regenerator material used of stainless steel were made into wire mesh of sizes 325 and 400 also, stainless steel metal foam, sintered stainless steel mesh and stack of micro-machined perforated plates. The results showed the anisotropic nature of the regenerator.

The regenerator fillers mentioned above were used by E. C. Landrum, T. J. Conrad et al., [2] (2009) to carry out the set of experiments to study the effect of pressure on hydrodynamic parameters of several pulse tube refrigerator regenerator fillers in axial flow. The helium superficial velocity through the porous samples covered a range from 0.2 to 19 m/s. The test section was modelled as porous structure using Ansys Fluent tool and, and the model porous media hydrodynamic parameters were iteratively adjusted to match the model predictions to the experimental results. Using this methodology, it was possible to determine axial viscous and inertial resistances related to the Darcy permeability and Forchheimer inertial coefficient, respectively, for all the porous samples.

L. Wilson, Arunn Narasimhan et al., [3] (2006) in their work discussed, permeability 'K' and form coefficient 'C' are the characteristic hydraulic properties of any porous medium. They are determined simultaneously, for known fluid thermo-physical properties by using the Hazen-Dupuit-Darcy model (HDD) to curve-fit the longitudinal global pressure-drop versus average fluid speed data from an isothermal, steady flow, hydraulic experiment across a test section of the porous medium. The co-efficient 'K' and 'C' thus measured are global parameters, i.e., valid for the entire porous medium and universal provided the flow throughout the porous medium is of plug flow nature as explained by them. Chin-Tsau Hsu, Huili Fu et al., [4] (1999) conducted experiments to investigate the pressure-drop characteristics of regenerators packed with wire screens. The experiments covered a wide range from very low to very high Reynolds numbers to determine the correlation between pressure drop and velocity.

T. J. Conrad, E.C. Landrum et al., [5] (2009) carried out analysis on regenerator for steady flow and oscillating flow Hydrodynamic parameters of stacked discs of 635 mesh stainless steel and 325 mesh phosphor bronze were determined using a CFD – assisted methodology, whereby the hydrodynamic resistance parameters for these fillers are specified when they are modelled as anisotropic porous media. Multiple test runs were performed for each mesh filler producing mass flow rates ranging from 0.042 g/s to 1.36 g/s. E. C. Landrum, T. J. Conrad et al., [6] (2010) 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. 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 using CFD, model viscous and inertial resistances are iteratively adjusted until agreement is reached between experimental results and simulated predictions.

B. Radial Flow

The experimental set up was done as mentioned in [1], [5], [6] to determine the hydraulic parameters of the regenerator in radial direction. The study shows for very low mass flow rates the velocity vector in annular porous medium was approximately; purely radial but with increasing mass flow rate significant two-dimensional effect is observed. The hydraulic parameters are determined by repetitive iterations as done for axial flow. For both the axial and radial steady flow cases, the viscous resistance could be determined at low flow rates because inertial effects were small. A trial and error method was used until a unique viscous resistance satisfied the first several data points of the low flow regime. This term was then fixed and only the inertial resistance was adjusted in the subsequent simulations. The iterative process was continued until good agreement was achieved between simulated and experimental pressure drops across the entire range of mass flow rates.

III. Oscillatory Flow Analysis of Regenerator

Since the Stirling-cycle machines are operated under the condition of periodically reversing flow, it becomes questionable if the steady flow correlation remains applicable in predicting the pressure-drop in the regenerator of these machines. Thus, to study the operation of these complex process accurately, oscillatory flow analysis is needed. Like steady flow, oscillatory flow can be studied in axial and radial direction.

Results [4], shows the term $Re_h^{-1/2}$ accounts for the boundary layer effect at intermediate Reynold number. The result also indicates that the correlation for oscillating flows in regenerator coincides with that of steady flows in $1 < Re_h < 2000$. This suggests that the oscillating flows in the regenerators behave as quasi-steady at the frequency range of less than 4.0 Hz, which is the maximum operable oscillating flow frequency of the facility [4]. All periodic measurements were done at the largest stable input pressure amplitude based upon the compressor response. Oscillatory flows in the axial and radial directions were implemented over the frequency range of 50 to 200 Hz, at charge pressures of 2.86 and 3.55 MPa [5]. Higher frequency operation is preferred for miniature cryocoolers, therefore periodic flow cases were performed over a frequency range between 50 and 200 Hz.

J. S. Cha, S.M. Ghiaasiaan et al., [7] (2008) had carried out the investigation experimentally on microporous media for oscillatory flow, in axial and, radial direction. They calculated the friction factor for steady and radial flow and comparison is made by taking the ratio of friction factor of oscillatory to steady flow for different Reynold number. Their study showed that the ratio was essentially same for lower Reynold numbers, but the variation is observed at the higher Reynold number. The directional permeability and Forchheimer inertial coefficients obtained for the tested regenerator fillers, 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.

Q. Q. Shen and Y.L. Ju [8], (2008) have summarized typical experimental results and correlations on the friction factor of regenerators, at different operating frequencies, at room and cryogenic temperatures. The comparison of those friction factor data is then presented to clarify the reason for their difference. Finally, a new universal correlation of friction factor for oscillating flow regenerator, in terms of two non-dimensional parameters is presented.

J. S. Cha, S. M. Ghiaasiaan et al., [9] studied longitudinal hydraulic resistance parameters of cryocooler and Stirling regenerator in periodic flow. An experimental apparatus consisting of a cylindrical test section packed with regenerator fillers are used for the measurement of axial permeability and Forchheimer coefficients, with pure helium as the working fluid. The regenerator fillers that are tested include stainless steel 400 mesh screens and stainless steel 325-mesh screens with 69.2% porosity, stainless steel 400-mesh sintered filler with 62% porosity, stainless steel sintered foam metal with 55.47% porosity, and nickel micromachined disks with 26.8% porosity. A CFD assisted methodology is then used for the analysis and interpretation of the measured data. The viscous resistance coefficient and the inertial resistance coefficient values obtained in this way are correlated in terms of the relevant dimensionless parameters.

IV. Conclusion

This review paper has considered the research work related to analysis of steady and oscillatory flow in regenerator. It is found that pressure drop under oscillatory flow is higher than under steady flow at the same Reynold number based on cross sectional mean velocity. The results show that except for very low oscillation frequencies and the sintered type regenerators the cycle-average friction factor under oscillatory flow conditions is typically larger than the steady-flow friction factor.

For CFD analysis the tool used is ANSYS and experiments were carried using test rig, as explained in papers above by various authors. Results of experimentation and CFD analysis of regenerator shows that at higher frequency the prediction of hydraulic parameter are found to be deviating from actual result and oscillating flow analysis gives more accurate values. It can also be inferred that; the result can vary as per the physical dimensions and matrix arrangement of the regenerator even if the matrix material used is same.

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