Modelling of a Stirling cryocooler regenerator under steady and steady – periodic flow conditions using a correlation based method

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ABSTRACT

The performance of a Stirling cryocooler depends on the thermal and hydrodynamic properties of the regenerator used in the system. CFD modelling is the best technique to design and predict the performance of a Stirling cooler. But the accuracy of the results depends on the hydrodynamic and thermal transport parameters used as the closure relations for the volume averaged governing equations. A methodology have been developed to quantify the viscous resistance term D and the inertial resistance term C required for modelling the regenerator as a porous medium in Fluent. Using these hydrodynamic resistance terms, the steady and steady – periodic flow of helium through regenerator was modelled and simulated. Comparison of predicted and experimental pressure drop reveals good predictive power of the correlation based method. For oscillatory flow, the simulation could predict the exit pressure amplitude and the phase difference accurately. Therefore the method was extended to obtain the Darcy permeability and Forchheimer's inertial coefficient of other wire mesh regenerators applicable to Stirling coolers. System level simulation using these parameters will lead to better material selection and improved design of regenerator and pave way to contrive high performance, ultra-compact free displacers used in the futuristic miniature Stirling cryocoolers.

INTRODUCTION

An efficient and appropriate methodology for the prediction of viscous resistance, D and inertial resistance C was developed and presented. Steady flow of helium through different wire mesh regenerators was simulated at different mass flow rates using the Darcy permeability and Forchheimer's inertial coefficient obtained from the present method. The predicted and reported experimental pressure drop were compared. Subsequently, steady periodic flow of helium through these regenerator structures were simulated using the above hydrodynamic resistance parameters. The predicted pressure amplitudes and phase differences were compared with the limited experimental results available in literature.

METHODOLOGY

The friction factor for a porous media is correlated as [7],

$$f_K = \frac{2\varepsilon}{Re_K} + 2C_f\varepsilon^2$$

$$Re_K = \frac{\rho_f u\sqrt{K}}{\mu}$$

Forchheimer's inertial coefficient C_f can be expressed as,

$$C_f = \frac{C\sqrt{K}}{2\varepsilon^3}$$

$$K = \frac{\varepsilon^2}{D}$$

Pressure drop in the matrix is caused by form drag and skin friction. Their effects on the equation for friction factor can be expressed as[9],

$$f = C_{fd} + \frac{C_{sf}}{Re}$$

Where C_{fd} and C_{sf} are correlation constants.
The Reynolds number Re is defined as ,

$$Re = \frac{\dot{m} l}{\beta A_r \mu}$$

Here ε , K , u, ρ_f, μ , $\dot{m}$, l and A_r represents the porosity, permeability, velocity of fluid, density of the fluid, viscosity, mass flow rate, mesh distance and cross sectional area of regenerator respectively. Using the above correlations, the friction factor was calculated at different mass flow rates. Landrum and Clearman [7,8] obtained the Darcy permeability, K and Forchheimer's inertial coefficient, Cf for 325, 400 and 635 mesh matrices from their experimental study. Using these empirical constants, friction factor f_K was calculated. The friction factor f obtained from different correlations is compared with f_K. The correlation which calculates friction factor values in close agreement with that obtained from Clearman's equation was identified. Then the friction factor data obtained from the matching correlation is substituted for f_K and the inertial resistance, C and viscous resistance, D were iteratively adjusted to get unique values of these parameters for a porous media.

Correlation	C_{sf}	C_{fd}
Gedeon/Wood	68.556	0.5274
Tong/London	44.710	0.3243
Blass	47.245	0.4892
Miyabe	33.603	0.3370
Tanaka	40.741	0.5315

Table 1. Values of correlation constants.

METHODOLOGY

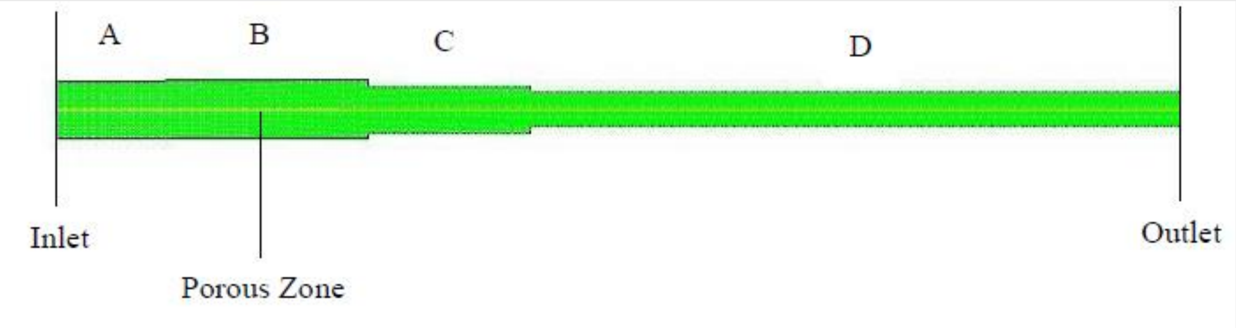

Figure 1. Steady flow model of 325 and 400 mesh regenerator test section

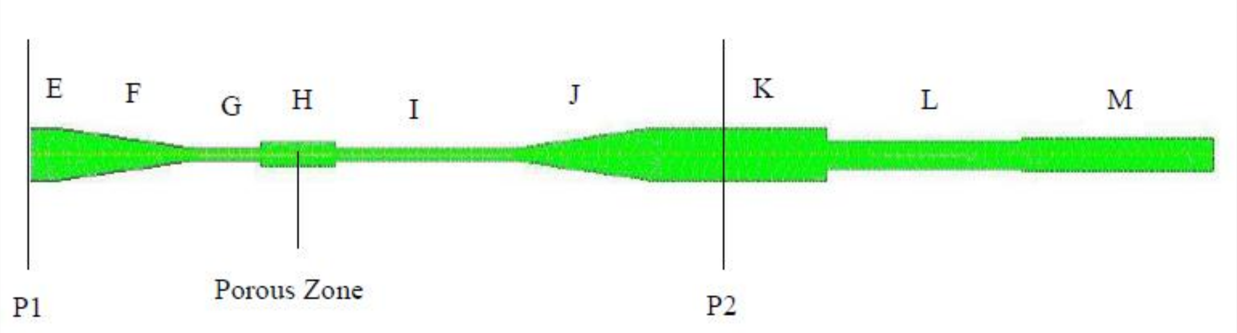

Figure 2. Oscillatory flow model of 635 mesh regenerator test section.

RESULTS

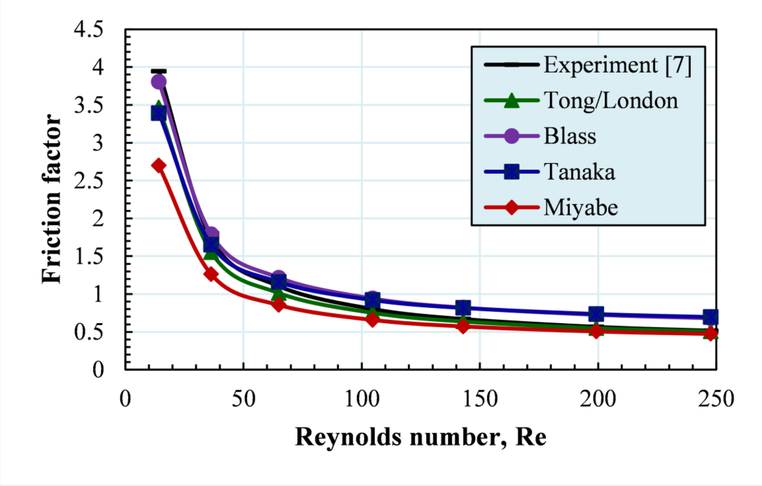

Figure 3. Variation of friction factor (#325)

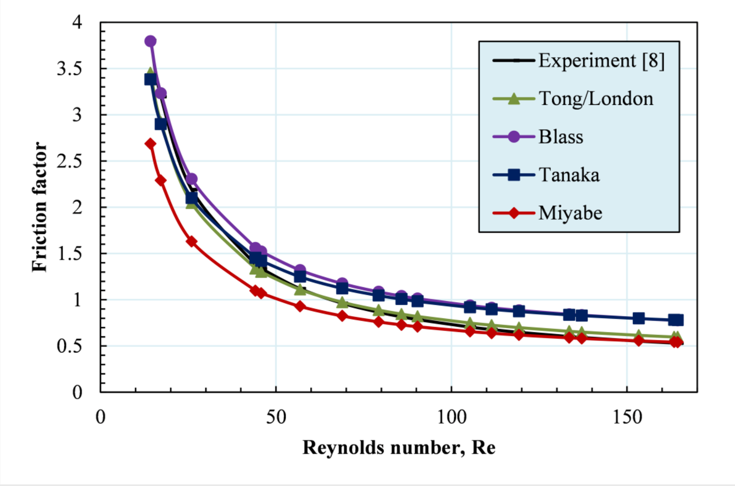

Figure 4. Variation of friction factor (#635)

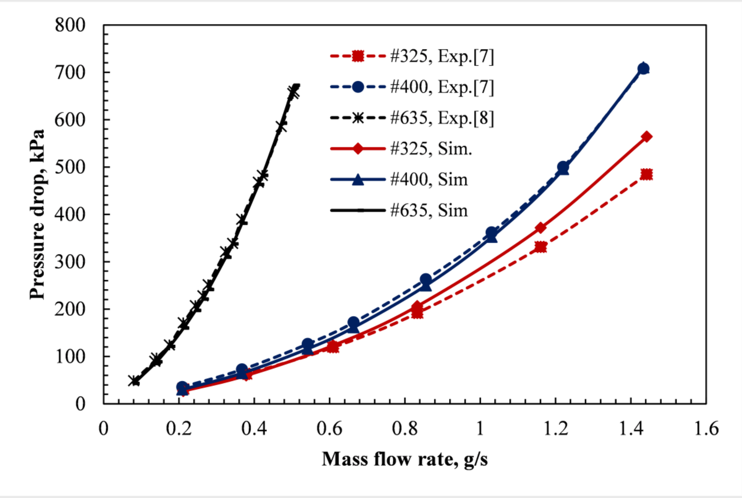

Figure 5. Pressure drop comparison (Steady flow)

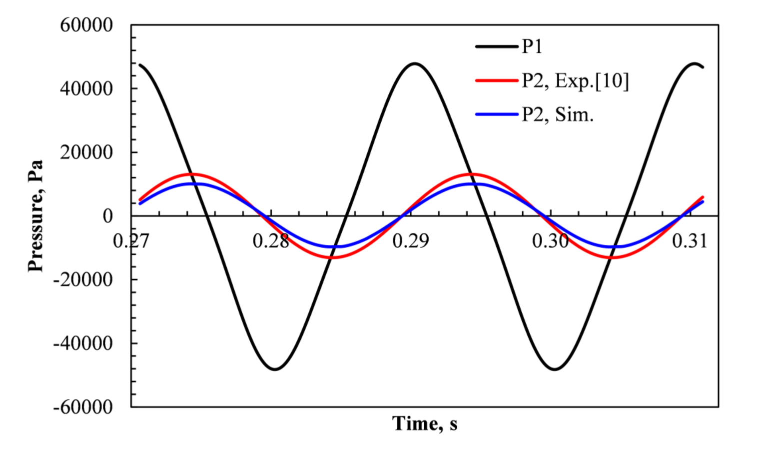

Figure 6. Pressure amplitudes at P1 and P2 Locations (#325, 50 Hz frequency)

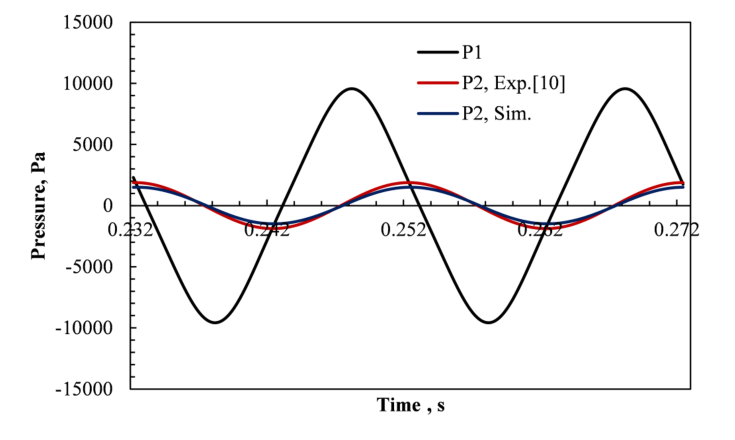

Figure 7. Pressure amplitudes at P1 and P2 locations(#400, 50 Hz frequency)

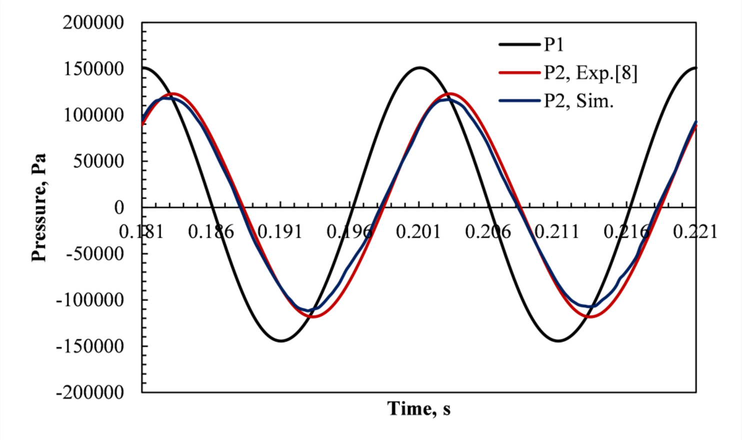

Figure 8. Pressure amplitudes at P1 and P2 Locations (#635, 50 Hz frequency)

Matrix Type	Viscous resistance (D, m^{-2})	Inertial resistance (C, m^{-1})	Permeability (K, m^2)	Forchheimer's coefficient (C_f)
#325	1.955E+10	68400	2.48E-11	0.5036
#400	2.418E+10	76050	2.01E-11	0.5036
#635	7.575E+10	89280	5.26E-12	0.4071

Table 2. Hydrodynamic resistance parameters of 325, 400 and 635 mesh regenerators from correlation based method.

Frequency, Hz	Pressure, $P2_{Exp}$ [6], Pa	Pressure, $P2_{Sim}$, Pa	Difference between $P2_{Exp}$ and $P2_{Sim}$ (%)	Difference b/n simulated and experimental phase angle (deg.)
50	122.82	116.49	5.16	0
100	35.23	33.01	6.32	0
150	12.35	12.59	-1.96	16.18
200	8.59	9.05	-5.37	0

Table 3. Comparison of experimental and predicted pressure amplitude at location P2 (635 mesh).

DISCUSSION

- Blass and Tong/London correlations are found to be suitable for prediction of Darcy permeability and Forchheimer's inertial coefficient of high and low porosity matrices respectively, using the present methodology.
- For steady flow of helium through 325, 400 and 635 mesh regenerators, the average deviation of pressure drop prediction from experimental data is 9.91 %, 6.12 % and 3.61 % respectively.
- The average difference between the predicted pressure amplitude and the corresponding experimental values are 19.32 %, 15.83 % and 4.7 % for 325, 400 and 635 mesh regenerator respectively.
- The % difference between the predicted and experimental pressure amplitude increases with the increase in frequency

CONCLUSIONS

- A methodology has been developed for the quantification of Darcy permeability and Forchheimer's inertial coefficient of wire mesh regenerators.
- The results of the steady and steady periodic flow simulation reveal the good predictive power of the method.
- periodic heating/cooling, free displacer with clearance seals and resonating miniaturized cryocoolers with constraints of low mass, length, diameter and pressure drop are not practical. Thus CFD simulation of regenerators using the closure parameters obtained from the current method will lead to contrive high performance, ultra – compact free displacers used in the futuristic miniature Stirling coolers.

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