Original Article

Institution of MECHANICAL ENGINEERS

Journal of MECHANICAL ENGINEERING SCIENCE

Proc IMechE Part C:
J Mechanical Engineering Science
0(0) 1–11

DOI: 10.1177/0954406215584393
pic.sagepub.com
SAGE

Theoretical and experimental investigation of pressure drop and refrigeration effect in pulse tube cryocooler

AD Badgujar and MD Atrey

Abstract

The design of a highly efficient pulse tube cryocooler (PTC) is a subject of recent research activities. The PTC performance depends on various operating and design parameters. Regenerator is one of the very important components of the PTC which decides the low temperature that the PTC can attain. Efficiency of regenerator should be high enough, 96% or above, in order to reach very low temperature while the pressure drop in the regenerator is one of the parameters which needs to be analysed in detail. In the present work, theoretical and experimental investigations are carried out on two different single stage U type PTC. The volumes of regenerators and pulse tubes, in both the cases are kept same while the length to diameter (L/D) ratios of regenerators are changed. Investigations are carried out on these PTC with respect to pressure drop in the regenerator and net refrigeration effect obtained from the PTC at 80 K. The pressure drop increases from 0.29 bar to 2.07 bar with an increase in L/D ratio from 1.93 to 9, resulting in decrease in refrigeration effect from 6.1 W to 1.7 W at 80 K with 300 W input power. The study is further extended to understand the effect of coarse size stainless steel mesh size in the regenerator. Coarse size meshes filled up to 60% of regenerator length improved the refrigeration effect from 1.7 W to 2.8 W; however, further filling degrades the performance of the PTC. The experimental results are compared with theoretical results obtained by Sage software and Isothermal model.

Keywords

Pulse tube cryocooler, pressure drop, regenerator mesh, L/D ratio

Date received: 12 May 2014; accepted: 30 March 2015

Introduction

The Stirling type pulse tube cryocoolers (PTC) are widely used to provide moderate refrigeration effect at 80 K. Most of the research work in this field is focused on the development of efficient PTCs. The performance of the PTC can be improved by increasing the refrigeration effect or by minimising the power input. This further depends on regenerator material and pressure drop in regenerator. Various losses that affect the PTC performance are heat conduction, regenerator ineffectiveness, radiation, pressure drop losses etc. Amongst these pressure drop losses are the major losses and need to be investigated. In this regenerative-type cryocooler, the regenerator is the most crucial part and also a source of major pressure drop. A significant pressure drop takes place in the regenerator which further depends on the length of the regenerator and its porosity. Thus, regenerator length to diameter ratio (L/D ratio) and effect of various mesh sizes are important parameters to be investigated in order to improve the performance of a PTC.

In fluid flow, the Darcy Weisbach equation[1] as given in equation (1), relates pressure drop due to friction (along a given length of pipe) to the average velocity of the fluid flow.

$$\Delta P = f_D \frac{L}{D}\left(\frac{\rho V^2}{2}\right) \tag{1}$$

In the above equation, f_D is Darcy friction factor and V is mean velocity of flow, ρ is density of gas and D is diameter of pipe. This equation is valid for steady flow conditions. The PTCs are subjected to oscillating flows. The regenerators are filled with meshes of stainless steel, phosphor bronze or lead spheres depending

Department of Mechanical Engineering, Indian Institute of Technology Bombay, Mumbai, India

Corresponding author:
AD Badgujar, Department of Mechanical Engineering, Indian Institute of Technology Bombay, Mumbai 400076, India.
Email: amarishbadgujar@gmail.com

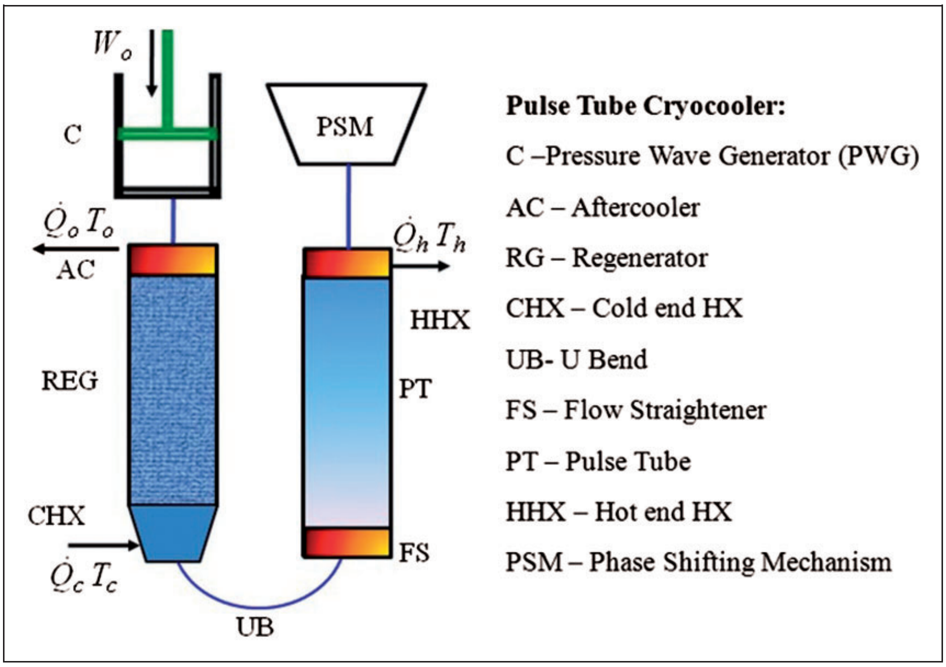

Figure 1. Schematic of U-type pulse tube cryocooler.[5]
REG, regenerator.

on the temperature to be achieved. Experimental investigation has been reported regarding the study of pressure drop for oscillating flow in the regenerator[2] for low operating frequencies below 10 Hz. Gedeon and Wood,[3] derived a correlation for pressure drop in oscillating gas flow which is reported by Thomas and Pittman[4] as given in equation (2). They have derived a correlation for the flow friction factor and Nusselt number for both, wire screens and metal felts, and these equations are incorporated in Isothermal model to find the pressure drop in the regenerator.

$$\Delta P = c_f \frac{L(1-\varepsilon_{\text{avg}})}{d\varepsilon_{\text{avg}}} \frac{\rho u^2}{2} \tag{2}$$

The equation shows that pressure drop (ΔP) depends on porosity (ε) of regenerator matrix material and total length (L) of the regenerator matrix. Theoretical and experimental investigations on single-stage and multistage PTC, to achieve temperature below 20 K, have already been reported,[5] where the single-stage and two-stage PTC have regenerator L/D ratio of 1.93 and 5, respectively. In order to design a multistage PTC, the length of the regenerator needs to be increased. Zhu and Chen[6] presented an Isothermal model for an orifice type PTC. The Isothermal model with cyclic analysis[7] is used to design the single stage U type PTC considering various losses. Also, commercially available Sage software[8] is used to analyse the PTC performance. In the present paper, the Isothermal model and Sage software are used to investigate the effect of L/D ratio and different mesh sizes on the performance of the PTC. The theoretical predictions obtained using these models are compared with the experimental results. The present work is the first of its kind where experimental measurements of pressure drop across the regenerator in a PTC are reported.

Working of PTC[5]

Figure 1 shows the schematic of the PTC with U configuration where regenerator and pulse tube (PT) are parallel to each other. The pressure wave generator generates the pressure waves in the system, which pressurises and depressurises the Helium gas in the system. During pressurisation, the aftercooler takes the heat of compression. The gas is cooled in the regenerator due to heat transfer from the gas to the regenerator mesh. During depressurisation, the gas in the PT expands to a lower temperature than the temperature at which it enters the PT. This cold gas, while passing through the regenerator, becomes warm due to heat transfer from the regenerator matrix to the gas. The temperature at the hot end of the PT and at the aftercooler is maintained at room temperature by using water. The phase shifting mechanism is used to optimise the phase shift between the mass flow rate and pressure in the PT, which is essential for improving the performance of the PTC.

Theoretical analysis

Theoretical investigation is carried out using Isothermal model and Sage software. Sage incorporates numerical methods for accurate solutions. The results obtained by both the models, in terms of refrigeration effect at lower temperature and pressure drop, are compared with experimentally obtained results.

Isothermal model

Isothermal model is very useful for analysis of Stirling type cryocoolers. Zhu and Chen applied this model to a Stirling type inline PTC. Atrey et al.[9] extended Isothermal model to account for various losses in the PTC using cyclic analysis. For each interval of the cycle, ideal gas law is applied and pressure–volume variation and mass flow rates for the corresponding time intervals are obtained. Based on these, ideal refrigeration effect and ideal power requirement are calculated. Net refrigeration effect and power are obtained by taking the losses into account. The pressure drop across the regenerator, which works under oscillating flow conditions, is obtained using equation (2), while the friction factor is calculated using equation (3)[5]

$$c_f = \frac{129}{R_e} + \frac{2.91}{R_e^{0.103}} \tag{3}$$

where R_e is Reynolds number given by Robert et al.[1]

$$R_e = \left|\frac{m_r d}{A_r \mu}\right| \tag{4}$$

where m_r is mass flow rate through regenerator and A_r is the regenerator flow area, d is diameter of pipe and μ is dynamic viscosity of the fluid. The pressure drop across the regenerator is obtained by using equation (2). The porosity (ε) of regenerator is calculated by taking the average porosity of different mesh sizes based on the fill factor of respective meshes.

$$\varepsilon_n = 1 - \frac{\left(\pi d_{wn}\sqrt{s_n^2 + d_{wn}^2}\right)}{4s_n^2} \tag{5}$$

$$\varepsilon_{\mathrm{avg}} = \sum_1^n x_n \varepsilon_n \tag{6}$$

In the above equations, d_w and s represent the wire diameter and pitch for different meshes, respectively, n is an integer which represents various mesh sizes and x is the fraction of meshes filled in the regenerator.

Sage simulation for PT cryocooler

Sage is a simulation software and can be used to design a PTC. It has drag and drop visual interface where a user can assemble complete system from standard components such as pistons, cylinders, heat exchangers, etc. The single stage PTC is modelled using Sage. Figure 2 shows this model which is used to analyse the pressure drop and the performance of PTC.

Models are created using different components, which are principally a set of equations which are solved using various numerical methods. The connection numbers are generated by the software itself in the sequence of the connections made. These connections are the set of equations, for mass and heat interaction between the components.

As shown in Figure 2, the PTC mainly consists of the linear compressor, the cold head and the phase shifter assemblies. The charging pressure of the system is defined in the pressure source component and the surrounding temperature is defined in the point heat source component. Back volume, front volume and constrained piston-cylinder are used to model the compressor (pressure wave generator). On the similar line, the cold head components consisting of aftercooler, regenerator, cold-end heat exchanger, etc. and the phase shift mechanism may be modelled. The regenerator is a very important component of PTC and its detailed model is discussed by Badgujar and Atrey.[5] Using Sage, optimisation of various design and operating parameter can be carried out to study the effect of these parameters.

The governing equations for the model are given below.

$$\text{Continuity} \quad \frac{\partial \rho A}{\partial t} + \frac{\partial \rho u A}{\partial x} = 0 \tag{7}$$

$$\text{Momentum} \quad \frac{\partial \rho u A}{\partial t} + \frac{\partial u \rho u A}{\partial x} + \frac{\partial P}{\partial x}A - FA = 0 \tag{8}$$

$$\text{Energy} \quad \frac{\partial \rho e A}{\partial t} + P\frac{\partial A}{\partial t} + \frac{\partial}{\partial x}(u\rho e A + uPA + q) - Q_w = 0 \tag{9}$$

where A is the flow area, e is the mass specific total gas energy and u is flow velocity. These gas dynamic equations determine three implicit solution variables ρ, $\rho u A$ and ρe. F in the momentum equation is the viscous term and the Q_w in the energy equation is the heat flow per unit length, through the negative z surface, due to film heat transfer. The equations are discretised over a grid of points (xi, tj). Upon this grid, the above equations are solved implicitly. Staggered-grid formulation is used to solve the above equations accurately.

The major pressure drop in a PTC system takes place across the regenerator. Both these models, Isothermal and Sage, are used to predict the pressure drop in the PTC and the prediction of the model is compared with the experimental results. An experimental setup is developed with proper instrumentation for this purpose.

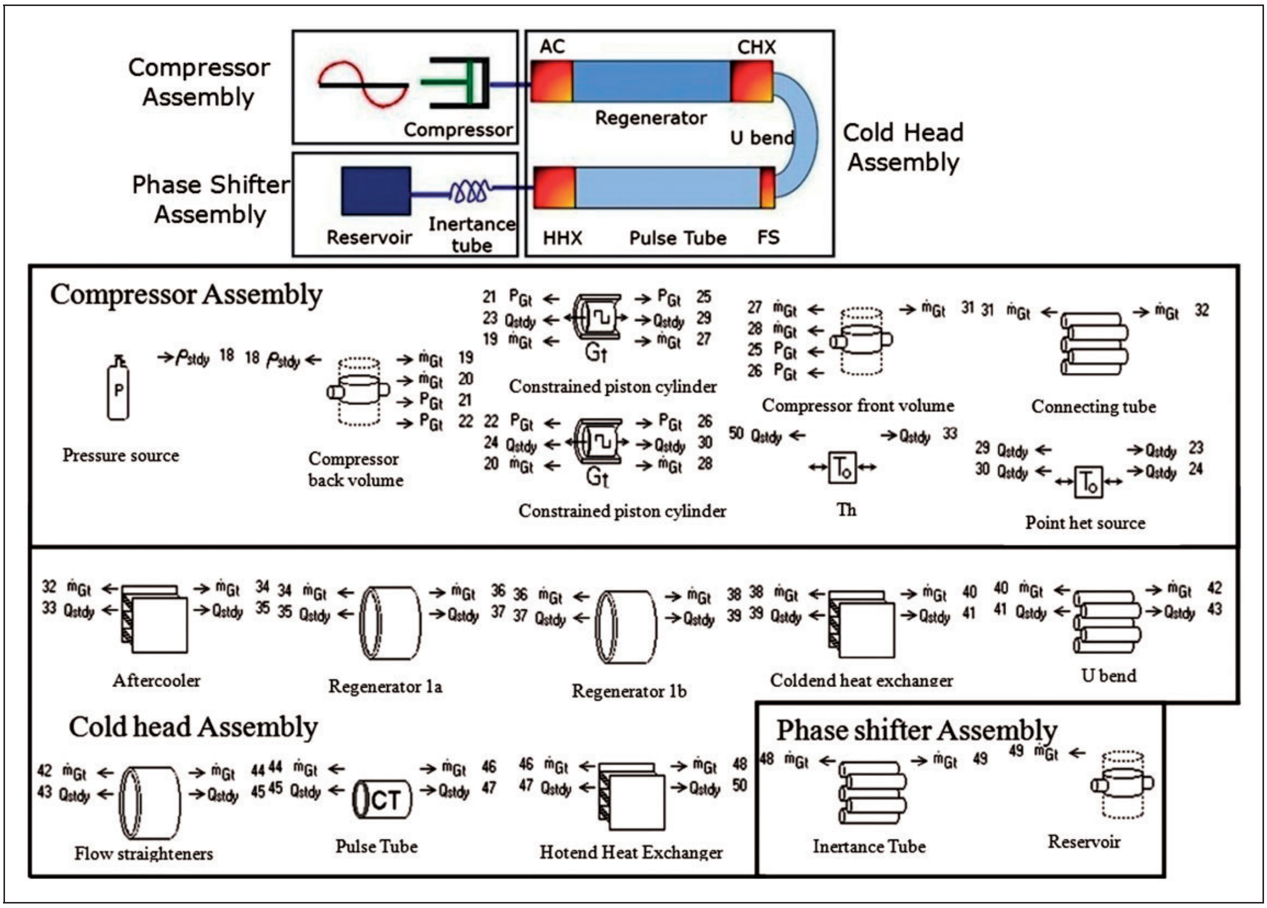

Figure 2. Sage model for single stage pulse tube cooler assembly.
AC, aftercooler; CHX,– cold end HX; FS, flow straightener; HHX, hot end HX.

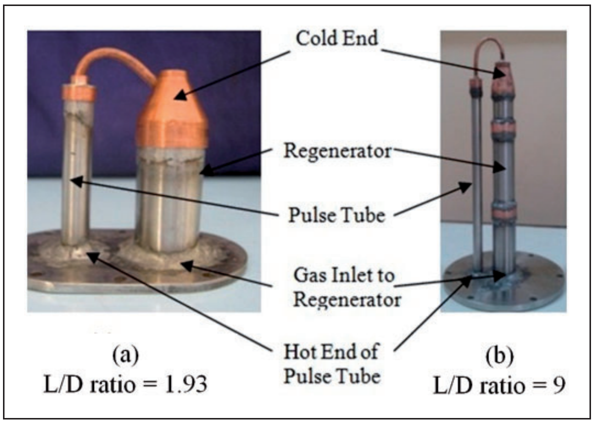

Figure 3. Pulse tube cryocooler cold head assembly.

Experimental setup

Figure 3(a) and (b) shows assemblies of PTC cold head with regenerator L/D ratios as 1.93 and 9, respectively. The change in L/D ratio is required to be studied for designing multistage PTC where the regenerator needs to be of higher length.

For comparison purpose, regenerator and PT volumes for both the cases are kept the same.

Table 1. Dimension of cold head for two cases.

	Regenerator	Pulse tube
Case 1 (L/D = 1.93)	$28 \times 54 \times 0.15$	$12.2 \times 74 \times 0.15$
Case 2 (L/D = 9)	$16.8 \times 150 \times 0.15$	$8.7 \times 46 \times 0.15$

Note: $\Phi \times l \times t_h$ (Inside diameter × length × thickness in mm).

The regenerators consist of stainless steel meshes with mesh size of 400 having a wire diameter of 25 µm and porosity of 0.587. In the subsequent experiments, a coarse mesh of size 80, having wire diameter of 55 µm and porosity of 0.689 is used in combination with 400 size mesh. The dimensions of regenerator and PT for both the configurations of PTC are given in Table 1.

Figure 4 shows the schematic of the experimental setup which consists of a linear compressor (CHART make, model 2S132W) with a variable frequency drive (Allen Bradely Flex 700). ENDEVCO make piezoresistive pressure transducers are used for dynamic pressure measurement. The dynamic pressure is amplified using DC differential voltage amplifier (ENDEVCO make, Model 136) and recorded using Yokogawa make DL 750 oscilloscope. Silicon diode sensors are

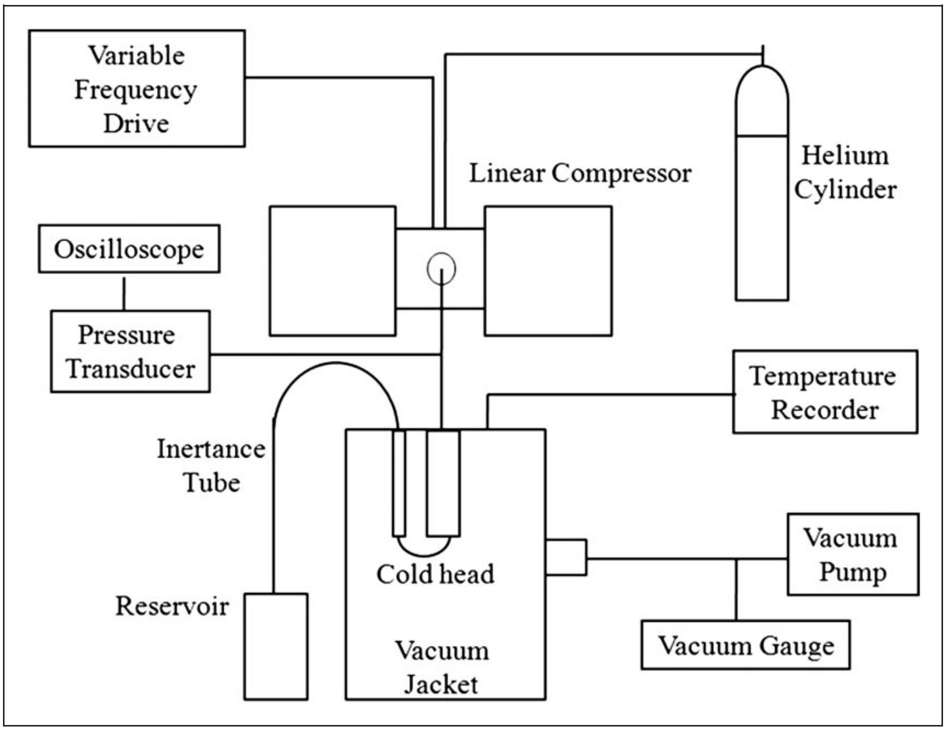

Figure 4. Experimental setup.[5]

used for measuring the temperature at the cold end of the PT which gives an accuracy of around ±19 K at 50 K.

The system is first cleaned by evacuating it to 10^{-6} mbar, followed by purging with helium gas for three to four times. The cold head of the PTC is kept inside the vacuum jacket, which is also evacuated to 10^{-6} mbar using a diffusion pump. Multi-layer insulation is wrapped around the cold head of the PTC to reduce radiation losses. The input power is given using variable frequency drive by setting the desired operating frequency. The cooldown time and the temperatures are noted when the minimum temperature shows variation within ±0.01 K. The PTC reaches the steady state at this time. The pressure variations and pressure drops, at the steady state temperature, are measured and stored in the oscilloscope.

Results and discussion

An experimental investigation is carried out to investigate the performance of U-type PTC with different L/D ratios. In both the cases, the regenerator and the PT volumes are kept the same. As highlighted earlier, the first configuration studied has a regenerator L/D ratio of 1.93 (case 1) while the second configuration has a regenerator L/D ratio of 9 (case 2).

Comparison of two PTCs with different L/D ratios

Investigations are carried out for the charging pressure of 17 bar and 300 W electric input power using 400 size mesh. Figure 5(a) and (b) shows pressure variations at the inlet to the regenerator and at the outlet of the PT for case 1 and case 2, respectively. A noticeable pressure drop (ΔP) of 2.07 bar is measured for case 2 as shown in Figure 5(b), as compared 0.29 bar for case 1 as shown in Figure 5(a). Pressure drop in case 2 is higher due to increased length of the regenerator. The increased length of the regenerator results in higher pressure drop.

Figure 6 shows the cooldown characteristics of the PTC for both the configurations. It may be observed that it takes about 60 min to reach to the steady state temperature (temperature variation of ±0.01 K) for case 1. For this case, the hot end temperature is 276.4 K, while the lowest temperature obtained at the cold end is 54.7 K. The operating frequency of the PTC is 50 Hz and the compressor input power is 300 W. The hot end temperature of 276.4 K signifies axial heat conduction from the hot end to the cold end due to small L/D ratio in case 1. The refrigeration effect produced at the cold end is transferred to the hot end of the regenerator and reduces its temperature. By increasing the length of regenerator the conduction losses along the axis can be reduced. This indicates that the performance of the PTC may be further improved by increasing the length of regenerator.

The cooldown time for case 2 is 90 min as compared to 60 min for case 1. The slow cooldown in case 2 is due to the reduced pressure amplitudes at the cold end of PT. It can be observed from Figure 6 that the hot end temperature is 316 K as compared to 276.4 K in case 1. The increased length of regenerator reduces heat conduction from hot end

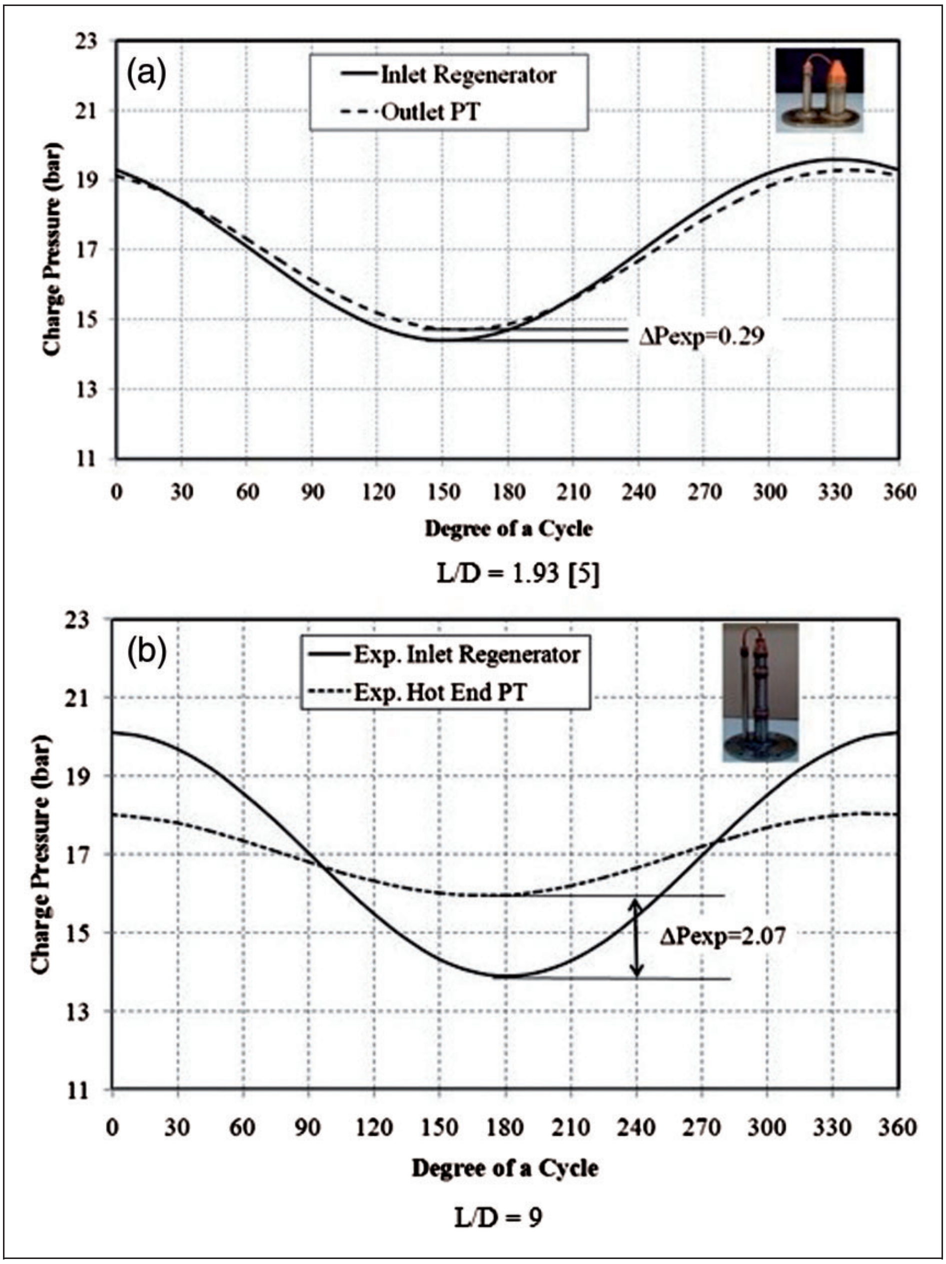

Figure 5. Pressure variation in single stage PTC with 400 size mesh. (a) L/D = 1.93,[5] (b) L/D = 9.

to cold end. A minimum temperature of 57.6 K is recorded in case 2 for the charge pressure of 17 bar with the operating frequency of 60 Hz, and the power input of 300 W.

Pressure variations – experimental and theoretical

Figure 7 shows the pressure variation obtained during the cycle for a PTC using 400 size meshes in the regenerator for case 2 (L/D = 9). These variations are obtained using Sage model and Isothermal model and are plotted along with experimentally obtained variations. The pressure pulses are shown for two distinct locations of the PTC, at the regenerator inlet and at the hot end of the PT. It may be observed that the pressure amplitudes are low at the hot end of the PT as compared to the inlet to the regenerator, which signifies the pressure drop across the length of regenerator. It may be noted that experimentally obtained pressure drop, calculated as difference between peak to peak pressures, is 2.07 bar while the theoretically predicted values by Sage and the Isothermal model are 1.88 bar and 2.5 bar, respectively.

Table 2 gives the comparison of pressure ratio, defined as ratio of maximum pressure to minimum pressure, for both the cases with 400 size meshes in the regenerator. The experimentally obtained pressure ratios at the inlet to the regenerator and at the hot end of the PT are 1.40 and 1.11, respectively for case 2. Sage software predicts 1.29 and 1.07, and the Isothermal model outcome is 1.46 and 1.10, respectively. The theoretical results thus show a reasonable match with experimentally obtained values and therefore their credibility for designing the PTC

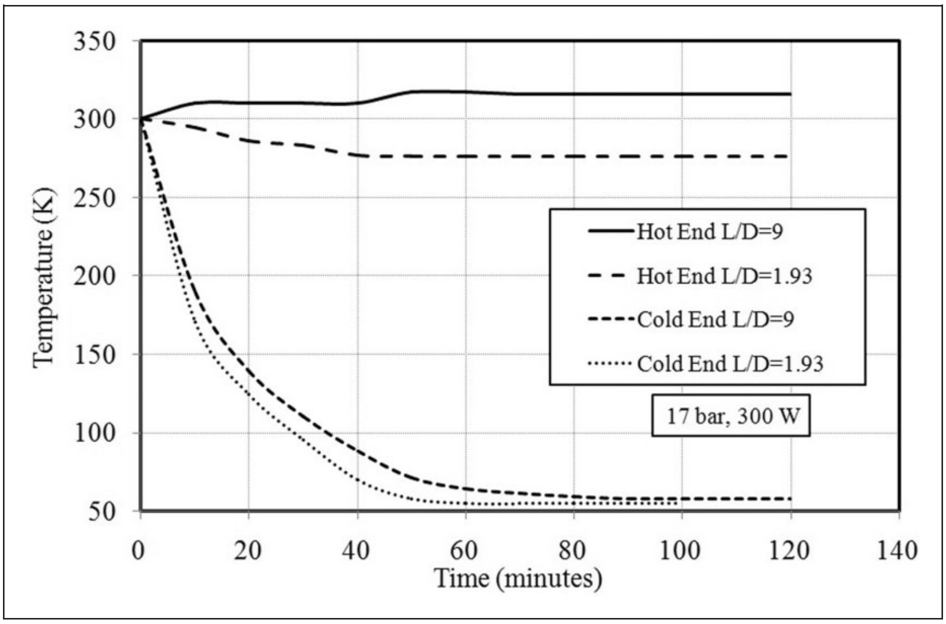

Figure 6. Cooldown curve for both the configurations.

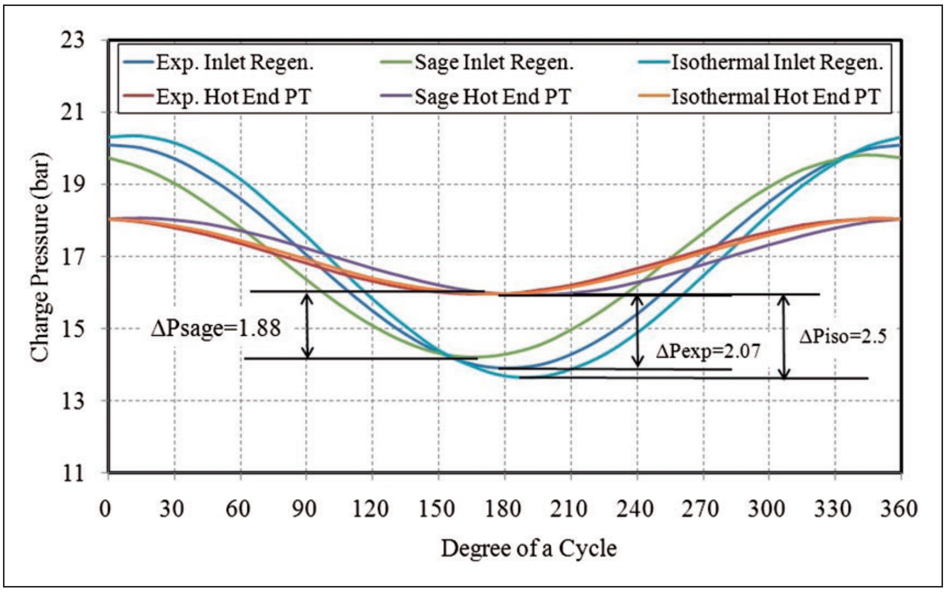

Figure 7. Comparison of dynamic pressure for 400 size mesh with L/D = 9.

Table 2. Pressure ratio regenerator filled with 400 meshes.

	Case 1 (L/D = 1.93)		Case 2 (L/D = 9)	
Experimental/theoretical results	Inlet to regenerator	Outlet PT	Inlet to regenerator	Outlet PT
Experimental	1.28	1.24	1.40	1.11
Sage	1.25	1.20	1.29	1.07
Isothermal model	1.31	1.18	1.46	1.10

gets established. Higher pressure ratios at the outlet of the PT signify higher refrigeration effect per cycle.

It may be observed in Table 2 that the pressure ratio is higher at the regenerator inlet for case 2. This is due to higher temperature of the gas at the regenerator inlet as discussed earlier and shown in Figure 6. The refrigeration effect depends on the pressure ratio at the hot end of the PT. The experimentally obtained pressure ratios at the hot end of PT are 1.24 and 1.11 for case 1 and case 2, respectively. This is endorsed by the fact that the refrigeration effect available in case 1 is 6.1 W as compared to 1.7 W in case 2, measured at a temperature of 80 K.

Effect of 80 size mesh size

As deduced experimentally, the refrigeration effect obtained by the PTC for case 2 is less than the one obtained for case 1. This is essentially due to more pressure drop in case 2 and due to longer length of the regenerator. To improve the performance for case 2, coarser meshes, e.g. 80 size stainless steel meshes, are packed in the regenerator. An experimental investigation is carried out in a systematic way to understand the effect of packing of 80 size meshes in the regenerator on the PTC performance for case 2. The 80 size meshes are packed at the hot end of the regenerator and are increased in steps of 20% of the total length of the regenerator. Experimental investigation is carried out in terms of pressure drop and refrigeration effect. Also, a comparison of experimental results with the model predictions is carried out. This study is carried out for case 2 only. Figures 8–11 present these results.

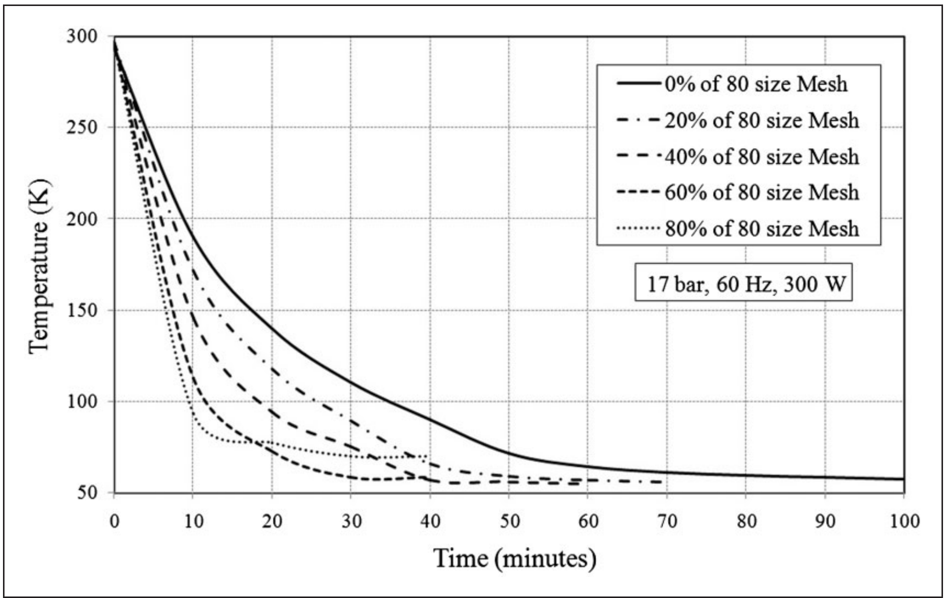

Figure 8. Cooldown characteristics for varying amount of 80 size mesh.

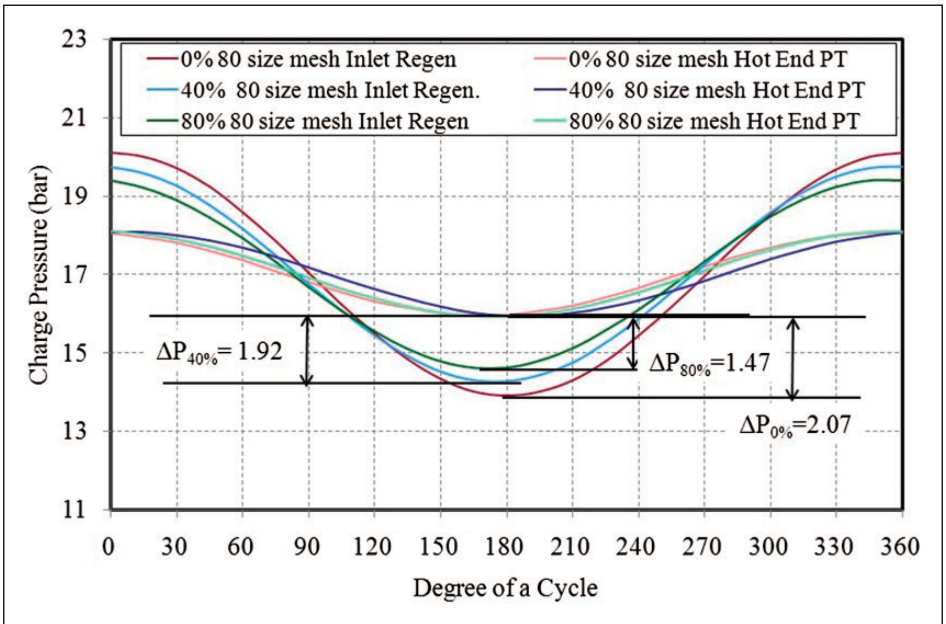

Figure 9. Pressure variation for varying amount of 80 size mesh.

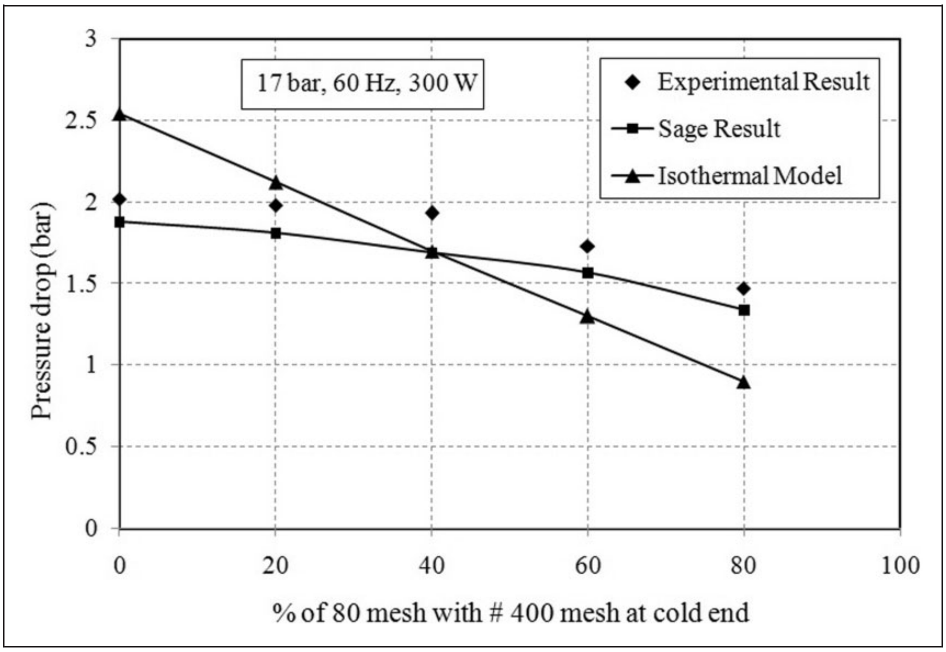

Figure 10. Pressure drop characteristics for varying amount of 80 size mesh.

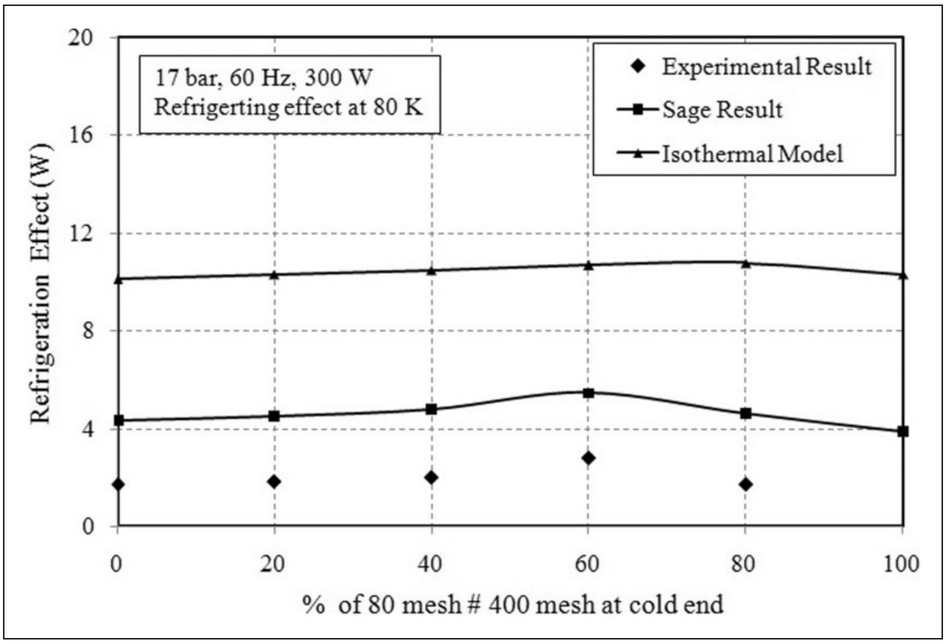

Figure 11. Refrigeration effect for varying amount of 80 size mesh.

Effect on cooldown time and no-load temperature. Figure 8 shows cooldown characteristics of varying percentage of 80 size meshes for case 2. It may be observed that it takes 90 min to reach the steady state temperature for the regenerator having 400 size meshes only. It can be observed that addition of 80 size mesh reduces the cooldown time, and also it affects the no-load temperature. The cooldown time reduces to 40 min for the regenerator filled with 80 size mesh in the 80% of the regenerator length. This is due to the decrease in the pressure drop because of the increased porosity of the regenerator, while the no-load temperature reduces from 57.6 K for 0% filling of 80 size meshes to 55 K for 40% filling. However, it may be noticed, that further filling of 80 size meshes increases the no-load temperature up to 70 K at 80% filling of the meshes. This is due to the dominance of the losses associated with regenerator ineffectiveness as compared to the losses associated with pressure drop. The regenerator effectiveness depends on the area of heat transfer which is lesser in the coarser size mesh, due to less numbers of wires, as compared to the finer mesh. It may be noted that it is the net result of decreased heat transfer between gas and the mesh, and the gain derived by decrease in pressure drop due to the addition of coarse mesh that decides the performance of the PTC.

Effect on pressure drop. Figure 9 shows the pressure variation obtained experimentally during a cycle for different amount of packing of 80 size meshes. It can be seen from the figure that the pressure pulses are shown for two distinct locations of the PTC, at the regenerator inlet and at the PT outlet. The experimentally obtained pressure drop is 2.07 bar for 0% of 80 size meshes, while for the packing of 40% and 80% of 80 size meshes, the pressure drop decreases to 1.92 bar and 1.47 bar, respectively. This is due to increase in the porosity of meshes.

Figure 10 shows a comparison between theoretically and experimentally obtained pressure drop. Sage software predicts the pressure drop of 1.88, 1.69 and 1.34 bar for 0%, 40% and 80% of 80 size mesh, respectively. The theoretical results obtained by Sage model shows a good match with the experimental results since this model is based on numerical analysis and takes care of changes in properties of gas at very low temperatures. The prediction of Isothermal model shows a little divergence due to the assumption of ideal behaviour of the gas (ideal thermodynamic processes and the properties) and isothermal regions in the hot and cold ends of the PT.

Refrigeration effect. As mentioned earlier, the refrigeration effect is measured at 80 K with 17 bar charge pressure and an input power of 300 W. The refrigeration effect available in case 1 is 6.1 W, as compared to 1.7 W in case 2 with packing of 400 size meshes in the regenerator. The decrease in refrigeration effect is due to high pressure drop in case 2, as discussed earlier. In order to improve the refrigeration effect of PTC in case 2, 80 size meshes are filled in the regenerator.

The effect of 80 size mesh on the refrigeration effect at 80 K is shown in Figure 11. The refrigeration effect increases from 1.7 W to 2.8 W with the increase in 80 size meshes up to 60% length of regenerator. Filling of the meshes beyond 60% length reduces the refrigeration effect due to decrease in regenerator effectiveness. The results predicted by Sage model and Isothermal model show similar trends; however, they are on higher side of the experimental results. Sage results are closer to experimental results because of the use of various numerical methods and realistic gas properties at low temperature.

Conclusions

- Regenerator of the PTC experiences oscillating flows in both the directions and is subjected to very low temperature. It is for the first time experimental results are reported in the terms of pressure drop in the regenerator and overall performance of the PTC.
- In the present work, theoretical and experimental investigations are carried out to investigate performance of U-type PTC with different L/D ratios. The regenerator L/D ratio is changed from 1.93 to 9. In both the cases, the regenerator and the PT volume are kept the same.
- The pressure drop increases from 0.29 bar to 2.07 bar with an increase in L/D ratio from 1.93 to 9, resulting in decrease in refrigeration effect from 6.1 W to 1.7 W at 80 K with 300 W input power.
- In order to improve the refrigeration effect, coarse meshes of size 80 are stacked in the regenerator. This reduces the cooldown time due to an increase in porosity of regenerator and decrease in pressure drop.
- With the filling of 80 size mesh up to 60% length, the refrigeration effect increases from 1.7 W to 2.8 W. Further increase reduces the refrigeration effect due to decrease in regenerator effectiveness.
- The theoretical results obtained with Isothermal model and Sage software are compared with experimentally obtained results. Sage predictions show a better match with the experimental results as compared to Isothermal model.

Conflict of interest

None declared.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

1. Fox RW, McDonald AT and Pritchard PJ. *Introduction to fluid mechanics*. 6th ed. John Wiley & Sons, Inc., 2004. ISBN: 0-471-20231-2, 337-338.
2. Zhao TS and Cheng P. Oscillatory pressure drops through a woven-screen packed column subjected to a cyclic flow. *Cryogenics* 1996; 36: 333–341.
3. Gedeon D and Wood JG. Oscillating flow regenerator test rig: hardware and theory with derived correlations for screens and felts. NASA Contractor Report. Report no. 198442, 1996.
4. Thomas B and Pittman D. Update on the evaluation of different correlations for the flow friction factor and heat transfer of stirling engine regenerators, American institute of aeronautics and astronautics (AIAA-2000-2812), 2000, 76–84.
5. Badgujar AD and Atrey MD. Theoretical and experimental investigations on stirling type pulse tube cryocoolers with U type configuration to achieve temperature below 20 K. *Proc IMechE, Part C: J Mechanical Engineering Science* 2014; 0: 1–10.
6. Zhu SW and Chen ZQ. Isothermal model of pulse tube refrigerator. *Cryogenics* 1994; 34: 591–595.
7. Atrey MD and Narayankhedkar KG. Development of second order isothermal model of orifice type pulse tube refrigerator (OPTR) with linear compressor. In: *Proceedings of the International Cryogenic Engineering Conference, Vol. 18*, 2000, pp.519–522.

8. Gedeon D. Sage User's Guide Stirling, Pulse-tube and low-T cooler model classes. Sage v9 ed, 2011.
9. Atrey MD, Bapat SL and Narayankhedkar KG. Cyclic Simulation of Stirling Cryocoolers. *Cryogenics* 1990; 29: 341–347.

Appendix

Notation

A	flow area (m^2)
c_f	friction factor
e	mass specific total gas energy (J/kg)
F	viscous pressure gradient term (N/m^3)
m_r	mass flow rate through regenerator (kg/sec)
P	density of gas (kg/m^3)
ΔP	pressure drop (Pascal)
Q	instantaneous axial heat flux (W/m^2)
Q_w	film heat transfer per unit length (W/m)
Re	Reynolds number
u	flow velocity in matrix (m/s)
ε_n	porosity of matrix
ε_{avg}	average porosity of regenerator matrix