American Journal of Science and Technology
2017; 4(4): 67-73
http://www.aascit.org/journal/ajst
ISSN: 2375-3846

American Association for Science and Technology

Theoretical Analysis and Optimization of Regenerator of Stirling Cryocooler

Kadayam Venkatraman Srinivasan[1, *], Manimaran Arunachalam[2], Rahul Pokale[3], Arulprakasajothi Mahalingam[2]

[1]Low Temperature Facility, Tata Institute of Fundamental Research, Mumbai, India
[2]School of Mechanical Engineering, Veltech Dr RR & Dr SR Technical University, Chennai, India
[3]Manjara Charitable Trust's Rajiv Gandhi Institute of Technology, Mumbai, India

Email address

kvsrini@tifr.res.in (K. V. Srinivasan), mullaimaran@rediffmail.com (M. Arunachalam), rahulpokale7310@outlook.com (A. Mahalingam)
[*]Corresponding author

Citation

Kadayam Venkatraman Srinivasan, Manimaran Arunachalam, Rahul Pokale, Arulprakasajothi Mahalingam. Theoretical Analysis and Optimization of Regenerator of Stirling Cryocooler. *American Journal of Science and Technology*. Vol. 4, No. 4, 2017, pp. 67-73.

Keywords

Cryocooler,
Regenerator,
Optimization,
Simulation, Porosity

Received: April 14, 2017
Accepted: May 10, 2017
Published: August 21, 2017

Abstract

Stirling cryocooler operates in a reverse Stirling cycle to produce refrigeration from work. Machines operating on the Stirling Cycle theoretically have the highest efficiency possible for any practical thermodynamic system. The regenerator is the key element of Stirling cryocooler and the performance of the regenerator directly affects the cryocooler performance. Regenerator is a compact periodic heat exchanger in which the fluid is in direct contact with the solid heat transfer area. Thus, it is essential to analyze the regenerator matrix, geometry, porosity and material along with the analysis on the thermal and flow characteristics of the regenerator for its optimization using numerical analysis. The preliminary studies were carried out on the porous sintered material type of cryocooler regenerator. Using the energy balance and continuity equation, matrix and fluid thermal equations were derived. CFD simulation has been carried out using ANSYS 16.0 and the porosity of the regenerator is predicted using the REGEN 3.3 Numerical Analysis Software for Regenerators. The main objective of this study is to maximize the available refrigeration by optimizing the key regenerator parameters such as the porosity and matrix material.

1. Introduction

Cryogenic regenerator is the heart of the Stirling cycle based cryocooler and the performance of the regenerator directly affects the cryocooler performance. Cryogenic regenerator is a compact periodic heat exchanger in which the fluid is in direct contact with the solid heat transfer area. It is highly essential to have a systematic study on the regenerator matrix, geometry, porosity, material along with the thermal and flow characteristics which influence on the performance of the system. The paper is intent to study on the thermal energy balance using continuity equations; Simulation study of Pressure/temperature/velocity variation along the regenerator length using Computational Fluid Dynamics (CFD) and porosity prediction of the porous sintered material based cryogenic regenerator using numerical analysis.

2. About Stirling Cycle

Stirling cryocooler [1] operates in a reverse Stirling cycle to produce refrigeration from work. The Stirling cycle cryocooler is a constant volume cryocooler. Typically helium gas is used as working fluid. Reverse Stirling based cryocooler (cryo-condenor/ cryo-refrigerator / cryogenerator) is widely being used in research institutes, animal husbandry units, Space cryogenics etc., for the liquefaction of nitrogen gas. These cryogenerator can produce temperature as low as 20-30K (i.e., -253 to -243 degrees Celsius). The working principle of Stirling cycle is explained in Figure 1 and the working of cryogenerator schematically explained in Figure 2.

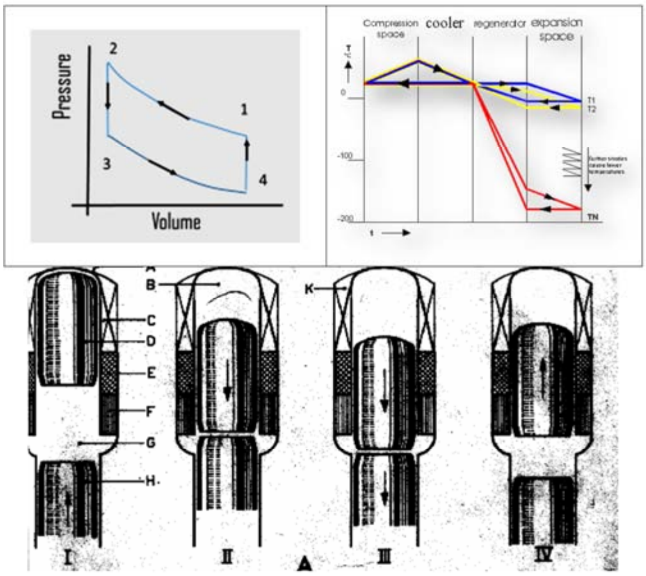

Figure 1. *Stirling cycle.*

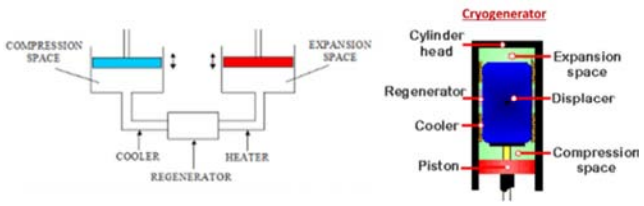

Figure 2. *Stirling Cryogenerator.*

3. Regenerator

Ideally, the regenerator should be without any pressure drop. Regenerator theory deals with the interchange of thermal energy occurring between the fluid and matrix material. An ideal regenerator has the properties as large volumetric heat capacity of the material; perfect heat contact between gas and matrix; zero flow resistance of the matrix; zero porosity; zero thermal conductivity in the flow direction and the gas is ideal. However, in practical cases, due to thermal losses, the gas leaving the regenerator leaves at a temperature higher than the cold end temperature. To develop the equations describing this exchange, it is required to establish the energy balance for the matrix material and fluid in a small element of the regenerator by employing the first law of thermodynamics, the equation for the conservation of mass, and the equations of motion for the fluid. The energy entering and leaving the volume is characterized by the mass flow rate, and the enthalpy of the fluid, which are defined by the fluid's velocity and properties of pressure, density, temperature, and specific heat. The definition of these terms and their application to a regenerator establish several basic principles that guide the derivation of the energy equations. The equation of state gives the relationship between the pressure, density and temperature of a substance. Comprehensive tables for cryogenic fluids are available which provide fluid properties over a wide range of temperature and pressure. Also, for cryogenic fluids at pressure and temperature removed from the critical point, the fluid can be treated as an ideal gas and the ideal gas equation [2] applies:

$$P = \rho R T \tag{1}$$

Other than the state of gas, compressibility and energy equation are basic principles to be considered. The governing equations of regenerator are quiet complex that no closed form solution exist and hence finite element method is used to obtain the solution. Complexity can be reduced by using certain assumptions and thus simple to understand. The flow is periodically reversed, with warm fluid entering from one end and heating the matrix for half of the cycle, referred to as the heating period, and cold gas entering from the other end and cooling the matrix for the second half of the cycle, referred to as the cooling period. Typically the temperature difference over the regenerator length which is approximately 40 mm, is more than 200 degrees Celsius. A typical porous medium regenerator of Stirling cryocooler and its dimensional details are shown in Figure 3 [3].

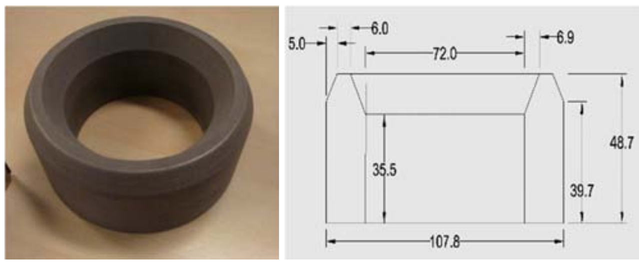

Figure 3. *Porous Regenerator of Stirling Cryocooler.*

The porous regenerator sponge is made up of sintered stainless steel SS304L granules. The average pulsating pressure range of the regenerator is in the range of 18 to 24 bar. The cross-section area at the cold end is less than at the hot end side. The properties like specific heat capacity and thermal conductivity are available as per data provided by NIST. REGEN 3.3 software was used for this analysis, which is developed by NIST exclusively for analysis of regenerators with different packings. The REGEN 3.3 plots graphs, using the inputs provided and as per requirements of output parameters. It considers the real conditions such as sinusoidal pressure variation. The REGEN 3.3 is used to get the first predicted values for the analysis of regenerator in determining its porosity.

4. Regenerator Optimization

Regenerator optimization is the process of choosing various regenerator design parameters which maximizes a system performance. For cryogenics refrigerators, optimization generally refers to maximizing the available amount of refrigeration by systematically selecting regenerator parameters such as type of matrix design, geometry and matrix material. The critical parameters affecting the thermal performance of regenerator are the number of heat transfer units, the fluid heat capacity ratio, the matrix heat capacity ratio and the thermal losses such as the longitudinal conduction. The study with the preliminary assumptions as heat stored in matrix is small compared to that of the heat stored in the matrix material; flow is one dimensional; axial thermal conductivity is zero and infinite in radial direction; flow is incompressible & steady; mass flow rate at hot end & cold end are constant and zero void space in the regenerator.

Considering the complexity of the regenerator, the optimization analysis was focused on the characterization of regenerator by altering the possible initial boundary conditions and regenerator porous material. The optimization of regenerator is tabulated in details as Figure 4.

Optimization of REGENERATOR of Stirling Cryocooler				
Sl. No	Property / Condition	Parameters	Possible parameters for alteration	Proposed Methodology
1	Physical condition	Length, diameter, height	No change	No change
4	Types of regenerator	Mesh type, Porous, fibrous, micro porous, etched foil	Porous material	Theoretical analysis and optimization
2	Initial Boundary conditions	Temperature, Pressure, mass flow	Pressure, mass flow	Theoretical analysis
3	Material	Brass/copper mesh, SS304 porous/micro-porous material, Nano fiber, Nano coated material, Nano coated alloys, composite material	possible combination of SS304 porous/micro-porous material, Nano fiber, Nano coated material, Nano coated alloys, composite material	Theoretical analysis

Figure 4. Optimization parameters of Regenerator.

5. Regenerator Modelling

The dimensions of the regenerators are calculated precisely, and the values were used for modelling the regenerator in ANSYS Computational Fluid Dynamics (CFD) tool as mentioned in the Figure 5 [3]. The net weight was also calculated using highly precise electronic mass balance.

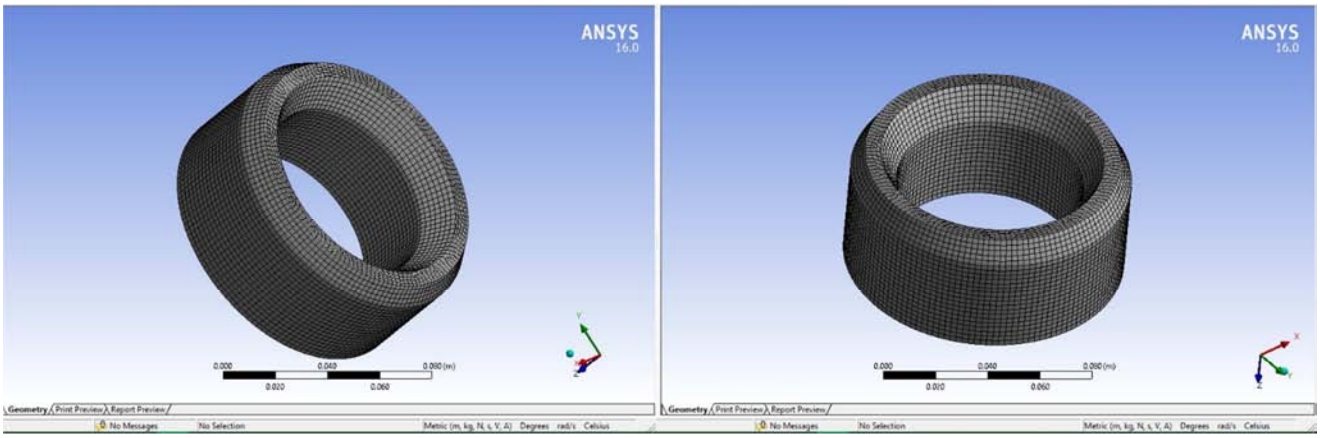

Figure 5. Regenerator modelled in ANSYS workbench.

6. Governing Equations

The working fluid helium flows through the porous regenerator which has porosity, *'ε'*. The governing differential equations used to depict the flow through the regenerator is as follows [4]:

Continuity Equation: $\frac{\partial}{\partial t}(\varepsilon\rho) + \nabla(\rho\vec{v})=0$ (2)

Momentum Equation

$$\frac{\partial(\varepsilon\rho\vec{v})}{\partial t} + \nabla\cdot(\varepsilon\rho\vec{v}\vec{v}) = -\varepsilon\nabla p + (\varepsilon\bar{\bar{\tau}}) + \varepsilon\vec{B} - \left(\frac{\varepsilon^2\mu}{K}\vec{v} + \frac{\varepsilon^3 C_2}{2}\rho|\vec{v}|\vec{v}\right) \quad (3)$$

The thermal non-equilibrium model is adopted to denote the energy transfer in the regenerator. The conservation equations for energy are solved separately for the fluid and solid zones [3] [4] [5].

Fluid Energy Equation

$$\frac{\partial(\varepsilon\rho_f E_f)}{\partial t} + \nabla\cdot\left(\vec{v}\left(\rho_f E_f + p\right)\right) = \nabla\cdot\left(\varepsilon k_f \nabla T_f + (\bar{\bar{\tau}}\cdot\vec{v})\right) + h_{fs}A_{fs}(T_s - T_f) \quad (4)$$

Matrix Energy Equation

$$\frac{\partial((1-\varepsilon)\rho_s E_s)}{\partial t} = \nabla\cdot\left((1-\varepsilon)k_s\nabla T_s\right) + h_{fs}A_{fs}(T_s - T_f) \quad (5)$$

For above equations, the heat transfer co-efficient and Nusselt number in porous region can defined as [5]:

$$h_{sf} = \frac{Nuk_f}{d_h} \quad (6)$$

$$Nu = (1 + 0.99(RePr)^{0.66})\varepsilon^{1.79} \quad (7)$$

Where, $k = k_f\varepsilon$

Momentum Equation

The momentum equation for a porous region can be modelled by adding the source terms, viscous resistance, and inertial resistance, as seen from bracketed term in equation (3). In ANSYS, the superficial velocity is used as default. Where superficial velocity is the product of porosity and physical velocity. The formulation of viscous resistance and inertial resistance, using physical velocity will be as follows [3].

$$viscous\ resistance = \frac{\varepsilon^2\mu}{K}\vec{v} \quad (8)$$

$$inertial\ resistance = \frac{\varepsilon^3 C_2}{2}\rho|\vec{v}|\vec{v} \quad (9)$$

Where, K is Darcy's permeability and C_2 is inertial resistance coefficient.

7. Analysis - Parameters and Calculations

The boundary conditions used for preliminary analysis is, average charge pressure, pressure ratio, mass flow rate, hydraulic diameter, temperature at hot end and cold end, and, specific heat capacity of working fluid and matrix material. The specific heat capacity of the regenerator material, SS304L is not constant and is found to be varying with the temperature. The variation of specific heat with temperature can be depicted accurately with polynomial equation of higher order. For simplicity, the equation is approximated to the order 2, with constant coefficients. By curve fitting function in MATLAB, it is found that, the polynomial equation obtained using the values obtained from the complex higher order polynomial function is accurate with very small error. Three different equations are obtained for different temperature ranges for better accuracy in curve fitting. The equations for different ranges, selected for matrix material are given as below:

$$30 - 80K: f(T) = -85.07 + 3.608T + 0.001347T^2 \quad (10)$$

$$80 - 200K: f(T) = -66.61 + 4.176T - 0.009065T^2 \quad (11)$$

$$200K - 300K: f(T) = 283.4 + 0.6496T - 0.0001245T^2 \quad (12)$$

Similarly, the curve fitting equation for helium is found, but as the properties of helium does not have steep changes in the range 300K to 30K, the polynomial is developed for complete range instead of intermediate temperature ranges, and thus to maintain accuracy, polynomial of order 3 is defined instead of order 2. The equation of specific heat capacity of helium is given as below:

$$30K - 300K: f(T) = 865.4 - 11.82T + 0.05831T^2 - 9.42e - 05T^3 \quad (13)$$

Thermal and Fluid Flow Parameters

The calculations are done to find the parameters like Colburn factor, heat transfer coefficient, wetted area and thus interfacial area density. The Colburn factor 'J_h', for a mesh wired regenerator is determined as given below in equation (14), considering the regenerator sponge under study analogous to wire mesh, the same equation can be used [6].

$$J_h = C\,Re^{-n} \quad (14)$$

$$C = 1.415 - 2.490(1-\varepsilon) \quad (15)$$

$$n = 0.483 - 0.236(1-\varepsilon) \quad (16)$$

Now using this Colburn factor, the heat transfer coefficient can be found out as follows:

$$h_c = \frac{J_h c_f G}{Pr^{2/3}} \quad (17)$$

Where, $Pr = \frac{\mu c_p}{k}$

The Reynold number is determined from REGEN 3.3, and its average value is used in equation (14) to determine Colburn factor. The area of fluid flow is given $A_{ff} = \varepsilon\,A_{fr}$ where 'A_{fr}' is cross sectional free flow area. Also, the hydraulic diameter is given as,

$$D_h = \frac{4A_{ff}}{A_w/L} \quad (18)$$

Where, A_w is heat transfer area between solid matrix and fluid. From the above equation, heat transfer area can be calculated, which cannot be calculated just by knowing the physical dimensions. And thus, area density can be calculated, the parameter to be defined in ANSYS Fluent for porous media is given as follows:

$$Interfacial\ area\ density = A_w/V_0 \tag{19}$$

8. Regenerator Porosity

As a case study, the existing Stirling Cryocooler at TIFR, Mumbai, with the preliminary assumption on actual input parameters like working fluid, charging gas pressure, mass flow rate, geometry, material, temperature and with the observed output parameters as Temperature after expansion and pressure drop. The REGEN 3.3 software is used for initial guess values for analysis of steady flow in regenerator in ANSYS Fluent. The values for inputs in REGEN 3.3 used are taken from the working Stirling cryocooler plant. The detailed input parameters for the analysis is tabulated as Figure 6 [7].

Input parameters for REGEN 3.3 program

BASIC INPUTS	
PRES RATIO	1.2
AVE PRESS	20 bar
PRES PHASE	25 deg
FINAL CYCLE	50
GAS TEMP COLD	32 K
GAS TEMP HOT	300 K
HERZ	50
HYDRA DIAM	5.8e-5 mtr
MASS FLUX COLD	1.2 g/sec
GEOMETRY	4
POROSITY	0.6962
RG AREA	5055.5 mm²
RG LENGTH	48.7 mm

PARAMETERS FOR HELIUM GAS	
GAS COND COLD	-
GAS COND HOT	-
USE GAS COND	0
TABLE PRES MAX	-
TABLE PRES MIN	-
USE PRES CORR	1
TABLE PRES PTS	200
TABLE TEMP MAX	-
TABLE TEMP MIN	-
TABLE TEMP PTS	200
USE PROPS TABLE	-
USE IDEAL GAS	-

PROPERTIES OF MATRIX AND TUBE	
COOLING MULT	1
MAT COND COLD	-
MAT COND HOT	-
USE MAT COND	0
TUBE H	0
MAT COND FACTOR	1
MAT CPVOL COLD	-
MAT CPVOL HOT	-
USE MAT CPVOL	0
MAT CP FACTOR	1

PARAMETERS CONTROLLING NUMRICAL RESOLUTION, METHOD	
DECAY CYCLE	0.05
EPS NEWTON	1E-06
EPS STEPS	0
NUM ITT STEP	2
HTALP	0.04
USE GRADED MESH	0
GRADED CUTOFF	-
GRADED RATIO	1
METHOD	1
USE ADVEC	0
NUM POINTS X	50
NUMSTEPS CYC	80
MID TEMP RATIO	0.5
BDY ORDER	1
MFLUX DC	0
LOCATE HEAT	-
VOL HEAT	0

Figure. 6. *Input Parameters for REGEN 3.3.*

Using the values like average pulsating pressure and mass flow rate the calculations are performed. Keeping mass flow rate as constant for different charge pressure values, the analysis has been done. Depending on this values, various iterations are performed using REGEN 3.3 and ANSYS 16.0. The figure 7 shows four plots consisting of variation of specific heat with temperature for matrix and fluid, average temperature variation along the length, heat transfer coefficient and Reynold number [8].

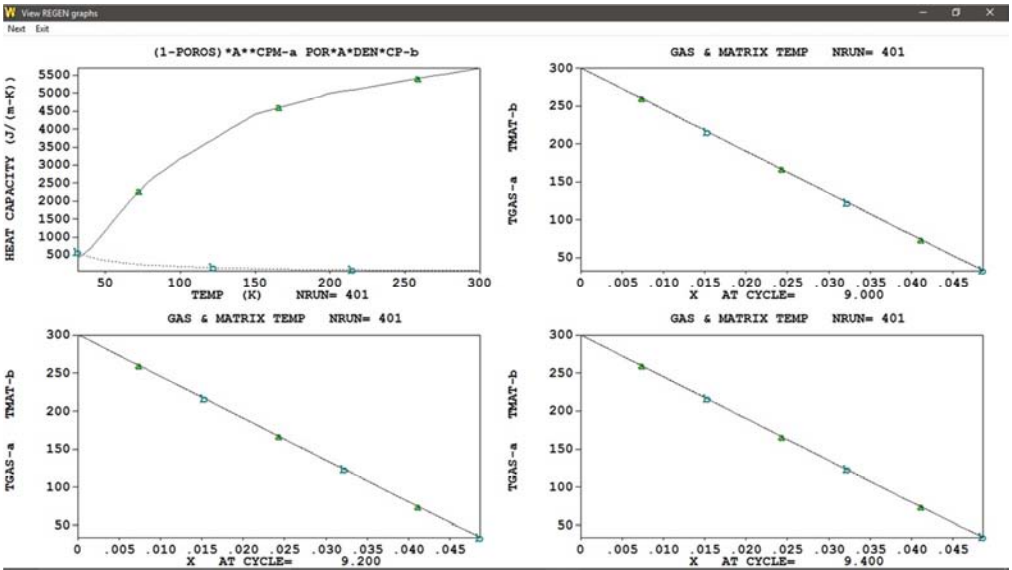

Figure 7. *Variation of matrix and fluid properties in regenerator.*

The figure 8, shows average flux over cycle, temperature fluctuation at hot and cold end over a cycle and, pressure volume variation.

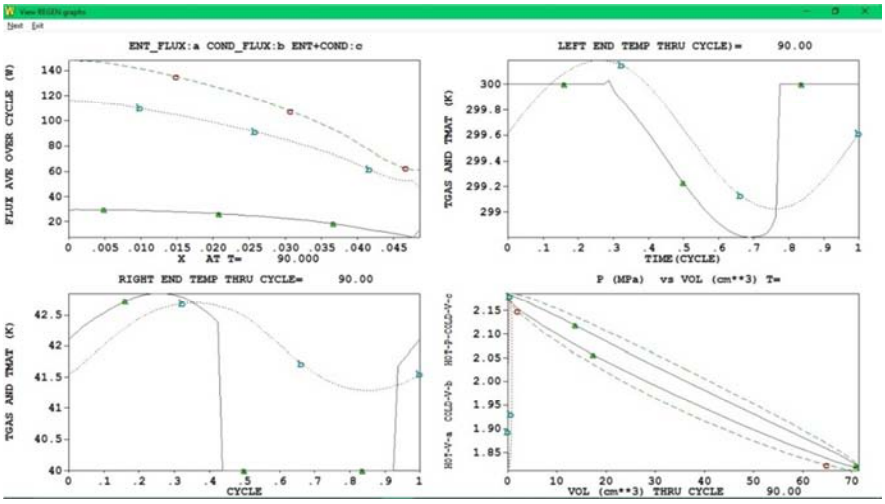

Figure 8. Temperature and pressure fluctuation for a complete cycle.

The temperature difference between hot end and cold end ideally is 268K and the temperature difference obtained using simulation is 266K [6]. Thus, the error found in temperature drop across the entire length of regenerator is less than 1%. Figure 9 and 10 depicts the variation of temperature and pressure along the length of the regenerator for mass flow rate of 1.2g/s at 2 MPa charge pressure respectively using ANSYS [3].

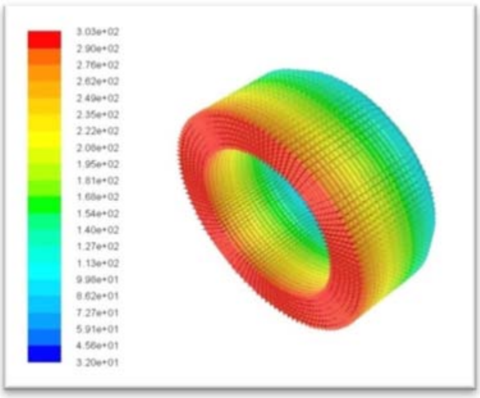

Figure 9. Temperature variation along the regenerator.

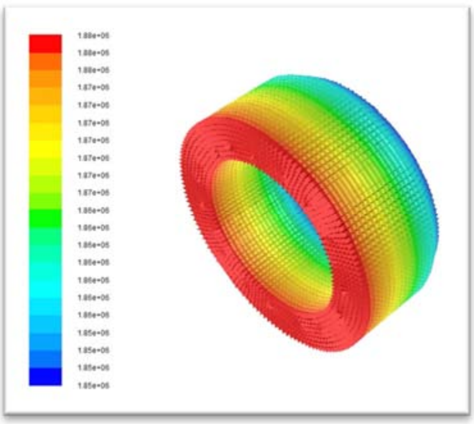

Figure 10. Pressure variation along the regenerator.

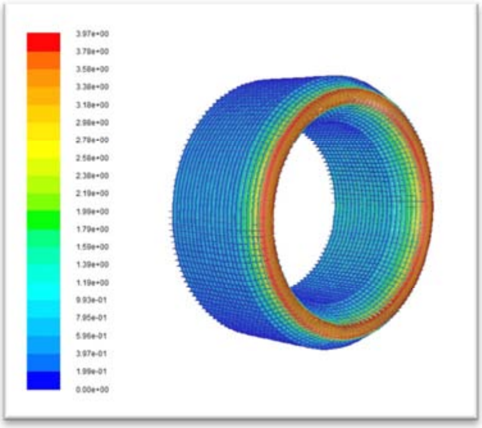

Figure 11. Velocity variation along the regenerator.

9. Conclusion

The initial analysis has been done for predicting porosity assuming steady flow, for the simplicity and initial guess purpose. With the various iterations results using the software REGEN 3.3, the results were analyzed and the best matching regenerator porosity was found to be at 69.62%. Considering the available literature survey and the experimental values for the regenerator used in the similar operating conditions wherein the porosity varies in the range of 69-71%, which is very well matching with the above calculated value of 69.62%.

10. Present Status

The present status and the future scope of the above works includes the following.

i. Numerical analysis and modelling using commercial software for the unsteady or oscillating gas flow in the Stirling cycle such as Numerical modeling using software SAGE, PROSA ((Program for Stirling machine Analysis); Schmidt analysis for the Stirling engine performance prediction; Martini simulation modeling and analysis of Stirling cycle; Simulation of

Schmidt analysis using program written in MatLab; Two-dimensional geometry (axis symmetrical model) of Stirling cryocooler using GAMBIT and flow patter analysis using FLUENT modeling techniques etc., for the better and more accurate results.

ii. Detailed study on the regenerator materials with the possible combination of SS304 porous/micro-porous material, Nano fiber, Nano coated material, Nano coated alloys, composite material.

iii. Possibility of manufacturing the regenerator (both on the metal and composite material) along with the other critical components such as cold seal of Stirling cryocooler using "Additive Manufacturing" process.

References

[1] Technical note on Stirling cycle by M/s Stirling Cryogenics, Netherlands. Ref: https://www.stirlingcryogenics.com/files/__documents/3/StirlingCycle.pdf

[2] Robert A. Ackermann, Cryogenic Regenerative Heat Exchangers, Plenum Press 1997.

[3] ANSYS Fluent 16.0, the fluid and thermal simulation software.

[4] W. M. Clearman et al., J. S. Cha et al., "Anisotropic steady-flow hydrodynamic parameters of microporous media applied to pulse tube and Stirling cryocooler regenerators," Cryogenics 48 (2008) 112-121.

[5] Y. B. Tao et al., "Numerical analysis on pressure drop and heat transfer performance of mesh regenerators used in cryocooler," Cryogenics 49 (2009) 497-503.

[6] Randall F. Barron, Gregory F. Nellis., Cryogenic Heat Transfer, Second Edition, CRC Press.

[7] "Analysis of Porous Regenerator material of Stirling cryocooler using numerical techniques" – Poster presented by R. D. Pokale, K V Srinivasan et al., at 26th National Symposium on Cryogenics (NSCS-26), Kolkatta, India, February, 2017. Ref: http://indico.vecc.gov.in/indico/getFile.py/access?contribId=35&sessionId=14&resId=0&materialId=0&confId=44

[8] REGEN 3.3 Numerical Analysis software for regenerator, NIST.

[9] K V Srinivasan, A Manimaran, et al., paper on "Study on Stirling Cryocooler" presented in NAFEMS International Conference on Engineering Modelling, Analysis Simulation and 3D Printing – NAFEMS-3D, August 2016.

[10] C. O. Yadav et al., "CFD assisted prediction of hydrodynamic parameters for regenerator of cryocooler," Procedia Technology 14 (2014) 328-335.