Computer Aided Design and Performance Prediction of Cryogenic Regenerator for Stirling Cycle Cryocooler

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Abstract

The Cryogenic regenerator is one of the most critical components of a Cryocooler. It is a device which transfers energy between two fluids by storing it in a matrix. Thermal energy is temporarily stored and used to heat or cool a fluid flowing through the matrix. It is a compact periodic heat exchanger in which the fluid is in direct contact with the solid heat transfer area. The practical realization of a Cryocooler is possible only with the development of efficient regenerators. The regenerator is the heart of the Stirling cycle Cryocooler, plays a major role in determining and subsequently obtaining the required temperature and refrigerating effect. In this dissertation work, a computer aided model of regenerator is designed in CAD software for Stirling cycle Cryorefrigerator. The present work aims to study the influence of regenerator matrix on its effectiveness. This research study attempts to simulate the actual conditions existing in the regenerator of Stirling cycle Cryocoolers. CFD simulati on has been carried out to predict the performance of the regenerator and the results have been compared with the results of open literature. Once the results have been compared the design is modified to get minimum pressure drop maximum effectiveness. Wall storage effect is also simulated in CFD simulation which gives higher effectiveness than without considering the wall storage effect. One can fabricate it by using optimized data and evaluate its performance. Thus, the designed regenerator will surely give higher thermal performance as against lower pressure drop...

Keywords: *Cryogenic regenerator*

I. INTRODUCTION

In cryogenics the cryocoolers are very important device to produce the temperature in cryogenic range. A cryocooler consists of a compressor, a heat exchanger, an expansion device and an evaporator. Cryogenic regenerator is the heart of a cryocooler. It plays a major role in obtaining lower expansion space temperature for cryocoolers. Out of four processes of Stirling cryocooler, two processes take place inside the regenerator. It is a storage type heat exchanger which is made from material having high specific heat even at low temperature. The design of cryogenic regenerator is a challenging task which calls for precision as well as proper judgment.

II. REGENERATOR

A regenerator is a bidirectional storage type heat exchanger. The regenerator is essentially a porous matrix which transfers the heat between two fluids. The working fluid displaced from the expansion space cools the regenerator matrix and subsequently this cold matrix cools the hot fluid displaced from compression space to the expansion space in next cycle. The performance of Stirling cycle cryocooler largely depends upon the effectiveness of the regenerator. For a well-designed stirling machine operating in the temperature range of 300-75K, it can be shown that the loss of refrigeration effect is 21% when the regenerator effectiveness is 99% and that loss is about 42% when the effectiveness is 98%. A regenerator with effectiveness of 95.24 percent the loss of refrigeration effect is 100 percent i.e. no cooling effect is produced although all the other components are perfect. This calls for the use of regenerator of very high effectiveness. These are the efficient regenerator which made the practical realization of Stirling cycle machine possible.

The regenerator is a periodic type heat exchanger in which the porous matrix exchanges the heat with the gases passes through it. The effectiveness of the regenerator is the ratio of actual temperature difference of the gas at the ends of the regenerator to the maximum possible thermodynamic temperature difference. Ideally the regenerator should able to lower down the temperature of the hot fluid to the expansion space temperature and to rise the temperature of cold stream to the compression space temperature without any pressure drop. Due to thermal losses in regenerator the gas leaving the regenerator leaves the regenerator at temperature higher than the regenerator cold end temperature.

The effectiveness of the regenerator is mainly governed by the heat transfer coefficient, area available for heat transfer, mass of the matrix, specific heat of the matrix material, mass flow rate of the gas and the blow period. However there are several other parameters which influence the effectiveness such as void volume of regenerator, axial conduction effect, variable specific heat of matrix, pressure and flow cycling etc.

III DESIGN AND MODELING

W. M. Clearman et. al performed experiment on steady flow pressure drop for different mass flow rate keeping the inlet pressure constant. Dimension for regenerator for theoretical study as well as CFD simulation are adopted from this experiment.

- Regenerator length = 38 mm
- Inner diameter = 7.9 mm
- mesh size 400*400
- Charge mean pressure 20.6 bar
- Porosity 0.6968
- Wire diameter 0.0256mm
- Mass flow rate 1.2 g/s

Other parameter calculation

Hydraulic Diameter Dh

$$D_h = \frac{\alpha d_w}{1-\alpha} = \frac{0.6968 \times 0.0256}{1-0.6968} = 0.058mm$$

Regenerator Area and free flow area

$$A_r = \pi/4 * 7.9^2 = 0.4899cm^2$$

$$A_{ff} = \alpha A_r = 0.6968 \times 0.4899cm^2 = 0.3413cm^2$$

Mass flow rate per unit area

$$G = m / A_{ff} = 0.003/0.007998 = 35.73kg/m^2 s$$

Reynolds number Re

$$\mathrm{Re} = \frac{GD_h}{\mu} = \frac{35.73 * 0.058 * 10^{-3}}{19.9 * 10^{-6}} = 146$$

To estimate pressure drop and friction factor in regenerator wire mesh screen a relation reported by Miyabe et al.[10] is used.

$$f_{st} = \frac{33.6}{\text{Re}} + 0.337 \quad (4 < \text{Re} < 1000)$$

$$f_{st} = \frac{33.6}{146} + 0.337 = 0.5671$$

Equation given by fenning for finding the pressure drop in a regenerator based on friction factor is given by

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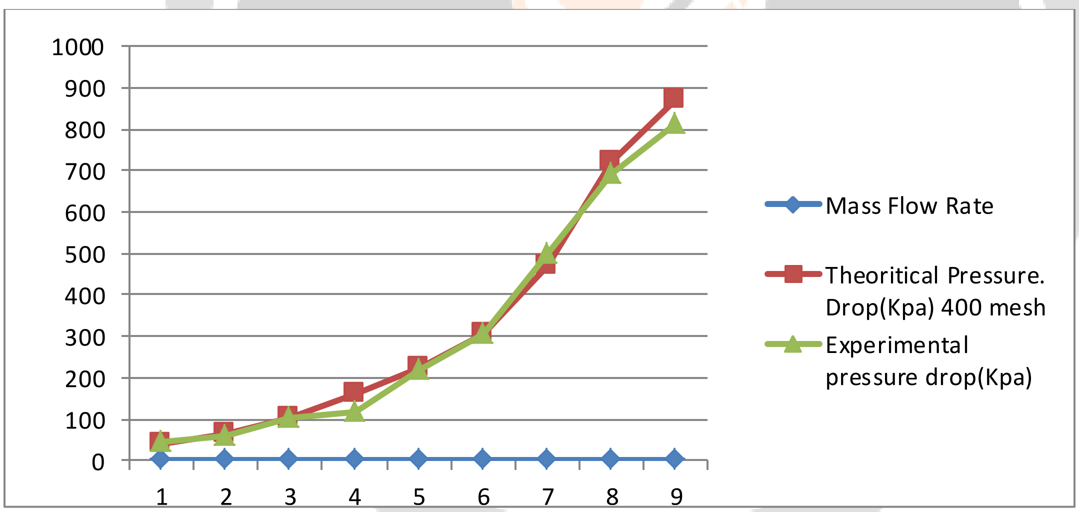
$$\Delta p = f\left(\frac{L}{r_h}\right)\left(\frac{G^2}{2\rho_f}\right)$$

$$= 0.5671 * \left(\frac{38}{0.058832}\right) * \left(\frac{35.73^2}{2*0.5}\right)$$

$$= 467.83 kPa$$



Theoretical vs experimental pressure drop

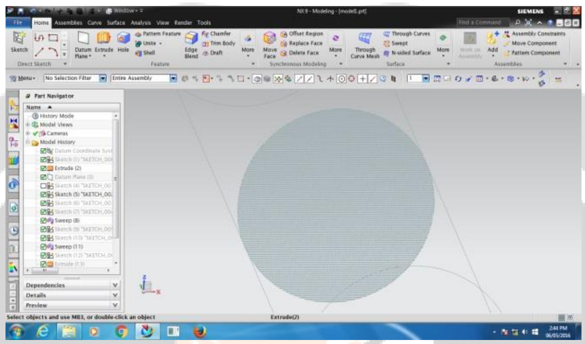
Mass Flow Rate(kg/s)	Theoritical Pressure. Drop(Kpa)	Experimental pressure drop(Kpa)
0.0002	38.5916532	43
0.0003	63.49088475	60
0.00043	101.4446127	101
0.0005	160.0805749	120
0.00075	221.7655176	220
0.00093	306.2562415	304

0.00122	467.838322	501
0.00133	721.3642199	690
0.0015	871.7371996	810

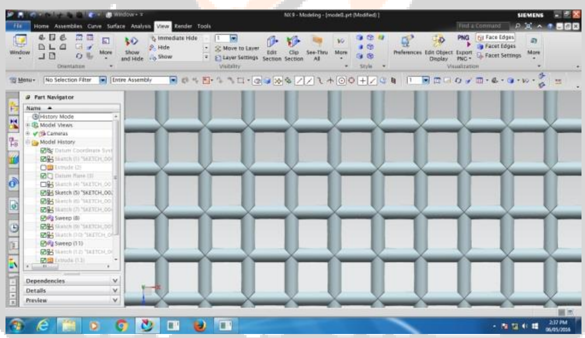
Comparison of theoretical work with experimental data.

Procedure for cfd analysis of cryogenic regenerator

1)Create a model of wire mesh of 0.0256mm diameter and having pitch of 0.68 mm. Wire mesh created here is very close to that of actual one, Save the file in .PRT format. Fig 3.5 shows close view of wire mesh of a single slit. NX 9.0 software is used to model this design.

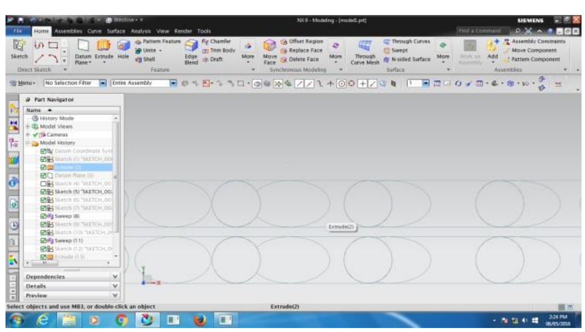


Wire mesh of single screen



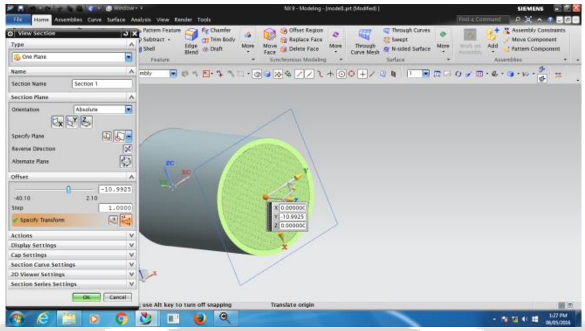
Close view of wire mesh screens of a regenerator

2)This wire mesh is cut into circular section of diameter 7.9 mm. Now replica of these model is created, and placed near to each other at a distance of 0.03mm. Each slit is placed at different angular orientation. Closeness between two slits is shown in fig



Closeness between two slits

3)All these slits are placed in a cylinder of inner diameter of 7.9 mm and length of 38mm keeping a distance of 0.3mm. Figure shows the cut view of the model



sectional view of regenerator

4)Now inlet and outlet domain for fluid flow are defined in which only the stack of wire mesh is considered not the housing. Figure 3.8 shows the inlet and outlet domain for fluid.

5)For computational analysis flowing fluid is helium gas, screen material is stainless steel. Boundary conditions are defined as follows

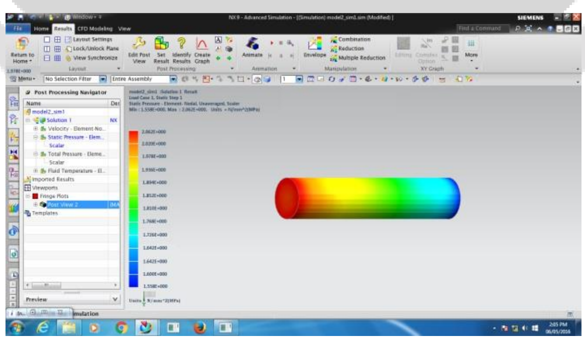
Inlet pressure 20.62 bars

Inlet mass flow rate 1.2g/s

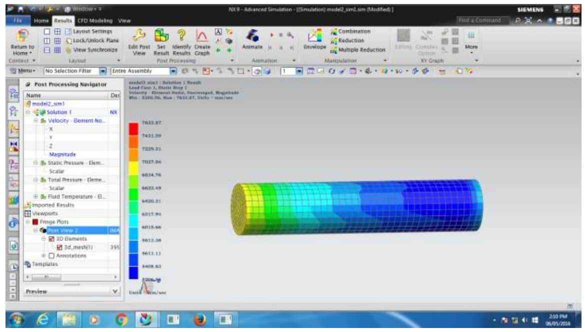
Inlet temperature 300 K

Cylindrical boundary is assumed adiabatic

6)Based on this boundary condition, calculations are performed in CFD solver and we get the following results for pressure and velocity.



Pressure Contour

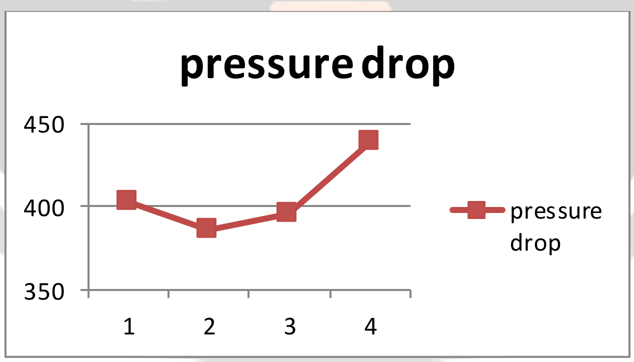


Velocity profile

Mass Flow Rate(kg/s)	Theoritical Pressure. Drop(Kpa)	Experimental pressure drop(Kpa)	Present CFD (kPa)
0.00075	221.7655176	220	196.26
0.00122	467.838322	501	450.968
0.0015	871.7371996	810	783.168

comparison of different approach

Further CFD analysis is carried out for 150, 200,250 and 300 mesh size and pressure drop from each of these meshes is shown here in graph.



Pressure drop for different wire mesh based on CFD analysis

IV THERMAL ANALYSIS OF REGENERATOR

For thermal analysis temperature difference is assumed as follows.

Temperature difference – 300 K to 80 K

Blow period – 0.5 s

Properties for matrix material as well as helium gas for the given temperature range is taken from Ackerman [6]. This analysis has been done for mass flow rate of 1.2g/s.

Mean helium viscosity - 0.0000144 kg/m K

Mean helium density – 0.5 kg/m3

Mean Helium specific heat -5200 J/kg K

Mean Helium thermal conductivity – 0.1 W/m-K

The heat transfer coefficient and Nusselt number in porous media region are defined as [11]

$$h_{sf} = Nuk_f / d_h$$
$$Nu = (1 + 0.99(\mathrm{Re}\,\mathrm{Pr})^{0.66})\phi^{1.79}$$

The temperature difference between fluid and matrix material we get 38 K

So overall heat transfer from fluid to matrix is

$$Q_1 = hA\Delta T = 204.229 * 0.08819 * 38 = 684.45J$$

Now ideal heat transfer for bringing the temperature of given mass of helium from 300K to 80K is calculated as

$$Q_2 = mC_p\Delta T = 0.00061 * 5200 * 220 = 697J$$

So the effectiveness based on heat transfer without considering the storage effect of wall is given by

$$\varepsilon = \frac{Q_1}{Q_2} = \frac{684}{697} = 0.98134864$$

Now secondary if we consider the heat transfer to the wall of the regenerator then the heat transfer co efficient for forced flow through a circular tube is given by [7]

So heat transfer between fluid and wall will be

$$Q_3 = hA\Delta T$$
$$= 139.75 * 0.0009426 * 38 = 5.005J$$

So effectiveness considering the heat transfer to housing wall

$$\varepsilon_2 = \frac{Q_4}{Q_2} = \frac{689}{697} = 0.988522$$

V RESULTS AND DISCUSSION

From the above research on regenerator we found the effect of various parameters on regenerator. Here flow through regenerator is steady flow. Regenerator theoretical pressure drop is calculated which agrees with the experimental pressure drop. As mass flow rate increases pressure drop also increases for 400 wire mesh screen. Also pressure drop increases as the porosity decreases and for a given porosity it depends on mass flow rate. Further a computer aided design is modeled in NX 9.0 software. The design dimension is taken from Clearman's work. NX software is able to model the design as well as we can also analyze the design. CFD analysis can also be performed in this software. Meshing is done of wire 0.063mm of 0.025mm wire diameter. The gap between two slits is kept only of 0.0044mm. Thus the model is very close to actual regenerator. First analysis is done for mass flow rate of 1.2 g/s and pressure drop obtained from CFD result is compared with experimental results. And results are near to experimental one. Mass flow rate is varied and result for each one of them is compared with experimental data. Further independent CFD analysis is carried out for performance prediction of regenerator. In this case size of wire mesh is varied from 150 to 300 keeping mass flow rate constant that is equal to 1.2 g/s. It is found from the results that 200 mesh size with porosity 0.74 and wire diameter of 0.04mm gives the least pressure drop among all other mesh.

Further investigation is carried on wall storage effect of regenerator. Regenerator housing wall itself act as thermal storage material as matrix material. So Heat transfer considering the wall is higher compared to without considering the wall.

VI FUTURE SCOPE

Further CFD analysis can be carried out to find out the performance for hybrid type regenerator. A Hybrid regenerator consist more than one of mesh size along its length. The pressure drop calculated here is for steady flow further analysis can be done for oscillating flow pressure drop. As in actual condition in stirling cycle cryocooler the pressure variation is cyclic and cyclic pressure drop is found less compared to steady flow. So analysis for pressure drop and heat transfer for oscillating flow can be done.

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