Investigation of regenerator mesh characteristics for a pulse tube cryocooler

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Abstract. An investigation of regenerator mesh characteristics on a Pulse tube cryocooler’s performance is conducted using Sage V11 software. The cryocooler operates between temperatures of 300 K and 80 K. The components of the cryocooler are free piston linear compressor, aftercooler, regenerator, pulse tube, warm heat exchanger, and inertance tube-bounce space as the phase shifter. The performance of the regenerative cryocoolers depends on the regenerator. The regenerator of this cryocooler consists of a stack of stainless steel meshes. In this paper, a comparison of regenerator stainless steel meshes with mesh number #200, #300, #400, #500 and its combinations were analysed. To choose the best multi mesh combination, the length of the individual meshes is varied so that the total length of the regenerator is unchanged. The performance was analysed based on the Coefficient of Performance of cryocooler for single mesh type and mesh combinations (combination two) at acceptor temperature of 80 K. The maximum performance with single mesh was with #400 mesh with COP of 6.12%. The cryocooler’s maximum Coefficient of Performance was with the combination of #400 and #500 meshes in the regenerator. The best multi mesh combination gave 4.071 W cooling power with an input power of 61.92 W with a COP of 6.57%. There was an improvement of 7.26% with the use of multiple mesh regenerator.

1. Introduction
Cryogenic engineering is a branch of science which has flourished recently. It has a wide range of applications such as superconductivity, superfluidity, cryopumping, cryosurgery etc. To attain Cryogenic temperatures with the help of thermal cycles a cryocooler can be employed. Cryocoolers are used for the cooling of infrared sensor arrays which are used in satellites to have high resolution thermal imagers. At 80K, the cooling capacity required for such an application is less than 5W [1, 2]. A Pulse Tube Cryocooler (PTC) is one such kind of cryocooler used in similar applications. It does not have any moving components in the cold head, making it highly reliable. It was invented by Gifford and Longs worth in 1963 [3], a pulse tube is a gas tube to replace a displacer for a regenerative Stirling Cryocooler. However, the PTC’s efficiency is poor, and numerous efforts have been made to improve since then.

1.1. Cryocooler with inertance tube-bounce space as phase shifter
To increase the performance of a pulse tube cryocooler, a phase shifting device such as an orifice, inertance tube, or double inlet may be added. An Inertance pulse tube cryocooler has inertance tube-reservoir as a phase shifter. The phase shifter allows the mass flow to lag the pressure to have a cooling effect at the cold end (also known as Acceptor). The inertance type, it has the disadvantage of bulky construction and geometric constraints as the inertance tube is connected to the reservoir (a large tank).
Reservoir volume should be as large as possible to compensate for the pressure fluctuation. A feasible modification to this is the use of bounce space to replace the reservoir. Bounce space as the name signifies it is the backspace of the compressor. The phase difference between the compressor and bounce space flow is around 180° with less amplitude. If we can make use of this phase difference in favour, inertance tube-bounce [4, 5] space combination can act as a compact phase shifter. A pulse tube cryocooler that uses the inertance tube-bounce space as phase shifter is shown in figure 1. The cryocooler consists of a moving magnet linear compressor, aftercooler, regenerator, acceptor, pulse tube, warm heat exchanger and inertance tube-bounce space (phase shifter). Input parameters, which effect performance, are the charge pressure and the frequency. Because the pressure ratio rises with operation frequency and average pressure, the mass flow amplitude may be decreased while maintaining the same PV power input, and regenerator losses can be minimised [6]. Helium is used as the working fluid in the cryocooler, which has a charge pressure of 3.2 MPa and a frequency of 50-55 Hz.

1.2. Multi mesh regenerator

A pulse tube cryocooler that uses the inertance tube-bounce space as a phase shifter works on a regenerative cycle i.e., the Stirling cycle. The performance of the regenerator is the key to its best performance. The regenerator plays a critical role in regenerative cryocoolers such Stirling and pulse tube cryocoolers, and increasing the performance of different types of regenerators is critical. In regenerative cryocoolers, the regenerator has a micro-porous metallic structure, which is generally the biggest cause of power loss. Irreversibility is caused by axial heat conduction, poor gas-solid heat transfer, and frictional losses.

A regenerative cryocoolers uses stacks of stainless wire mesh as the regenerator. Cha et al. [7] and Landrum et al. [8] studied the characteristics of mesh fillers relevant to the regenerative cryocoolers. A mesh with low pressure drop and high heat transfer is required for a better performance regenerator. Boroujerdi et al. [9] report that when a single mesh regenerator is used, the heat transfer coefficient gradually decreases along the length. The increase in wire diameter decreases the heat transfer area and the heat transfer coefficient. To improve the performance of the regenerator, a stacking of different types of meshes are adopted by Shital et al. [10] and Kishor et al. [11] in Stirling cryocooler. An increase in cooling capacity is obtained with the use of less porous wire-mesh at the outlet of hybrid regenerator and, high porosity wire-mesh at the inlet of hybrid regenerator leads to a reduction in power consumption [12]. In this work, the regenerator uses a combination of meshes called multi mesh. Figure 2 show the multi mesh regenerator, here reg1 and reg2 indicate the length of the first and second type of meshes.

Figure 1. Schematic of cryocooler which uses inertance tube-bounce space as phase shifter

Figure 2. Multi mesh regenerator
Table 1. Characteristics of cryocooler

| Component          | Radius (mm) | Length (mm) |
|--------------------|-------------|-------------|
| After cooler       | 13.4        | 5           |
| Regenerator        | 13.4        | 74.2        |
| Cold heat exchanger| 7.5         | 3           |
| Pulse tube         | 7.5         | 76.2        |
| Warm heat exchanger| 7.5         | 2           |
| Inertance tube     | 1.75        | 3147        |
| Bounce space       | 40          | 80          |

2. Modelling of Cryocooler

To simulate pulse tube cryocooler the effect, a cryocooler with an inertance tube and a bounce space as a phase shifter is simulated with a multi mesh regenerator. Sage V11 software was used to complete the modelling. David Gedeon of David Gedeon Associates in Athens, Ohio, created and supports Sage software. Sage has evolved into a modelling system for Stirling engines and Cryocooler systems development. Sage is a one-dimensional frequency domain modeller for thermodynamic systems that oscillate. Sage solves the simultaneous equations of motion and heat transfer for the objects with the given frequency. Sage then solves for the objects in the frequency domain at a particular frequency the simultaneous equations of motion and heat transfer. The amplitude, phase angles, and cycle averaged values are used to generate the solution. The objects can be solid or fluid, and there can be pressure force, heat transfer, or fluid flow pressure loss when solid and fluid contact.

2.1. Governing equations

The Navier-Stokes equations in integral form are the starting point for Sage’s governing equations[14], together with particular criteria for the sort of issue to be developed and simulated. The control volume is not fixed, and body forces are ignored. The inlet and exit borders are set in stone, while the side boundaries can vary. In Sage’s terminology, the governing equations have the following broad forms:

**Continuity**

\[
\frac{d}{dt} \int_v \rho dv + \int_s \rho n \cdot V_r ds = 0
\]  

(1)

**Momentum**

\[
\frac{d}{dt} \int_v \rho V dv + \int_s [(n \cdot V_r) \rho V - n \sigma] ds = 0
\]  

(2)

**Energy**

\[
\frac{d}{dt} \int_v \rho e dv + \int_s n \cdot (\rho e V_r - \sigma V - q) ds = 0
\]  

(3)

The generic equations are then transformed into one-dimensional conservative forms of equations. \(dv\) is substituted by \(Adx\) in the equations, where \(A\) is the flow area and \(x\) is the flow direction. The limit \(dx\) is then taken and divided by \(dx\). The equations are then transformed into:
Continuity
\[
\frac{\partial \rho A}{\partial t} + \frac{\partial \rho u A}{\partial x} = 0
\]  
(4)

Momentum
\[
\frac{\partial \rho A}{\partial t} + \frac{\partial \rho u A}{\partial x} + \frac{\partial P}{\partial x} A - FA = 0
\]  
(5)

Energy
\[
\frac{\partial \rho u e A}{\partial t} + P \frac{\partial A}{\partial t} + \frac{\partial}{\partial x} (U \rho e A + u PA + q) - Q_w = 0
\]  
(6)

The three implicit solution variables are \( \rho \), \( \rho u \), and \( \rho e \). Terms \( F \), \( Q_w \), and \( q \) are empirical terms with separate definitions for each of the kinds of objects provided by Sage.

In a heat exchanger, object of hydraulic diameter \( d_h \) and length ‘L’. The viscous pressure gradient ‘F’ is formulated in terms of local loss coefficient ‘K’ and Darcy friction ‘f’ as.

\[
F = -\left( \frac{f}{D_h} + \frac{K}{l} \right) \frac{\rho u |u|}{2}
\]  
(7)

\[
Q_w = h S_x (T_w - T_g) = Nu \left( \frac{k}{d_h} \right) S_x (T_w - T_g)
\]  
(8)

Equation (8) gives the heat transferred (\( Q_w \)) in the energy equation, where \( k \) is conductivity, \( S_x \) is the wetted perimeter, \( (T_w - T_g) \) is the temperature difference between the wall’s and the section’s average gas temperature, and \( Nu \) is the Nusselt number.

2.2. Dimensions and construction
A Stirling Pulse tube cryocooler consists of aftercooler, regenerator, acceptor, pulse tube, warm heat exchanger and inertance tube-bounce space assembly. The aftercooler is made of copper, heat exchangers are employed with a porosity of 0.65. The regenerator is made of stacked SS 304 mesh for varying mesh numbers. The acceptor is made of copper, it is a slit-heat exchanger. Pulse tube is a hollow tube made of SS304 with a tube wall thickness less than 0.15mm. The end of pulse tube is the warm heat exchanger made of copper, with slits having a porosity of 0.65. Important dimensions of the components are given in table 1. The assembled components, including aftercooler, regenerator, acceptor, pulse tube, and warm heat exchanger are called a cold tip. The cold tip has a coaxial arrangement with a regenerator as the annular region, and a pulse tube is placed inside coaxially. The regenerator and pulse tube wall thickness is less than 0.15 mm to reduce the conduction loss between the cold and hot tips.

The purpose of the analysis is to choose a multi mesh regenerator for an inertance pulse tube cryocooler that uses inertance tube-bounce space as a phase shifter. The performance of the cryocooler with the single and multi mesh regenerator is studied with four stainless steel wire meshes with mesh sizes #200, #300, #400, #500 and its combinations. The cryocooler operates in a temperature between 300 K at the hot end and 80K at the cold end. The charge pressure is 3.2 MPa. The working fluid and the material properties are modelled with temperature dependent thermophysical properties. The stainless steel meshes and its geometric properties used for the simulations are given in table 2.

The Sage output contains the net cooling power (at 80K), input power to the cryocooler, pressure and mass phase at different components, and heat transfer in various components. An apt regenerator design will minimize the required work input to the cryocooler to achieve the desired cooling power at the cold end (Acceptor).

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Table 2. Properties of the regenerator mesh[8, 13, 15]

| Mesh size | Wire diameter(µm) | Porosity(%) | Material |
|-----------|------------------|-------------|----------|
| #200      | 52               | 68.78       | SS 304   |
| #300      | 31               | 71.37       | SS 304   |
| #400      | 25               | 69.09       | SS 304   |
| #500      | 25               | 61.37       | SS 304   |

3. Simulation of pulse tube cryocooler

Different SS304 meshes layered to create a regenerator, but with the same volume, have been modelled to replicate a cryocooler with an inerance tube and a bounce space as a phase shifter. Wire-mesh parameters are taken from former works has been adjusted from 25 to 51 µm for the meshes considered. The working fluid is helium gas with a filling pressure of 3.2 MPa. The ambient temperature, after-cooler temperature, and hot heat exchanger temperature are all 300 K, whereas the cooling temperature is 80 K. The regenerator is 28.74 cm³ in volume. The pulse tube is 15 mm in diameter and 76.2 mm in length.

The simulation of the cryocooler includes a single mesh and multi mesh regenerator. There is a wire diameter value that maximises the cryocooler’s coefficient of performance (COP) for a given regenerator length. Furthermore, there is an ideal regenerator length for given wire diameter. The ratio of heat absorbed by gas in a cold heat exchanger (as cooling power) to compressor work is known as COP. The effectiveness of the regenerator material is concluded as that which gives the maximum Coefficient of Performance (COP).

3.1. Single mesh regenerator

The performance of the single mesh regenerator with meshes #200, #300, #400, and #500 is shown in table 3. Regenerator with mesh size #400 had the best performance with COP of 6.6% at 80 K. The maximum performance was at a frequency of 54Hz with an input power of 59.75 W and cooling load of 3.984 W. The increase in mesh number increases the cooling power due to the increase in heat transfer characteristics and effectiveness of the regenerator. The increase in mesh number increased the input power because of the increased pressure drop across the regenerator.

Table 3. Cryocooler performance with different meshes

| Input power (W) | Cooling load (W) | COP(%) |
|-----------------|------------------|--------|
| # 200           | 57.52            | 0.6484 | 1.13   |
| # 300           | 55.58            | 3.103  | 5.58   |
| # 400           | 65.01            | 3.984  | 6.12   |
| # 500           | 71.62            | 4.387  | 6.13   |

3.2. Multi mesh regenerator

A regenerator filled with multiple meshes are known as Multi mesh regenerator. As inferred from the analysis using single meshes, more the mesh number higher the cooling power developed. When fine meshes are used regenerator losses occur in its hot end, so to improve the performance of the regenerator coarse mesh are preferred a the hot end and finer meshes near cold end. The regenerator is arranged in such a way that the length of stainless steel meshes (combination of #200, #300, #400, and #500) are
given as reg1 and reg2. Figure 2 gives the pictorial view of the regenerator construction. To analyze the multi mesh regenerator performance a series of combinations of mesh lengths. The length reg1 and reg2 is such that the sum of length reg1, reg2 is 74.2 mm. The simulation for the various length and its corresponding performance is plotted in figures 3 and 4. Maximum performance of the system was obtained with the regenerator combination of #400 and #500 with reg1 and reg2 lengths 45 and 29.2 mm respectively.

Table 4. Cryocooler performance with multi mesh meshes

| reg1  | reg2  | reg1(mm) | reg2(mm) | Input power (W) | Cooling load (W) | COP(%) |
|-------|-------|----------|----------|-----------------|-----------------|--------|
| #200  | #300  | 5        | 69.2     | 54.28           | 2.879           | 5.30   |
| #200  | #400  | 30       | 44.2     | 57.81           | 3.526           | 6.09   |
| #200  | #500  | 45       | 29.2     | 60.44           | 3.824           | 6.30   |
| #300  | #400  | 15       | 59.2     | 57.14           | 3.748           | 6.55   |
| #300  | #500  | 15       | 59.2     | 57.14           | 3.748           | 6.55   |
| #400  | #500  | 45       | 29.2     | 61.92           | 4.071           | 6.57   |

Figure 3. Variation of cooling load with regenerator (reg2) length

Figure 4. Variation of COP with regenerator (reg2) length

3.3. Pressure drop characteristics cryocoolers

The single mesh and multiple mesh regenerator has different pressure drop characteristics. Figure 5 and 6 shows the variation of pressure at the inlet and outlet of the regenerator for single mesh(#400) and multi mesh (#400 and #500). The pressure drop for the single mesh was found to be $0.461 \times 10^5$ Pa whereas for the multi mesh was $0.565 \times 10^5$ Pa. The best combination provided a cooling load of 4.07W at 80 K with an input power of 61.92 W. This cryocooler had a phase shift of -40.83° was found between mass flow and pressure flow at the acceptor. Whereas in the middle of the regenerator, the phase shift was found to be 16.18°. Figure 7 and 8 shows the variation of mass and pressure flow at the acceptor and the middle of regenerator, from which the phase shift could be calculated(verified).
3.4. Performance comparison cryocoolers

Performance comparison of the cryocooler with single mesh and multi mesh are shown in tables 3 and 4. The multi mesh regenerator has a better performance compared to the single mesh type. For the single mesh type, as the mesh number increased, the performance increased. The mesh number increased there was an increase in input power consumption. When the multi mesh regenerator was used the performance of the system increased with a decrease in power consumption.

The power consumption decreased by 4.75% when the input power was compared to the single mesh #400 and optimal Multi mesh. The best performing single mesh regenerator was #400 with a COP of 6.12%, with an input power of 65.01W. The best performing multi mesh gave a COP of 6.57%, with an input power of 61.92 W and a cooling load of 4.071W. The maximum cooling load achieved by cryocooler with optimal multi mesh was 2.1% more than the one with #400 single mesh regenerator.

4. Conclusion

The cooling load and pressure drop properties of oscillatory flow through wire-mesh screen regenerators, such as heat transfer area per unit volume as a function of mesh screen wire diameter, are relevant to all regenerative cryocoolers. With four distinct SS304 mesh regenerators and their combinations of varying regenerator lengths, a cryocooler with an inertance tube and a bounce space as a phase shifter has been modelled and explored.
A Sage model was developed to study the effect of using the multi mesh regenerator and frequency on a Pulse tube cryocooler with inertance tube- bounce space as phase shifter was conducted. The cryocooler operated at a temperature between 300 and 80K with a charge pressure of 3.2 MPa. The porosity regenerator mesh was taken from the journal, which considers the experimentation results. The simulated results conclude that:

- The multi mesh regenerator outperformed the single mesh regenerator.
- The performance improvement is because low number mesh reduces the loss at the regenerator hot end, and finer mesh at the cold end significantly increased the heat transfer properties.
- The value of pressure drop of the regenerator with multi mesh was found to be between the value of individual single mesh regenerators.
- The COP of the system increases considerably when the multi-mesh regenerator and inertance bounce space phase shifter are used in collaboration.

5. References

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