A REVIEW OF DIFFERENT REGENERATOR MESH ON COOLING PERFORMANCE

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Abstract – *The fluid flow and heat exchange of regenerator are investigated under various conditions like geometric parameters and material characteristics. The regenerator used in Stirling cycle is having large surface area and high heat capacity. The low temperature regenerator mesh was designed to give cooling performance of different applications. Improvement in cooling performance is defined by position and quantity of meshes inside the regenerator.*

Wire mesh regenerator are commonly used because it gives high heat exchange area. Different types of Stirling cryocooler working at 30 – 25 K uses the stainless steel and phosphor bronze mesh. To get high cooling effect and efficiency we can combine different meshes. There are various relations for calculating the heat exchange and pressure drop of regenerator mesh.

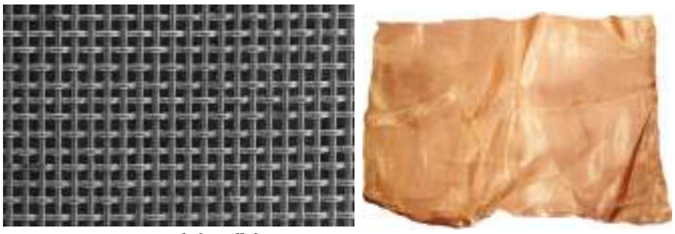
Key Words: Regenerator, Porosity, Heat exchange, Wire Mesh,

1. INTRODUCTION

The Stirling Engine is the term usually refers to a class of external combustion closed cycle Air Engines. These engines are specially used in various applications like cryocooler and power generation in space [7]. First use of regenerator is used by Robert Stirling in 1816 in hot engine heat exchanger. The Stirling cycle cryocooler uses the linear motor as primary drive for piston and expander unit which eliminates various mechanical links for conversion of rotary motion to linear motion. Regenerator is the thermal storage which absorbs and rejects the heat from hot fluid [8]. It is one of the components of regenerator type cryocooler.

The regenerator should have:
1. a large heat exchange area
2. a large thermal inertia to reduce temperature fluctuations
3. minute pressure drop to reduce use of power.

The regenerator mesh contains porous sections and large solid area for more heat transfer due to which we get better thermal performance i.e. cooling effect [1]. Mostly metal mesh of different materials is preferred for regenerator. There are many factors which influence the regenerator performance such as material properties, flow resistance, surface heat transfer area and working efficiency [6]. This regenerator mesh is used in infrared applications having very long wavelength and more important in military applications, space exploration fields, etc. [4]. The performance of cryocooler is depends upon performance of regenerator [3]. Different material used for regenerator mesh is Stainless steel and phosphor bronze (fig-1). Mostly stainless-steel regenerator mesh gives the design, fabrication and used for future applications [4].



(a) (b)
Fig -1: (a) Stainless Steel, (b) Phosphor Bronze

The regenerator having low diameter in cold region and large diameter in hot region will lead to regenerator losses. Investigation of regenerator have been carried out theoretically and will carry experimental further which has impact on performance of Cryocooler.

The thermal capacity ratio (TCR) is defined as the ratio of heat capacity of mesh matrix material to the heat capacity of gas per pass at constant rate with uniform density. To get high effectiveness the thermal capacity ratio should larger than 10. And it is given by following relation:

$$TCR = N_{TCR}\left[\frac{\gamma-1}{\gamma}\right]\epsilon_r\left[\frac{1-\varphi}{\varphi}\right] \quad (1)$$

Where

$$N_{TCR} = \left[\frac{\rho CT}{P_{Ref}}\right]$$

γ = Ratio of specific heats

ϵ_r = Ratio of regenerator dead space

φ = Porosity

ρ = Density of material

C = Thermal Capacity of material

T = Sink temperature

P_{Ref} = Reference charge pressure

1.1 Regenerator Design

The regenerator design measures the volume of mesh which requires for absorbing and releasing of heat energy so as to reduce temperature of working substance or fluid when it leaves the regenerator. The design parameters like length of regenerator, mesh material (stainless steel or phosphor bonze) and geometry with porosity. The material selected should have high heat carrying capacity for large heat transfer [8]. Most of design requirements and required solutions are given in Table – 1.

Table -1: Requirement of Good Regenerator [8]

Requirements	Solution
Maximum heat capacity	Large solid matrix
Minimum flow losses	Small porous matrix
Minimum dead space	Small dense matrix
Maximum heat transfer	Fine divide of matrix
Minimum contamination	No obstruction

2. REGENERATOR MESH PARAMETERS (PHOSPHOR BRONZE)

Different parameters which affects the cooling performance of various systems. Generally small change in these parameters affects mostly and in large amount. Following are the parameters:

2.1 Displacer Diameter:

The gap between cryocooler cylinder and displacer is held constant. Further thickness of displacer is also kept constant. Thus, change in displacer diameter also affects the regenerator diameter [2].

Table -2: Net Refrigeration effect of Different Diameter

Dia. of regenerator, mm	Net Refrigerating effect, W	Pressure drop in regenerator, W	Actual power , W
15	0.985	1.33	44.65
16	1.009	1.29	45.77
17	6.78E-01	1.30	46.84
18	2.85E-01	1.32	47.86

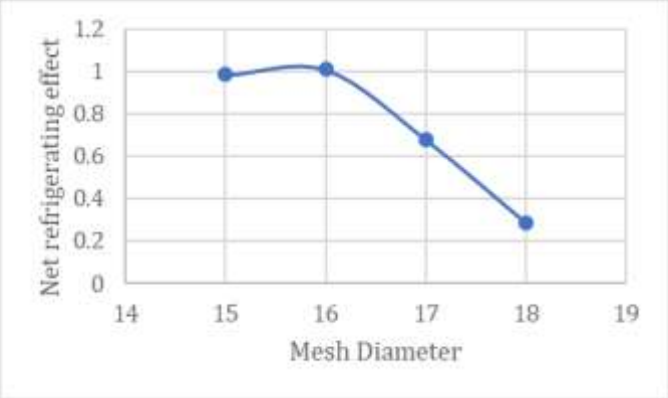


Chart -1: Net Refrigeration effect of Different Diameter

2.2 Piston Diameter:

For a fixed stroke of the opposed pistons, the mass flow rate in the system will be increasing with increase in the diameter. For a desired average pressure, the system may be in position to operate with lower charge pressure as the pressure ratio is expected to increase [2].

2.3 Length of regenerator:

With other parameters held fixed, the increase in the length of regenerator will lead to improvement in effectiveness of regenerator. However, the increase in the pressure drop across the regenerator will also increase the P-V loss. Increase in length, leading to reduced temperature gradient, will also decrease the conduction [2].

Table -3: Net Refrigeration effect of Different length of regenerator

Regenerator length, mm	Net Refrigerating effect, W	Pressure drop in regenerator, W	Power loss, W
40	1.23	9.74	1.96
45	1.27	9.84	1.97
50	1.28	10.05	1.94
55	1.02	10.25	2.01
60	6.00E-01	10.4	2.08

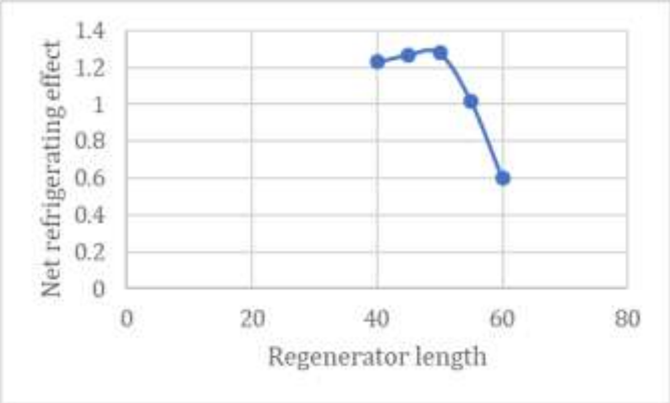


Chart -2: Net Refrigeration effect of Different length of regenerator

2.4 Mesh Size and Wire diameter:

Due to increased surface area available for finer mesh the regenerator ineffectiveness loss can decrease substantially. However, the pressure drop will increase through the regenerator. Once the effect of various geometric parameters is considered, the geometric configuration to provide the best results is arrived. The unit can then be fabricated. The wire diameter can be taken in the range of 0.01mm to 0.11mm. It affects porosity, screen thickness and regenerator mass directly [2].

2.5 Number of Screens:

This term sets the number of screens that will be stacked on the top of each other to form the regenerator.

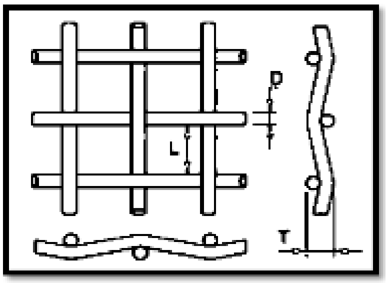


Fig -2: 2D view of Regenerator mesh

Where,
D = Diameter of wire in micron
L = Length of square opening or pitch

The main reason behind selection of number of screens are that the solid material with high mesh number has large area for heat transfer.

2.6 Mesh Density:

It defined as the no. of opening in screen disc. As an Industry standard, it is defined as no. openings per sq. inch. Mesh density is related to the porosity. As density increases porosity of mesh decreases and number of opening increases so that heat capacity increases.

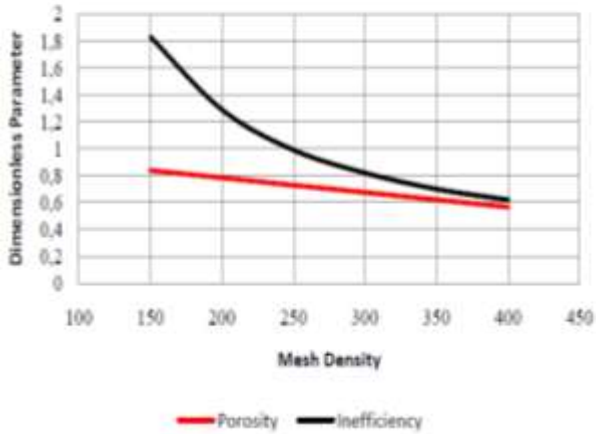


Chart -3: Effect of Mesh density on Porosity and inefficiency

2.7 Porosity:

It is defined as ratio of total volume of connected wide spaces to the total volume of matrix. Mesh density has strong effect on porosity.

$$\text{Porosity} = 1 - \left(\frac{\pi DW\sqrt{\text{pitch} \times (2 + DW)}}{4 \times \text{pitch}}\right) \qquad (2)$$

Due to porous nature of mesh there is decrease in fluid velocity. And also increase in pressure drop with increase in mesh number [2]

2.8 Effectiveness:

The effectiveness defines how well a real heat exchanger is performing relative to an ideal exchanger operating across same temperature differences [2].

$$\varepsilon = \frac{Q}{Q_{actual}} \qquad (3)$$

3. REGENERATOR LOSSES

3.1 Regenerator Ineffectiveness:

In an ideal regenerator, the gas gets cooled from TC to TE considering 100 % effectiveness. In actual regenerator, due to regenerator ineffectiveness gas gets cooled from TC up to (TE+ΔT), which is higher than the required temperature of TE. A part of refrigerating effect is therefore lost at the expansion stages due to the ineffectiveness of regenerator. This results in reduction in refrigerating effect. Proper selection of the regenerator mesh of a material with high heat capacity in the operating temperature range is essential for high effectiveness of the regenerator.

If the regenerator mesh is fine (high mesh number and small diameter) the required large surface area will be available when densely packed and may give the desired regenerator effectiveness. However, this will result in excessive pressure drop when the gas passes through the regenerator. Thus, the sum of the regenerator ineffectiveness loss and Pressure loss needs to be minimized to provide maximum refrigerating effect at the desired temperature [5].

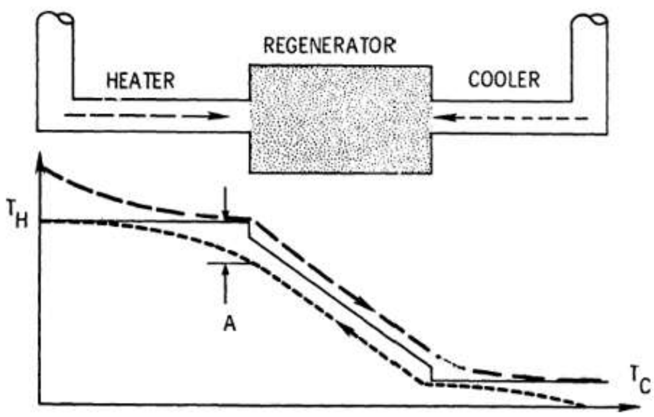


Fig -3: Temperature variation in regenerator of Stirling cryocooler

3.2 Loss due to Temperature Swing:

This loss accounts for the temperature changes in the matrix of the regenerator during the cycle. It is the heat taken up by the matrix due to its finite heat capacity. The temperature swing loss is calculated for half cycle time i.e. during the forward motion of the gas from compression space to the expansion space.

This loss should be considered only if the regenerator ineffectiveness loss is estimated assuming the steady state conditions. However, if the regenerator analysis considers the temperature variation of the matrix, there is no need to consider the swing loss separately [5].

3.3 Pumping Losses:

A gap is provided between the cryo-cylinder and the displacer in order to avoid any rubbing / friction between the two. The pumping loss is due to volume of this gap between the displacer and the cryo-cylinder. The mass of gas in this volume at any instant of time is dependent on the pressure in the system at that instance. At the minimum pressure condition there is a minimum mass of gas in this clearance volume.

Hence, the clearance between the displacer and the cryo-cylinder becomes a very important parameter in determining the performance of the cryo-cooler. For the miniature cryo-cooler clearance of the order of 15 to 20 microns is preferred to reduce the pumping loss.

When the displacer moves towards cold end, comparatively hot gas pressurizes this gap volume and when the displacer moves away from the cold end (during expansion), this gas enters the expansion space and picks up some cooling effect thus resulting in loss. This loss is called as the pumping loss [5].

3.4 Loss due to Conduction:

This loss is independent of the machine speed. It is simply the heat transferred between the hot and cold ends of the following components.

1. Displacer Material
2. Cryo-cylinder
3. Regenerator Matrix Material

Usually, the regenerator of Stirling cryocooler is made up of layers of fine screens that are tightly packed or sintered together.

Effective thermal conductivity of the regenerator matrix, Kmx is given by Martini

$$K_{mx} = K_G = \frac{\frac{\left(1+\frac{Km}{Kg}\right)}{\left(1-\frac{Km}{Kg}\right)} - FF}{\frac{\left(1+\frac{Km}{Kg}\right)}{\left(1+\frac{Km}{Kg}\right)} + FF} \tag{4}$$

Where,
FF = Fill factor = (1- Porosity), for the mesh.
The loss is then calculated by simple conduction formula considering the cross-sectional area of the regenerator matrix,

$$Q_{cmx} = K_{mx} \times A_R \times \frac{\Delta T}{L_R} \tag{5}$$

Expressions can be utilized by considering the conductivity, area, temperature difference and the length of the regenerator [5].

4. REGENERATOR MATERIALS

The regenerator material is selected in such a way that its heat capacity must be larger than that of working gas. Based on the temperature range in which the regenerators operate, its design and analysis can be divided into two main groups.

The first group is the efforts to find the optimum regenerator from 300 K to 30 K and the second is the research below 30 K. The first group from 300 K to 30 K are the Stainless steel and copper alloy materials which are ductile and can be woven into screen meshes. Erbium, Neodymium and other rare earth alloys have been developed as regenerator materials [8].

Table -4: Properties of Material

Sr. No.	Parameters	Stainless Steel	Phosphor Bronze
1.	Copper Contain	3 to 5 %	85 to 90 %
2.	Thermal Conductivity	12 – 45 w/mk	Above 46 w/mk
3.	Specific heat capacity	480 J/kg-k	380 J/kg-k
4.	Thermal Expansion	17 µm/m-K	18 µm/m-K
5.	Young's Modulus	200 GPa	110 GPa
6.	Poisson's Ratio	0.28	0.34
7.	Electrical Conductivity	2.4 %	18 %
8.	Density	7.8 g/cm^3	8.8 g/cm^3

Research on regenerator materials below 30 K is experimental in nature as theories predicting the transition temperature and heat capacity of an alloy or intermetallic compound are lacking and materials are discovered by intuition or trial and error. Therefore, extensive studies on search of materials or combination of them with higher performance have been carried out [8].

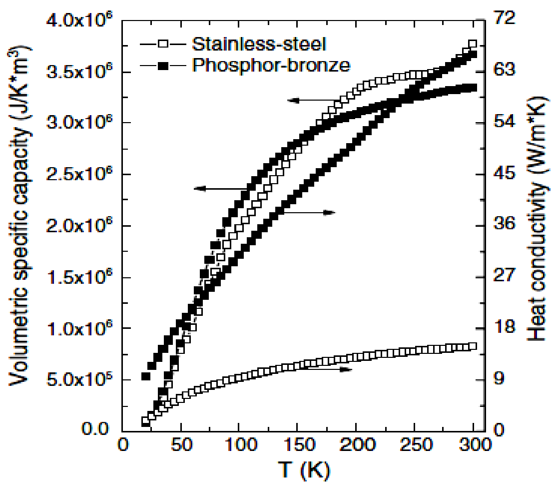


Chart -4: Specific heat and heat conductivity of Stainless steel and Phosphor bronze [8].

4.1 Features of Phosphor Bronze Mesh:

1. Corrosion, wear, tear, rust, fatigue, acid and alkali resistance.
2. Non-magnetic, good ductility, high toughness, high strength.
3. Good electricity and heat conductivity.
4. Phosphor copper wire mesh with higher copper content makes it more corrosion resistance than brass mesh cloth. It is harder and stronger than copper mesh cloth.

5. FACTORS AFFECTING HEAT EXHANGE

There are many factors which affects the heat exchange performance of regenerator. Following are some factors which influencing more on heat exchange performance:

5.1 Available heat capacity:

The heat transfer or heat exchange for stack of mesh is defined as the product of solid specific heat capacity, depth of heat exchange and mesh solid density [6].

$$C_S \delta_S \rho_S = \sqrt{\frac{K_r C_S \rho_S}{\pi f}} \quad (6)$$

5.2 Regenerator ineffectiveness:

Regenerator ineffectiveness is the main factor which is used to calculate or find out heat exchange performance [6]. It is calculated by:

$$\lambda = \frac{H_1}{H_2 - H_3} \quad (7)$$

Where,
H_1 = Loss of enthalpy at cold end
H_2 & H_3 = Change in enthalpy from hot end to cold end

6. CONCLUSIONS

As it is concluded that increase in mesh number i.e. mesh stack quantity, there is decrease in pressure periodically near the warm end due to rise in viscous obstacle. And heat exchange loss reduces very fast at cold end due to area density. There is change between junction of two different meshes, either pressure drop of heat exchange losses which produce temperature difference across junction.

Also phase shift plays important role in cooling performance. To get good cooling phase shift between two units, they should be tuned fine at frequency of 50 Hz.

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