

Design aspects and performance analysis of three-mesh hybrid regenerator for miniature stirling cryocooler

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Abstract: A hybrid regenerator is made by combining mesh matrices of different sizes in a single unit. The porous matrix, which has a larger hydraulic diameter, is placed at the warm end, while the dense matrix, which has a smaller hydraulic diameter, is placed at the cold end. In this study, a three-mesh hybrid regenerator is analyzed to reduce heat loss and improve overall performance. Special attention is given to the effect of mesh size on heat transfer and regenerator effectiveness. The performance of the three-mesh hybrid regenerator is compared with that of a homogeneous regenerator. The results show that a properly designed hybrid regenerator can achieve higher effectiveness and better thermal performance. The three-mesh hybrid regenerator performs better than both the two-mesh hybrid regenerator and the simple homogeneous regenerator. This improvement is mainly due to the gradual and more uniform decrease in hydraulic diameter along the regenerator, which helps improve heat transfer and reduce heat loss.

Index Terms: Hybrid regenerator, Mesh matrix size, Heat transfer, Regenerator effectiveness.

I. INTRODUCTION

The development of small-capacity cryocoolers requires the proper design and selection of important components to achieve better performance and higher efficiency. A Stirling cryocooler works on a closed regenerative thermodynamic cycle in which the same working gas is repeatedly compressed and expanded at different temperature levels. During this process, heat is exchanged at constant volume through a regenerative heat exchanger called a regenerator. The regenerator stores heat from the working gas during one part of the cycle and returns it during another part. Therefore, its performance has a direct effect on the overall cooling capacity of the cryocooler. In Stirling cryocoolers, a regenerator with an effectiveness greater than 98.5% is generally required. The amount of heat transferred through the regenerator is much greater than the refrigeration produced by the gas expansion process. As a result, even a small reduction in regenerator effectiveness can cause a significant decrease in refrigeration capacity. Hence, careful design and selection of the regenerator are essential for

improving the performance of small-capacity Stirling cryocoolers.

II. TYPE STYLE AND FONTS EFFECT OF MESH MATRIX ON REGENERATOR PERFORMANCE

The performance of a regenerator depends mainly on the size of the mesh matrix and the material used to make it. In the temperature range of 70 K to 300 K, the effect of mesh size is greater than the effect of matrix material [1]. This is because the matrix material has a much higher volumetric heat capacity than the working gas. Therefore, the effect of temperature on the overall regenerator performance is less significant, and changing the matrix material does not cause a large change in performance.

The loss of refrigeration in a regenerator mainly occurs due to three factors: low effectiveness, pressure drop, and heat conduction along the regenerator. The effectiveness of a regenerator depends on the number of transfer units (NTU) [1,2]. It is also strongly affected by mesh density and the specific heat of the matrix material. The specific heat of the matrix material decreases as the temperature decreases.

Therefore, a denser mesh matrix is generally required to improve heat transfer and increase regenerator effectiveness.

However, using a denser mesh also increases the resistance to gas flow and causes a higher pressure drop. To keep the pressure drop within an acceptable limit, the matrix must have sufficient porosity to allow the working gas to flow easily. The viscosity of the working gas is another important factor because it affects the resistance to flow. In a Stirling cryocooler using helium as the working gas, the viscosity of helium decreases as the temperature decreases.

In a homogeneous regenerator, the mesh size and hydraulic diameter remain constant along its length. Due to the changes in gas properties with temperature, the pressure drop caused by flow resistance is higher at the warm end, while the loss caused by insufficient heat exchange is greater at the cold end [1]. Therefore, selecting a single mesh size for the entire regenerator may not provide the best performance. Using different mesh sizes at different temperature levels may help balance pressure drop and heat transfer, reduce refrigeration losses, and improve overall regenerator effectiveness.

III. HYBRID REGENERATOR

The concept of a hybrid regenerator is developed to improve regenerator performance by placing a porous matrix at the warm end and a dense matrix at the cold end. In this design, mesh matrices of different sizes are combined and arranged along the length of the regenerator. A mesh matrix with higher porosity is placed at the warm end to reduce gas flow resistance and pressure drop. A denser mesh matrix is placed at the cold end to improve heat transfer and increase regenerator effectiveness. This arrangement helps to reduce the problems found in a homogeneous regenerator, where the same mesh size is used throughout its length. By selecting suitable mesh sizes for different temperature regions, it is possible to achieve a better balance between pressure drop and heat transfer, thereby reducing refrigeration losses and improving overall performance.

The hydraulic diameter (D_h) is an important parameter in the design of a hybrid regenerator. It represents the effective diameter of the passages through which the working gas flows inside the mesh matrix. The hydraulic diameter depends mainly on the size and structure of the mesh matrix [2]. Therefore, changing the mesh size along the regenerator length changes the hydraulic diameter. A properly selected combination of mesh matrices can provide a gradual decrease in hydraulic diameter from the warm end to the cold end, helping to improve gas flow and heat transfer performance.

$$D_h = 4L \left(\frac{A_{ff}}{A_{ht}} \right) \quad \dots(1)$$

where, A_{ff} = Free flow area through regenerator = $A \times \Phi$

and, A_{ht} = Heat transfer area of mesh matrix

All the terms can be determined in terms of mesh matrix characteristics and on solving,

$$D_h = d_w \times \left(\frac{\Phi}{1-\Phi} \right) \quad \dots(2)$$

The hydraulic diameter is considered as basis of study. The optimum hybrid regenerator would have a continuous variation in mesh size, or hydraulic diameter from warm end to cold end[1].

IV. DESIGN OF THREE-MESH HYBRID REGENERATOR

Following the design method for a two-mesh hybrid regenerator reported in an earlier study [4], three mesh matrices of different sizes are selected for the three-mesh hybrid regenerator. These mesh matrices are arranged in decreasing order of hydraulic diameter from the warm end to the cold end, as shown in Figure 1. The mesh with the largest hydraulic diameter is placed at the warm end, while the mesh with the smallest hydraulic diameter is placed at the cold end. This arrangement helps to balance gas flow resistance and heat transfer along the regenerator.

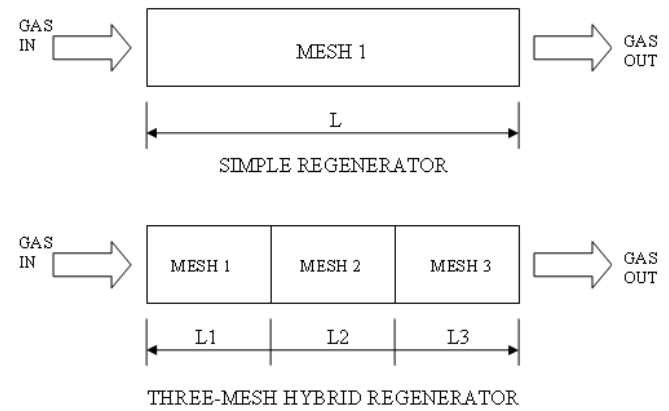


Figure 1. Schematic of three-mesh hybrid regenerator.

The main challenge in designing a three-mesh hybrid regenerator is to find the optimum length or proportion of each mesh matrix. The correct combination is important for reducing heat loss caused by pressure drop and improving regenerator effectiveness. If the proportion of any mesh matrix is not selected properly, the regenerator may not achieve the desired performance. Selecting the proportions by random trial and error is difficult because many possible combinations of the three mesh matrices are available. Therefore, a systematic method is required to determine the best proportion of each mesh matrix to achieve minimum heat loss and higher regenerator effectiveness.

The constraints that must be considered while selecting mesh matrix are [3]

The total of length of each sub-regenerator must be equal to length of regenerator, i.e.

$$L_1 + L_2 + L_3 = L_r = 52 \text{ mm} \quad \dots (3)$$

The sum of mass of each sub-regenerator mesh matrix must be limited to the mass of a homogeneous regenerator mesh matrix designed for the cryocooler, i.e.

$$M_1 + M_2 + M_3 = M_m = 8.89705 \text{ e}^{-3} \text{ kg} \quad \dots (4)$$

The mesh matrixes selected are set into the two equations of constraints in terms of length of each sub-regenerator as follows:

Total mass of mesh matrix is,

$$M_m = (n' \times m) \text{ kg} \quad \dots (5)$$

and, Number of wire screens in a regenerator (n') is calculated as

$$n' = \frac{L}{2 \times d_w} \quad \dots (6)$$

Thus,

$$M_m = \left(\frac{m}{2 \times d_w} \right) \times L \text{ or } M_m = (T) \times L \quad \dots (7)$$

The term in the brackets (T) is dependent on mesh size selected for each sub-regenerator. Above two equations are modified and formulated in the form of simultaneous equations as,

$$L_1 + L_2 + L_3 = L_r \quad \dots (A)$$

$$\left(\frac{m_1}{2 \times d_{w,1}} \right) \times L_1 + \left(\frac{m_2}{2 \times d_{w,2}} \right) \times L_2 + \left(\frac{m_3}{2 \times d_{w,3}} \right) \times L_3 = M_m \quad \dots (B)$$

Now above two equations (A) & (B) are solved by Gauss-Elimination Technique of numerical method to solve simultaneous equations [3]. The matrix formulated takes the form as

$$\begin{bmatrix} 1 & 1 & 1 \\ T_1 & T_2 & T_3 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} L_1 \\ L_2 \\ L_3 \end{Bmatrix} = \begin{bmatrix} L_r \\ M_m \\ 0 \end{bmatrix} \quad \dots (8)$$

The matrix is solved for a selected value of length of warm-end sub-regenerator, L_1 . On solving the matrix final equations are

$$L_2 = \left(\frac{(M_m - L_r \cdot T_1) - (T_3 - T_1)(L_r - L_1)}{(T_2 - T_1) - (T_3 - T_1)} \right) \quad \dots (6)$$

$$L_3 = (L_r - L_1 - L_2) \quad \dots (7)$$

Different combinations of mesh matrix lengths are developed by changing the length (L_1) of the first mesh matrix. A computer program is developed to solve the required equations and find the optimum combination of the three mesh matrices. The main aim is to select the suitable length of each mesh matrix to reduce heat loss and improve the overall performance of the regenerator.

Following the design method used for a two-mesh hybrid regenerator [4], each part of the three-mesh hybrid regenerator is treated as a separate regenerator. The number of transfer units (NTU), pressure drop due to gas flow resistance, and heat loss due to axial heat conduction are calculated separately for each part. These calculations help to understand the performance of each mesh matrix under different operating conditions.

The results obtained for the three individual parts are then combined to calculate the overall performance of the hybrid regenerator. The design and analysis are based on the established procedure used by various researchers for homogeneous regenerators [3,4]. This method provides a systematic way to compare different mesh combinations and identify a suitable arrangement. By adjusting the length of each mesh matrix and analyzing the resulting heat losses and effectiveness, the optimum design can be selected to achieve better regenerator performance.

Each sub-regenerator is analyzed separately, and the overall results for the hybrid regenerator are calculated by combining the results of all three parts as follows:

$$Ntu_H = Ntu_1 + Ntu_2 + Ntu_3 \quad \dots (8)$$

$$\epsilon_H = 1 - I_H = 1 - \left(\frac{1}{1 + Ntu_H} \right) \quad \dots (9)$$

Design Data [4]

Temperature of compression space, $T_c = 320 \text{ K}$.

Temperature of expansion space, $T_e = 80 \text{ K}$.

Regenerator Length, $L = 52 \text{ mm}$.

Charging pressure, $P_{CH} = 16 \text{ bar}$.

Temperature at charge condition, $T_{CH} = 300 \text{ K}$.

Mesh Punch diameter, $D = 8.6 \text{ mm}$

Working fluid = Helium.

Blow time, $t = 0.01 \text{ sec}$.

Mesh material = Phosphor-bronze

Regenerator tube material = Stainless steel.

Wall thickness = 0.10 mm.

V. RESULTS AND DISCUSSION

Different designs of the three-mesh hybrid regenerator are developed by changing the length of the sub-regenerator at the warm end. For each design, the lengths of the remaining mesh sections are selected to form a complete regenerator. A computer program is used to calculate the performance of each combination. The results are then

compared with those of a homogeneous regenerator made using a 200-mesh matrix. This homogeneous regenerator is used as a reference to study the improvement achieved by using different mesh sizes.

The calculations are carried out for different selected lengths of the warm-end sub-regenerator. The results help to show how changes in mesh size and the length of each section affect the overall performance of the regenerator. Figures 2 and 3 present the effects of matrix size and mesh fraction on regenerator performance for different combinations.

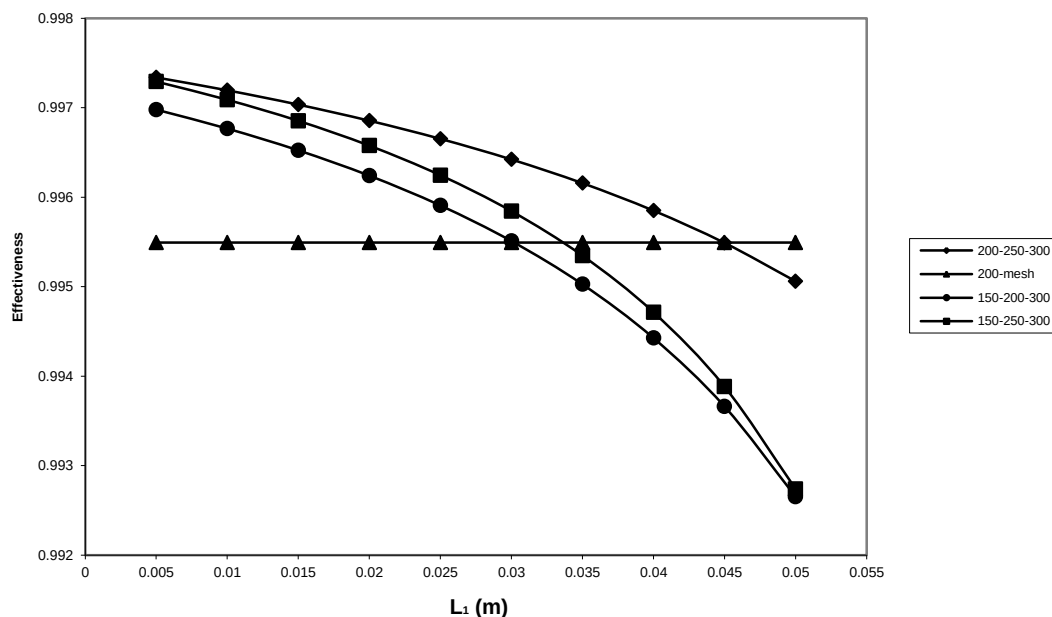


Figure 2. Effect of matrix size and mesh fraction on effectiveness of three-mesh hybrid regenerator.

The Fig. 2 shows how the length of the warm-end sub-regenerator (L_1) affects the effectiveness of different regenerator designs. The horizontal axis represents (L_1) in meters, while the vertical axis represents regenerator effectiveness. The results show that effectiveness generally decreases as (L_1) increases for most hybrid regenerator combinations. The 200-mesh homogeneous regenerator maintains nearly constant effectiveness at about 0.9955. Among the hybrid designs, the 200-250-300 combination shows a gradual decrease in effectiveness, while the 150-200-300 and 150-250-300 combinations show a larger decrease at higher values of (L_1). At ($L_1 = 0.05$) m, the effectiveness of these combinations approaches 0.9927–0.9950. This indicates that the choice of warm-end section length and mesh combination has an important effect on regenerator performance. A suitable value of (L_1) is therefore required to maintain high effectiveness.

Figure 3 shows the effect of warm-end sub-regenerator length (L_1) on the pressure drop across different regenerator designs. The horizontal axis represents (L_1) in meters, and the vertical axis represents pressure drop in N/m^2 . The results show that pressure drop decreases as (L_1) increases for most hybrid regenerator combinations. The 200-mesh homogeneous regenerator maintains an almost constant pressure drop of approximately 39,000 N/m^2 . The 200-250-300 combination has the highest-pressure drop, decreasing from about 53,000 N/m^2 to 43,000 N/m^2 . The 150-200-300 and 150-250-300 combinations show larger reductions, reaching approximately 27,000 N/m^2 at ($L_1 = 0.05$) m. These results indicate that increasing the length of the warm-end section can reduce flow resistance for several hybrid designs. However, the first graph shows that effectiveness may also decrease as (L_1) increases. Therefore, the design should balance low pressure drop with high regenerator effectiveness to achieve good overall performance.

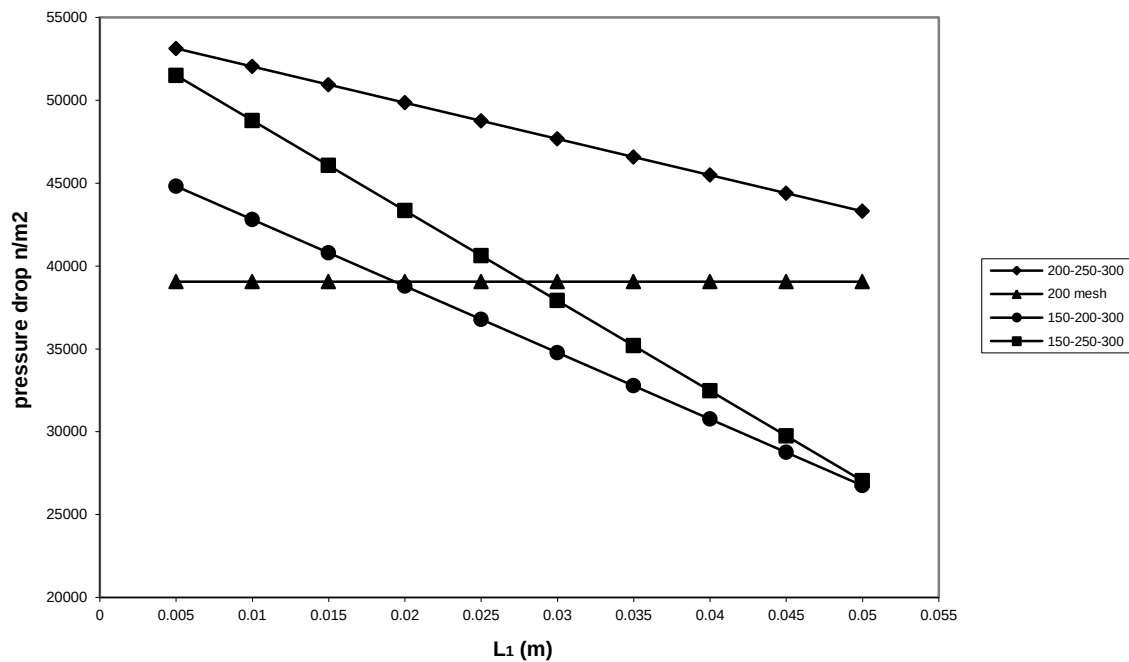


Figure 3. Effect of matrix size and mesh fraction on pressure drop of three-mesh hybrid regenerator.

These figures help to identify how the selection of mesh size and the proportion of each mesh section influence heat loss, pressure drop, and regenerator effectiveness. By comparing these results, a suitable combination of three mesh matrices can be selected to achieve better performance than a homogeneous regenerator.

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NOMENCLATURE

A Cross sectional area

D, d Diameter

I Ineffectiveness

L, l Length

M, m Mass

Ntu Number of transfer unit

Q Refrigeration, heat transferred

Greek Symbols

ε Regenerator effectiveness

Φ Porosity of matrix

Subscripts

h Hydraulic diameter

H Hybrid construction

m Mesh matrix

r Regenerator

w Wire of mesh

1 Warm end sub-regenerator

2 Intermediate sub-regenerator

3 Cold end sub-regenerator