International Journal of Advance Research in Engineering, Science & Technology(IJAREST),
ISSN(O):2393-9877, ISSN(P): 2394-2444,
Volume 2, Issue 9, September- 2015, Impact Factor: 2.125

Hybrid cryogenic Regenerator – New Era in the Cryogenics field

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Abstract
Analysis of cryogenic regenerator is one of the challenging tasks which play a major role for the performance predictions of the machine. Many investigators have contributed in the field of cryogenic regenerators. Still, this is one of the interesting topics of research. Till today, not a single literature is available in the open literature which covers all aspects of cryogenic regenerator. In this paper, efforts are made to analyze hybrid regenerator for Striling cryogenic regenerator.

Keywords- *Effectiveness, Homogeneous regenerator, Hybrid regenerator, Pressure drop, Cryocoolers.*

NOMENCLATURE

A_p	Constant defined by equation 3.36
CR	Heat capacity ratio
F	Flow loss coefficient
F_0	Fourier number
f	Friction factor
I_{eff}	Ineffectiveness
k	Thermal conductivity
L_r	Regenerator length
l	Mesh distance
Ntu	Number of heat transfer unit
Nu	Nusselt number
PR	Prandtl number
Pr	Dia. To pitch ratio
Q	Cold produced, heat transfer
t	Blow time
u	Velocity
u_o	Free flow area
V	Volume
x	Displacement
	Greek Symbol
α	Matrix heat transfer coefficient, phase angle
α^1	Thermal diffusivity, m^2 /h
β	Area opening ratio
ε	Regenerator effectiveness
η	Efficiency, dimensionless no. i.e. Ntu/CR
θ	Piston to displacer phase shift
ρ	Density , kg/ m^3
σ^1	Specific surface
τ	Temperature ratio (T_C/T_E)
φ	Porosity, mesh punch dia.
λ	Heat conductivity, w/m - k
ξ	Dimensionless no. i.e. Ntu* X

I. INTRODUCTION

The regenerator is nothing but a storage heat exchanger of matrix material that has the capacity to store energy in it. Hence, the hybrid regenerator opens new era in the field of Cryogenic. In homogeneous regenerator, it has been observed that for resistance term is large at hot end the effectiveness term is large at the cold due to constant hydraulic diameter.

Hybrid regenerator gives better performance as compared to single mesh regenerator. No requirement of any mechanical design complications are involved as same volume was utilized. Also the mass of regenerator has been kept same, and hence the dynamics of the system is not affected. The work carried out in this paper comprises of the realistic analysis of the miniature cryogenic regenerator of the Stirling cycle Cryocooler.

Thus, an optimum regenerator would have a matrix with continuous variation in hydraulic diameter. Consequently performance improvement by about 5% is attained.

II. DESIGN OF HYBRID REGENERATOR

The regenerator is very simple in construction design and working. In Hybrid regenerator combination of two or more than two matrices and also use different materials in one regenerator.

1. By varying the material used for matrix, for sane matrix size.
2. By varying the matrix size only, for same matrix material.
3. By varying the matrix material as well matrix size also.

2.1. Design of Two-Mesh Hybrid Regenerator

The total loss in the regenerator is the sum of losses due to flow resistance, ineffectiveness and axial conduction, since the viscosity of Helium decreases with decreasing temperature; it can be shown that for a homogeneous regenerator (Constant hydraulic diameter) that flow resistance term is large at warm end and the ineffectiveness term is large at cold end. The sum of these two losses can be reduced by decreasing hydraulic diameter of regenerator matrix as the gas temperature decreases i.e. employing a smaller matrix element at the cold end than at the warm end. This arrangement in regenerator is termed as Hybrid regenerator. It is experimentally concluded that two zone hybrid regenerator can increase system effectiveness by about five percent. To improve system efficiency two basic features must be satisfied;

The matrix volumetric heat capacity has to be higher than that of helium gas.

The total heat transfer area has to be large enough to obtain high NTU.

Thus, an optimum regenerator would have a matrix with continuous variation in hydraulic diameter. Consequently performance improvement by about 5% is attained.

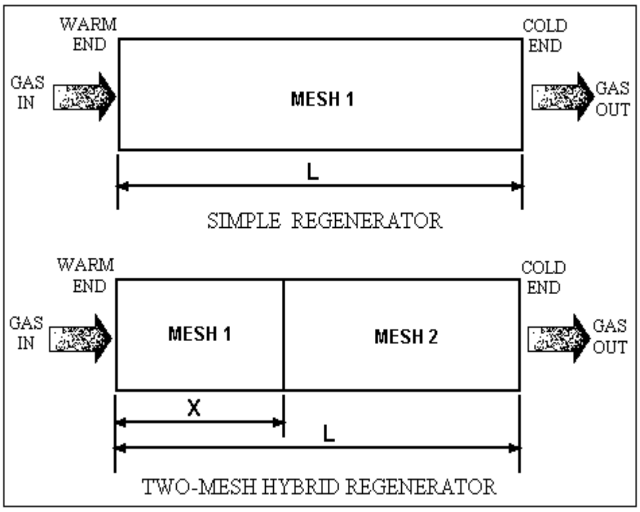

Figure 1. Simple and two mesh regenerator.

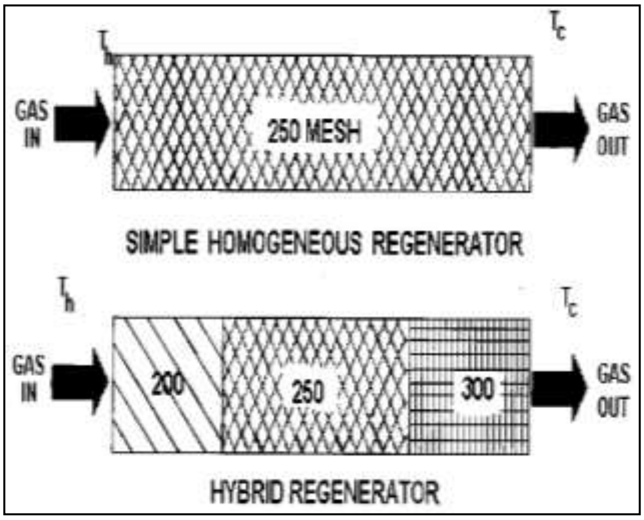

Figure 2.Simple and hybrid regenerator.

Calculation by using the following analysis.

1. NTU for hybrid regenerator.
   $(NTU)_H = NTU_1 + NTU_2$
2. Effectiveness of hybrid regenerator.

$$\varepsilon = (1 - I_H) = 1 - \left[\frac{1}{1 + (NTU)_H}\right]$$

3. Pressure drop
   $\Delta P_H = \Delta P_1 + \Delta P_2$
4. Axial heat conduction
   $Q_{A,H} = Q_{A,1} + Q_{A,2}$
5. Net refrigeration effect produced is
   $Q_{NET} = Q_{th} - (Q_{I,H} + Q_{\Delta PH} + Q_{A,H})$

2.2. Design of Three-mesh Hybrid Regenerator

Similarly, we can Design thee-mesh hybrid regenerator. The optimization of Hybrid regenerator would require a continuous variation in mesh sizes or hydraulic diameter from hot end to cold end. The results of different combinations are compared for the performance prediction of three-mesh hybrid regenerator.

The selection of optimum proportion of each mesh matrix is the key area in designing three-zone hybrid regenerator. The optimum combinations serve the purpose of minimum thermal loss due to ineffectiveness, pressure drop and axial heat conduction.

1. Total length of thee-mesh hybrid regenerator.
   $L_1 + L_2 + L_3 = L$ mm
2. Mass of thee-mesh hybrid regenerator.
   $M_1 + M_2 + M_2 = M$ kg.
3. Total mass of mesh metrix.
   $M_m = (n' \text{ x } m)$
4. No of wire screens
   $N' = L/2\ d_w$
5. $M_m = (m / 2\ d_w)\ L = [P]\ L$
   $L_1 + L_2 + L_3 = L$ …(1)
   $(m_1/2\ d_{w1})\ L_1 + (m_2/2\ d_{w2})\ L_2 +$
   $(m_3/2\ d_{w3})\ L_3 = M$ …(2)

Above two equation are solved by gauss-elimination technique and the length of each sub-regenerator is calculated. The NTU of each regenerator is calculated separately. Therefore, Total NTU for regenerator can be written as,

$$NTU_{HYBRID} = NTU_{200} + NTU_{250} + NTU_{300}$$

$$\text{Effectiveness} = \varepsilon_{,H} = 1 - \text{Ineffectiveness}$$
$$= 1 - [1/(1 + NTU_{,H})]$$

Similarly, Pressure drop is calculated for hybrid regenerator.

$$\Delta P = \Delta P_1 + \Delta P_2 + \Delta P_3$$

2.3. Design Data

(i) Wire properties (200 size, Phosphor bronze)

$\rho_f = 8866$ kg/m^3.
$C_p = 376$ J/kg-K.
$k_f = 71$ w/m-K.
$\alpha_f = 0.076$ m^2/s
$d_w = 0.060$ mm
$\Phi = 0.668$
$\sigma = 0.368$, $\sigma' = 21.72 \times 10^{-3}$

(ii) Working Fluid (Helium gas)

$\rho_f = 3.86$ kg/m^3.
$C_p = 5198$ J/kg-K.
$k_f = 0.1052$ w/m-K.
$\alpha_f = 3.964 \times 10^{-06}$ m^2/s

(iii) Regenerator/Displacer:
Tube size =52 mm
Inner Diameter = 8.6mm
Wall Thickness = 0.10 mm
Material = S.S. (Stainless Steel)

(iv) Additional Data:
Temp. of Compression space, T_C=320 K
Temp. of Expansion space, T_E =80 K
Charging Pressure, P_c=16 bar
No. of regenerator Punch, n' = 520
Piston Diameter, D_p = 16 mm
Displacer Diameter, D_d =9.4 mm
Piston Displacement, X_p = 8 mm
Displacer Displacement, X_d = 3 mm
Piston to Displacer phase shift, $\theta=45^0$
Blow time =0.01 sec.

Two-Mesh Hybrid regenerators combination; Phosphor Bronze for both sub-regenerators.
150-250 (Hot end-Cold end) d_{w1}= 0.061, d_{w2} = 0.041
l_1=0.11, l_2 = 0.061
Wire size no = 46 for hot end,
Wire size no = 48 for cold end

Three-Mesh Hybrid regenerators combination; Phosphor Bronze.
200-250-300 (Hot-Intermediate-Cold)
Wire size nos.= 47-48-49.
Wire Dia. d_{w1}=0.061, d_{w2} = 0.061, d_{w3} = 0.040.
Mesh distance, l_1=0.098, l_2=0.108, l_3=0.050.

Table 1. Regenerator Effectiveness of Two-mesh and Three-mesh Regenerator

Regenerator Effectiveness ε	*Two-mesh Regenerator*	Three-mesh *Regenerator*
	0.9965	0.9977
Pressure Drop, ΔP (KN/m^2)	31.340	41.995
Heat loss due to pressure drop, $Q_{P,T}$ (watt)	0.1635	0.4335

Table 2. Geometric factors of wire screen.

Mesh size no.	Wire size no.	Pitch mm	Wire dia., d_m	Mesh distance l	Opening area ratio	Porosity φ
200	46	0.127	0.05	0.077	0.368	0.668
250	48	0.101	0.04	0.061	0.365	0.665
300	48	0.084	0.04	0.044	0.274	0.586

Table 3. Comparison of Results for Hybrid Regenerator

A. Mesh proportion = 25 %

Sr No	*3- Mesh Hybrid Regenerator*	Pressure Drop ΔP (kN/m^2)	NTU	Regenerator Effectivenes s, ε
1	150-200-300	31.74	347	0.9971
2	150-250-300	39.44	352	0.9972
3	200-250-300	45.34	366	0.9972

Table 4. Comparison of Regenerators effectiveness

Regenerator Effectiveness ε	*Two-mesh Regenerator*	Three-mesh *Regenerator*
	0.9965	0.9977
Pressure Drop, ΔP (KN/m^2)	31.340	41.995
Heat loss due to pressure drop, $Q_{P,T}$ (watt)	0.1635	0.4335

Above table compare the result of 2-mesh and 3-mesh Hybrid Regenerator. Appropriate mesh proportion is to be selected to minimum pressure drop and maximum effectiveness of the hybrid Regenerator.

III. CONCLUSIONS

This paper reports the detailed analysis and Design procedure of hybrid regenerator for Stirling cycle Cryogenerators. Effort have been made to computerize analysis, thus this paper opens new area in the field of Cryogenic regenerator. Using the same operating condition, hybrid regenerator is more effective then the Simple homogeneous regenerator. In this process using a N-mesh hybrid regenerator give minimum pressure drop and maximum Efficiency.

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