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Analysis of Effect of Regenerator Geometry and Material on Performance of Stirling Engine

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Abstract
In this research, an alpha Stirling engine having phase angle and air as a working fluid is investigated. Regenerator simulation is performed on various pressure ranges, mesh sizes, temperature ratios and engine speeds. The focus of research is kept on analysis of effect of regenerator length, wire mesh size, wire mesh arrangement, porosity of mesh and wire mesh material on regenerator effectiveness. The theoretical study is made for above parameters and simulated with software. Study concluded that increased regenerator length leads to decrease in pressure drop which results into reduction in break power of the engine. Pressure drop in oscillating flow is nearly doubles compare to pressure drop in steady one directional flow. Regenerator effectiveness increases with mesh size with expense of pressure drop. Engine speed play major role in convection heat transfer at regenerator wire mesh. Heat transfer at wire mesh is depends on flow velocity which should be moderate one, so that, maximum heat can be transfer by convection. Temperature ratio does not have significant effect on pressure drop in side the regenerator. Regenerator effectiveness is directly proportional to wire mesh size and inversely proportional to the temperature ratio.

Keywords: *Regenerator effectiveness, Matrix material, Pressure drop, Wire mesh size*

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NOMENCLATURE:

R_h- Hydraulic radius
D_w - Wire diameter
E - Regenerator effectiveness
K - Thermal conductivity of material
L_R- Length of regenerator
t_w- Thickness of wire
A_w- Area of wire
ΔT - Temperature difference
T_s - Temperature of the solid matrix at location x and time t
T - Gas temperature at location x and time t
A - Heat transfer surface area of the matrix
L_R- Length of regenerator
M - Mass flow rate of gas through the regenerator
V_g- Void volume or gas volume within the regenerator
m_s- Mass of solid material of regenerator
c_s- Specific heat of solid material
ρ_w- Density of wire material
Q - Heat energy supplied
ϑ- Kinematics viscosity of fluid
ρ_g- Density of gas
$\nexists$ - Porosity

I. Introduction

Stirling engine is a basically closed thermodynamic heat engine which operates on cyclic compression and expansion of working gas due to temperature difference, so that net conversion of heat energy to mechanical energy. The flow is controlled by volume changes due to movement of both pistons. This engine has many attractive features like high efficiency, low noise and it can work on almost every fuel. It has potential to achieve efficiency more than I.C. engine with the help of regenerator. Ignacio Carvajal et. Al.[2] state that, regenerator is nothing but a temporary thermal storage which alternately absorb and emits heat with respect to flow. This results into increment in engine efficiency as less energy is required from the source to expand the working gas and also less heat required to be rejected in the heat sink.Bancha Kongtragool and Somchai Wongwises [1] found that, Heat input and Thermal efficiency of engine is very much affected due to regenerator effectiveness. According to A. Asnaghi and S. M. Ladjevardi [6],the mainly requirement of regeneration in Stirling engine is to increase the thermal efficiency by reusing internal heat which would otherwise pass through the engine irreversibly. The Stirling engine was unable to achieved high efficiency without regenerator. Bancha Kongtragool and Somchai Wongwises [1] found that, the efficiency of engine decreases with increasing dead volume and decreasing regenerator effectiveness.

In simple word regenerator act as thermal flywheel, which storing additional heat in one part of the cycle and discharging it in next. The regenerator's role is simple and it made of compact structure to limit the dead volume. Normally regenerator is made of porous media and it used to place between heating and cooling heat exchanger shown in figure 1. The regenerator basically divided into two main types, i.e. fixed matrix regenerator and rotary regenerator. By going through literature survey it was found that many researchers suggest fix type wire mesh matrix regenerator because it is easy to fix, compact and has large effectiveness factor.

To understand the phenomena of heat transfer, imperfect regeneration, irreversibility and flow friction in Stirling engine regenerators, many analytical and experimental research have been conducted.Regenerator heat exchanger is made of number of wire mesh matrix placing one over other. That wire mesh matrix is normally available in the form of woven screen at variety of weave structures, wire diameter sizes, porosity, mesh density and material used. These wire mesh matrix are manufactured in standard sizes like 18#, 40#, 100 #, 200 #, 400 # etc. To improve heat transfer coefficient as well as to establish the minimum temperature difference between matrix and the fluid it is necessary to expose the maximum surface area of matrix, therefore matrix should be finely divided.Two kind of wire were arranged i.e. parallel to flow and perpendicular to the flow. Yoshitaka Kato et. al. [3] found that, the regenerator efficiency having meshed layered normal to the stream line of the working fluid was significantly more in comparison to that of the parallel mesh layers.

REGENERATOR'S EFFECTIVENESS

Regenerator effectiveness is a vital parameter to explain regenerator's performance which Christoph Bergmann and Josev Alberto explain analytically [4].

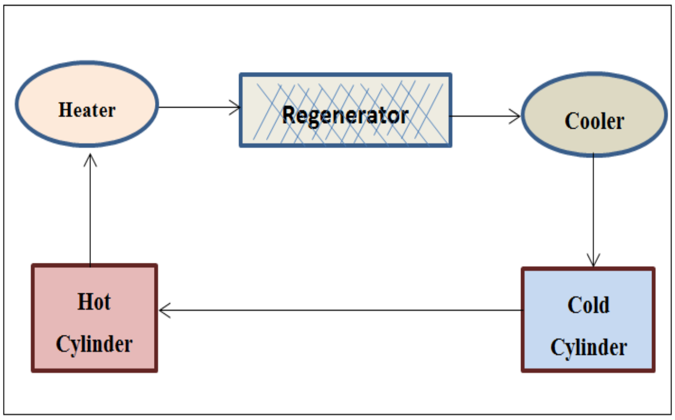

Fig. 1: Block diagram showing working fluid flow in the Stirling Engine

If the first law of thermodynamics is applied on differential element of gas flowing through the regenerator, then following equation obtained:

$$h(T_s - T)\left({}^{A}/_{L_R}\right)dx - mC_p\frac{\delta T}{\delta x} = \rho_g(V_g/L_R)C_p\frac{\delta T}{\delta t}dx$$

Heat transferred from to or from the gas is represents the first term on the left side of equation (4.1), and the second term on left side represent the change of enthalpy of gas in a length dx. The right side represents the change in energy stored within the element of gas equation. This also can be written following way:

$$T - T_s = -\frac{mC_pL_R}{hA}\frac{\delta T}{\delta x} - \frac{\rho_g C_g V_g}{hA}\frac{\delta T}{\delta t}$$

If first law applied to a differential element of solid material within the regenerator, the following equation is obtained:

$h(A/L_R)(T - T_s)dx = (m_s/L_R)c_s \frac{\delta T_s}{\delta t} dx$

The left side term of equation (3) represent the heat transferred to or from the matrix material, the right side represents the change in energy stored within the matrix. In this equation, the longitudinal heat conduction through the matrix is considered negligible. This equation (3) can be written in the alternate from as follows:

$$T - T_s = \frac{m_s c_s}{hA} \frac{\delta T_s}{\delta t}$$

The regenerator effectiveness is stated as,

$\in = \frac{\text{Actual enthalpy change of gas during a single pass through regenerator}}{\text{Equivalent maximum theoretical enthalpy change in an ideal regenerator}}$, $\in = \frac{T_3' - T_1}{T_3 - T_1}$

High regenerator effectiveness means it has high thermal drop and low pressure drop. Thermal drop I n the regenerator is depends upon the material property of wire mesh matrix. Relation of these material properties to regenerator effectiveness explain as follows:

These can be also written as,

$\in = \frac{Q}{C_{MIN}(T_{h1} - T_{c1})}$

The value of 'E' is mainly depend on two factors, i.e. material selection and regenerator design which is explain in following topics.

II. Material Selections

Material selection is very important phenomenon to work on regenerator effectiveness. Thermal conductivity is property of material which describes conducting capacity of material. Amount of heat flow through the material is directly proportional to the thermal conductivity. This stated as,

$k = \frac{Q t_w}{A_w \Delta T}$ It should be high enough to conduct heat from flow when engine working on high rpm and provide high heat transfer. Specific heat of the material is a prime property which is responsible to thermal drop. Wire Material should have high specific heat capacity to store maximum heat energy in short possible time. Heat energy store in the material is directly proportional to specific heat capacity. This a stated as,

$C_p = \frac{Q}{V \rho_w \Delta T}$

Thermal properties very much affected by oxidation of material. So, for better performance of regenerator for a long period wire meshmaterial should be corrosion resistance. Working temperature in Stirling cycle for expansion stroke is very high. Therefore, wires mesh material need to select which have high melting point

Table. 1. List of Material use for regenerator as per preference

Material	**K** $\frac{W}{m\,k}$	**ρ** $\frac{kg}{m^3}$	$C_p \frac{J}{kg\,k}$	**M. Pt.**°C
SS 304	26	8000	477	1400
Alumina	25	3720	880	2072
Nickel	67.49	8908	460.5	1455
Monel 400	22	8840	430	1299
Inconel 625	16.4	8497	460.5	1355
Aluminum	237	2712	902	501.6
Copper	390	8940	385	1082

SELECTION OF PARAMETER FOR WIRE MESH

For high regenerator effectiveness needs to design regenerator for high thermal drop and low pressure drop. Pressure drop in regenerator basically depend on two parameters such as geometry of wires mesh and porosity which explain as below.

a) Mesh geometry: There are two popular wire mesh geometry are used in regenerator i.e. hexagonal shaped and square shape wire mesh. Pressure reduction point of view square shape wire mesh matrix found effective also comparatively cheap due to simple in construction.Pressure drop in the regenerator inversely proportional to porosity of the wire mesh matrix. It is calculated by, Porosity = $\frac{\text{Void volume}}{\text{Volume of total screen}}$

Where void volume obtained calculated by, Subtracting total wire volume from total screen Volume.

For simplicity, calculation can be done on wire mesh having area 1 square inch. Also porosity can be calculate by equation given as,

$$∄ = \frac{2∍D_h^2}{R_{e_h}+C_f}$$

Where, C_f is a coefficient of pressure drop. These state that porosity increases pressure drop decreases. Investigation found that, porosity range in between 0.60 to 0.80 is better in pressure as well as thermal drop point of view.

b) Wire diameter: Beside material property thermal drop is very much depend on the wire diameter of mesh. It can be increase either by increasing wire diameter or by increasing fillfactor in the wire mesh. But, increased fill factor leads to higher pressure drop. Therefore, increase wire mesh diameter with suitable high porosity helps in both areas.

SIMULATION METHODOLOGY

The Stirling engine system with all necessary components was designed and data regarding working of engine at different operating condition is collected. Parameters like engine speed, pressure of working fluid and temperature ratio at hot and cold cylinder are prime focus to find out performance of regenerator. In case of regenerator designs following points are very important to consider,

Type of regenerator — Arrangement of wire mesh matrix

Shape of regenerator — Material of wire mesh matrix

Diameter of wire mesh — Porosity of matrix

In realistic world many parameters effect on regenerator effectiveness which is impossible to take in consideration at a time. So, to find the relation of design parameter and their results, the following important assumptions are made in regenerator design and simulation,

- The specific heats of fluid and matrix do not change with temperature.
- The fluid flow and temperature that is constant over the flow section.
- The thermal conductivity of the matrix material of regenerator is constant.
- The heat transfer coefficients and fluid velocities are constant with time and space.
- The pressure drop across the regenerator is negligible.
- The rate of mass flow is constant.
- The working gas is assumed to be a perfect gas.
- The gas flow in duct is one-dimensional.

To find the regenerator effectiveness, it is mandatory to know the value of heat transfer coefficient.

$h = \frac{Nu.k}{L_R}$

With the help of Nusselt number it can be calculated. Gedeon and wood [7] derive the equation of Nusselt number by using Peclet number which is indirectly correlated with Reynolds number.

Nu= $(1+0.99P_e^{0.66})∄^{1.79}$ Friction factor correlate with Reynolds number 0.45 to 6100:

$ff = 0.5274 + \frac{68.556}{\text{Re}}$

Relation of the wire diameter, hydraulic radius and porosity of the wire mesh matrix is given by,

$\text{R}_\text{h} = \frac{\text{D}_\text{w}}{4}.\frac{∄}{(1-∄)}$

This porosity of wire mesh matrix can be calculated by formula,

$∄ = 1 - \frac{1}{4}\pi.m_w D_w$

Reynold number of the fluid crossing the regenerator can be calculated by hydraulic radius where mean air velocity is known.

$Re = \frac{4\rho u_{mean}R_h}{\mu}$ Also $Re = \frac{u_{max}D_h}{\vartheta}$

Where, u_{max} is the maximum fluid flow velocity through cross-section. Also, Prandtl number is need, to calculate Peclet number.

$$P_r = \frac{C_p\mu}{k}$$

So, Peclet number is given as, $P_e = R_e = P_r$

By using equation (11) and (18), Nusselt number can be calculated. The heat transfer rate inside the regenerator can be calculated with the help of heat transfer coefficient. Heat transfer rate inside regenerator having inside area, A_{IR}, across the two end having different temperature can be calculated by,

Q= $-\text{h}\cdot A_{IR}\cdot (T_H - T_C)$

Geometry of regenerator has very important role in pressure loss. Length of regenerator is directly proportional to the pressure drop inside the regenerator. Friction factor and Pressure loss in the circular duct is given by equation (15) and (16) respectively as,

$$f_D = \frac{16}{R_e}$$

$$\Delta P_D = f_D \frac{4L_R}{D_h} \left({}^{1}/_{2}\, \rho \cdot u_{mean}{}^{2} \right)$$

Also, to calculate Friction factor of the wire meshes is,

$\Delta P_w = {}^{1}/_{2} ff \cdot n \cdot \rho \cdot u_{mean}{}^{2}$

So, friction with wire mesh as well as friction with duct wall is responsible for total pressure loss, which can be calculated by summation of these two terms. In regenerator design total friction should be try to minimize.

$\Delta P = {}^{1}/_{2} ff \cdot n \cdot \rho \cdot u_{mean}{}^{2}$

III. Result And Discussion

Simulation carried out on Stirling engine having phase angle 90° and compressed air used as working fluid. Purpose of simulation to know the effects of parameters like wire mesh size which has constant wire diameter 0.5mm and engine rpm effects on regenerator effectiveness, also the parameters responsible for pressure drop.In fig.2 shows the relationship between the wire mesh size with Reynolds number and state that with mesh size increase Reynolds number decrease. Fill factor of wire mesh introduce obstruction to streamline flow through the regenerator. Pressure Drop noted in different mesh size when oscillating flow circulated through virtual model and compared their results with basic one dimensional steady flow by applying friction factor by equation, these results shown in Fig.3 which state that pressure loss in oscillating flow is nearly doubles as compare to pressure drop in steady one directional flow, ΔP. Where, $\Delta P_{mean}$is cycle-averaged pressure drop.

In equation shows regenerator length has directly effect on pressure drop which results into loss of break power of the engine by increasing dead volume. Figure 4 shows that initially regenerator length helps to increase BP by saving effort of temperature source due to regenerator effect which was dominated over pressure drop and dead volume effect. But, later on with increase regenerator length, pressure drop and dead volume leads to decrease BP of the engine. Pressure drop is inversely proportional to the regenerator diameter. So, it is always better to increase regenerator diameter than regenerator height if possible.

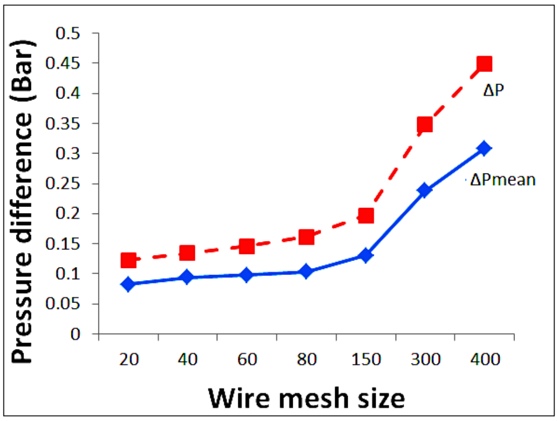

Fig.2: Effect of Wire mesh size on Reynolds number

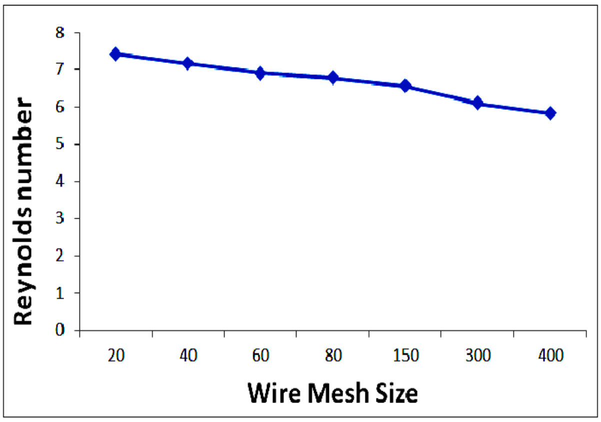

Fig.3 : Effect of Wire mesh size on Pressure difference

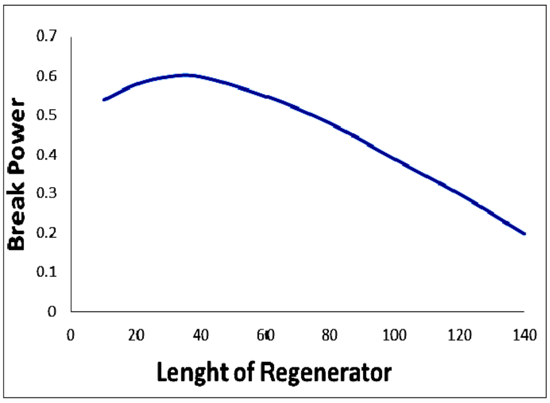

Fig. 4 :Effect of Regenerator length on Engine Break Power

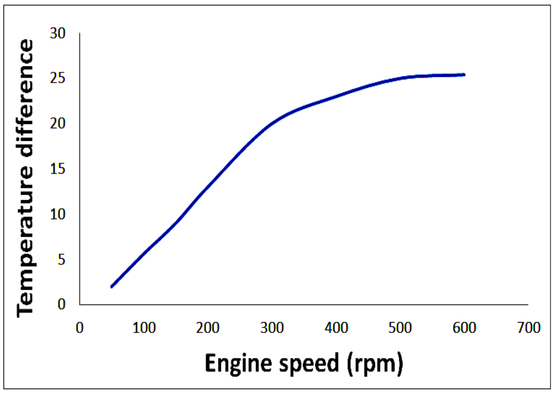

Fig. 5: Variation of Temperature differenceat regenerator both end

Temperature drop inside the regenerator is mainly depend on the number of wire mesh screen inside the regenerator and velocity of flow passing through numbers of Wire meshes screen. In simulation hot end temperature took as 900°C and 60 wire mesh screen. Figure 5 shows the heat exchange in the regenerator is initially increase with speed up to certain level due to better convection. But, more increase in rpm leads to reduce heat transfer time which results into reduction of regenerator effectiveness. Temperature of fluid has minor effect on pressure drop in regenerator. Figure 7 stated that as temperature ratio increases pressure drop increases. So, minimum temperature ratio gives lesser pressure drop as compare to temperature ratio 0.42, 0.37 and 3 results.

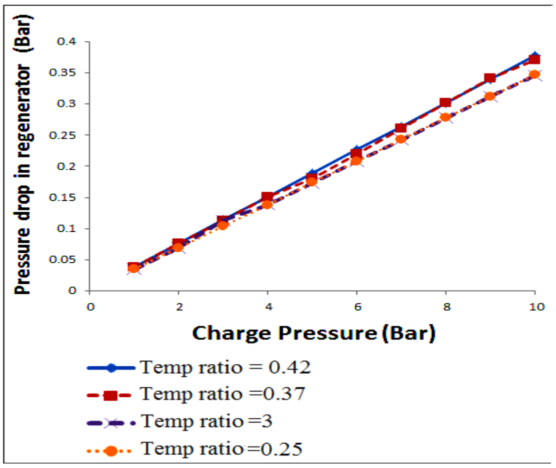

Fig. 6 : Variation in Pressure drop inside the regenerator with respect to charge pressure at various temperature ratio

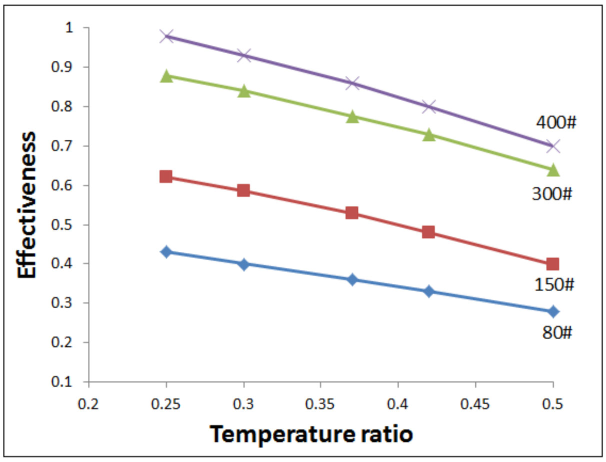

Fig.7 : Effect of Temperature Ratio on Regenerator Effectiveness

Figure 7shows the relation between various wire mesh sizes with regenerator effectiveness at various temperature ratios. Result indicates that wire mesh of 400# gives major heat transfer effect due to more heat transfer area.

IV. Conclusion

Selection of wire mesh size is very important parameter in regenerator design. It's strongly effect on pressure and Reynolds number of fluid flow. Result shows that most preferable range for wire mesh size is 200# to 400#. Increased regenerator length shows drastically change in pressure drop which results into reduction in break power of the engine by increasing dead volume.so, the optimize regenerator should has minimum length and moderate porosity which offers less possible pressure drop and high temperature drop. Heat transfer at wire mesh is depends on flow velocity which should be moderate one, so that, maximum heat can be transfer by convection. Temperature ratio does not have significant effect on pressure drop inside the regenerator.

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