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Design and Analysis of Solar Powered Stirling Engine (Alpha- Configuration)

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ABSTRACT: The following paper briefs with the design process of Solar Powered Stirling engine. A Stirling engine consists of rapid heating and cooling of a gas within piston/cylinder device. It is an external combustion engine since the heat applied externally and there is no exhaust or intake. Instead of using conventional fuels we have set out to utilize power of the sun to provide necessary energy input to the system. Also this engine is capable of utilizing air as a working fluid. The main purpose of the project is to promote the use of Stirling engines in 'Green and Clean energy' applications. For future solar energy generation research Stirling engines are of prime importance as it has high theoretical efficiencies.

KEYWORDS: Design, Solar Powered Stirling engine, Green and Clean energy.

I. INTRODUCTION

Stirling engine is an external combustion engine invented by Robert Stirling in 1816. Like any heat engine, the Stirling engine goes through the four basic processes of compression, heating, expansion, and cooling. Stirling engine runs directly on any available heat source, whether it be solar, geothermal, nuclear or waste heat from industrial processes. In this engine initially, air is compressed using work stored in the mechanical flywheel from a previous cycle. The working fluid is subjected to different temperatures so as to convert total heat energy into mechanical work. The working fluid is in thermal equilibrium. The main advantage with this engine is that it can operate with any heat source. These engines are suitable for concentrated form of solar energy which is inexhaustible.

Main aim is to design and develop a Stirling engine for 0.186 kW capacity. The Stirling engine is analysed using second order cyclic analysis approach. This includes the calculation of theoretical power output and heat input under pre-decided conditions. It also includes calculation of losses in the power output and heat input. The engine considered is a double cylinder, alpha-configuration (90deg out of phase) operating with Air as the working fluid with mean pressure of 4.78 bar, speed 600 rpm with air temperature range of 723 K to 773 K. The present status of the work indicates that the estimated thermal efficiency of the engine will be around 60%. The development will provide the electrical output of 0.186 kW or 0.1 HP. This may be used for lighting, fans, charging the storage batteries, and also for running small capacity pumps for irrigation application in remote areas.

There are many issues involved in exploring the possibilities of Stirling engine like as material selection, operating temperature, effective design, Material selection for fabrication is important and has to be considered during the design stage itself. The materials are selected referring to the applicability as given in Design of Machine Elements by V.B. Bhandari.

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II. DESIGN OF ENGINE COMPONENTS

Following given are the components that are required either to search a component of similar standard dimensions or to fabricate.

- **Frame:** The frame is used to support piston cylinders, flywheel connected shaft and other rotating parts. The frame was fabricated using mild steel plate which is cheap, sustains the required design and is easy to machine. Frame is brought to its shape with the help of cutter and grinder and circular holes are drilled by means of drilling machines. Bearings are provided inside the supports the crankshaft.
- **Piston:** The material selected for piston is aluminium alloy to ensure its thermal properties for the hot cylinder assembly. But due to machining complications it is preferred to acquire machined piston of standard dimension that suits the design requirements.
- **Cylinder:** The cylinder barrel and cylinder casting are of high grade C.I. -20 and the fins on the cylinder casting are made of copper and have vertical orientation for better heat transfer.
- **Crankshaft:** The crankshaft provides base for mounting of crank-weight and crankpin and connecting rod on it. The crank-weight and crankpin are machined on lathe machine out of cast iron and mild steel respectively. Whereas the connecting rod of material cast iron is acquired for standard dimension suitable to the design assembly.

III. DESIGN CALCULATIONS

Mechanical and thermodynamic design calculations by considering power output from the engine(reversed calculation to acquire the diameter of cylinder used in this configuration)

Step 1) Power Required by the Engine

Power application = 0.1hp

Load Factor, $k_f = 2.5$

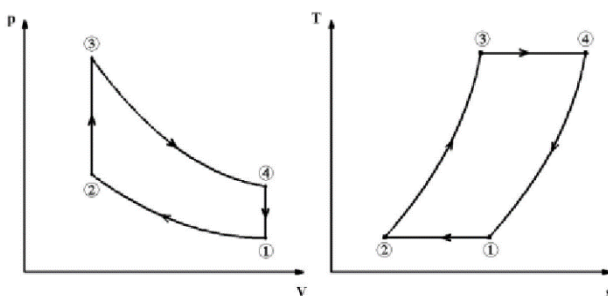
Design Power, $P_d = 0.25 \text{ HP}$

Therefore,

$$P_d = 0.186 \times 10^3 \text{ Watt}$$

$$P_d = 0.186 \text{ KW}$$

Step 2) Stirling Cycle



Process Involved :

1-2 : Isothermal Compression ($T_{\min}$)

2-3 : Constant volume heat addition

3-4 : Isothermal expansion ($T_{\max}$)

4-1 : Constant volume heat rejection

$$\begin{aligned} \text{Therefore,} \quad &= 500^\circ\text{C} \\ &T_{\max} = 500^\circ\text{C} \text{-----} \\ &T_{\min} = 37^\circ\text{C} \end{aligned}$$

(The temperature calculation is done for every month using the reference of insulation values provided by MNRE and by the use of fundamentals of solar geometry and thermodynamics and heat transfer relationships.)

Step 3) Selecting working fluid as [AIR]

Parameters, $R = 0.287 \text{ KJ/kgK}$

$C_p = 1.005 \text{ KJ/kgK}$

$C_v = 0.718 \text{ KJ/kgK}$

Gamma = 1.4

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Step 4) Work Done

$$\text{Work Done} = Q_1 \times \eta_{th}$$

Where Q_1 = heat added in the cycle

η_{th} = thermal efficiency

$$\eta_{th} = \frac{T_{max} - T_{min}}{T_{max}} \text{ Taking } T_{min} = 37^\circ\text{C} \text{ -----}$$

$$= \frac{(500 + 273) - (37 + 273)}{(500 + 273)}$$

$$= 60\%$$

(considering the lower temperature of cold cylinder during actual working condition)

$$\eta_{th} = 0.60$$

Therefore,

$$Q_{in} = \frac{\text{Work done}}{\eta_{th}}$$

$$= \frac{186}{0.60} = 310 \text{ J/s}$$

$$Q_{in} = 310 \text{ Watt}$$

Step 5: Calculation of actual mass in the system

$$Q_{in} = m_{act} \times C_v \times (T_{max} - T_{min})$$

$$310 = m_{act} \times 0.718 \times 10^3 ((500 + 273) - (37 + 273))$$

$$\text{Therefore, } m_{act} = 9.3251 \times 10^{-4} \text{ kg/sec}$$

Step 6: Calculation of volume

$$P_{atm} \times V_{comp} = m_{act} \times R \times T_{atm} \text{ (Ideal gas equation)}$$

$$\text{Where, } P_{atm} = 1.01325 \text{ bar}$$

$$T_{atm} = 27^\circ\text{C or } 300\text{K}$$

$$m_{act} = 9.3251 \times 10^{-4} \text{ kg/sec (mass of air is constant in the system)}$$

$$1.01325 \times 10^5 \times V_{comp} = 9.3251 \times 10^{-4} \times 287 \times 300$$

$$\text{Therefore, } V_{comp} = 7.92 \times 10^{-4} \text{ m}^3/\text{sec}$$

Step 7: Calculation of Initial Pressure

$$P_i \times V_{comp} = m_{act} \times R \times T_{summer}$$

$$\text{Where, } V_{comp} = 7.92 \times 10^{-4} \text{ m}^3/\text{sec}$$

$$T_{summer} = 37^\circ\text{C or } 310\text{K}$$

$$\text{Therefore, } P_i = \frac{9.3251 \times 10^{-4} \times 287 \times 310}{7.92 \times 10^{-4}}$$

$$P_i = 1.04753 \text{ bar}$$

Step 8: Calculation of swept volume

$$V_{act} = V_{compression} = \eta_v \times V_s \times \frac{N}{60}$$

$$7.92 \times 10^{-4} = 0.75 \times V_s \times \frac{600}{60}$$

$$V_s = 1.056 \times 10^{-4} \text{ m}^3/\text{rev} = 1$$

$$V_s = \frac{\pi}{4} \times d^2 \times l$$

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$$1.056 \times 10^{-4} = \frac{\pi}{4} \times d^2 \times d$$

Therefore, $d = 0.0512 \text{ m} \cong 51.2 \text{ mm}$

$l = 0.0512 \text{ m} \cong 51.2 \text{ mm}$

Therefore, the internal diameter of cylinder

Bore = 51 mm

Stroke = 51 mm

IV. HEAT SOURCE

As the title indicates, the input heat source is solar power. In here a concentrating type Fresnel collector is used to focus the solar rays on the surface of hot cylinder. For the perfect working of the engine the temperature gradient of 400degrees Celsius is required between the hot and cold cylinder. In this case, the temperature of 500degree Celsius is to be obtained on the cylinder head with the help of Fresnel lens. The temperature calculations are carried out by using Stefan Boltzmann's law considering the mean monthly global solar radiant exposure for Nagpur.

V. SIMULATION AND RESULTS

The diameter of cylinder is obtained using the calculation procedure of other engine components are designed respectively and analysis is being done on them. As a result the components are found to be safe and within the safety factor limit. Type of analysis method used is static structural and transient thermal.

The table shown below contains the various material physical properties used to fabricate engine components, so that the simulation and analysis result will be comparable with respect to its reading scale value shown.

Main Components	Type of analysis	Material	Ultimate tensile strength Mpa	Yield tensile strength Mpa	Poisson's ratio	Density Kg/m ³	Modulus of elasticity Gpa	Thermal conductivity W/mk
Frame	Static structural= To analyse the component under the behaviour of static loading considering in increasing order	Mild steel (low carbon steel)	841	247	0.3	7850	207	45
Cylinder casting with fins & Connecting link	Static structural= To analyse the part under designed pressure Transient thermal= To analyse the component under thermal loading condition	Cast iron IS200 FG	152 263(for different grade)	130 180(for different grade)	0.23	7800	67	47-80
piston	Static structural= To analyse the part under designed pressure Transient thermal= To analyse the component under thermal loading condition	Aluminium alloy	607	386	0.32	2700	70	76
Crank shaft	Static structural	Cast iron IS 200 weight with mild steel pin	152	130	0.2367	7800	67	47-80

Analysis software = ANSYS 16.0
Analysed Components and properties:

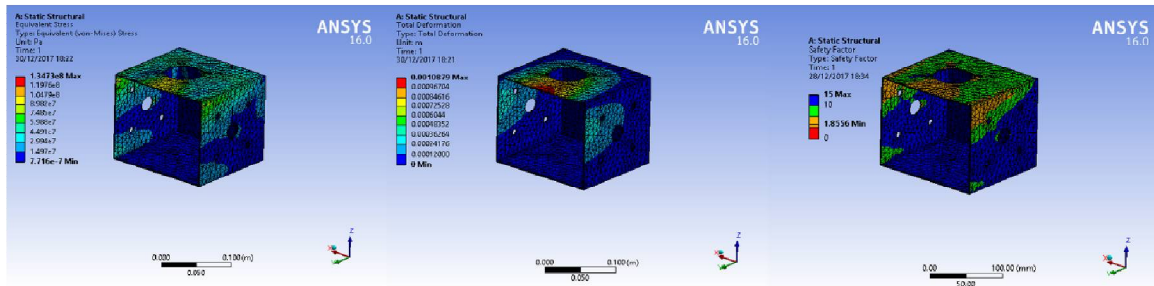
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FRAME

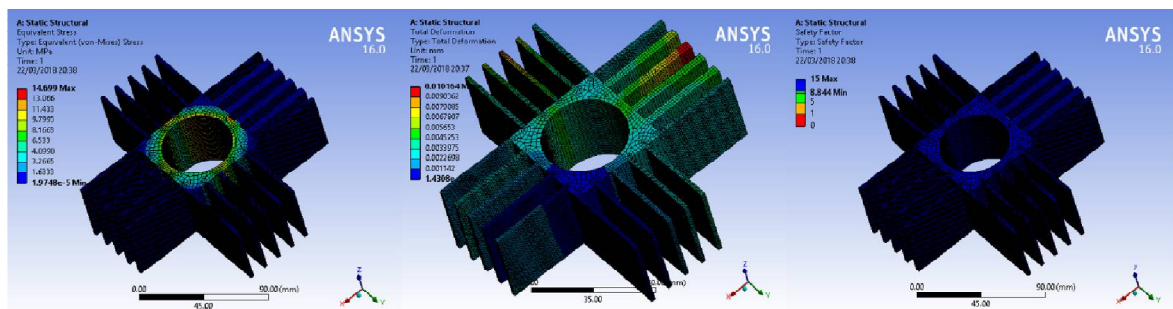


Frame = The frame is analysed as it is asupporting part for all the engine components.The forces are calculated accordingly by considering the maximum thrust and pressure ratio build up inside the barrel and piston arrangement . The force obtained by considering the crankshaft assembly as a simply supported beam.And we used these forces as boundary condition for frame analysis.

RESULT

Induced stress MPa	Allowable stress MPa	Safety factor
134.73	247	1.85

CYLINDER CASTING



There are two cylinder block is used in alpha configuration with same dimension one is of hot and another is of cold side, the hot side cylinder casting is designed and considered as cuboidal body with internal barrel of CIIS 200FG with inside 15to 25 R_a . The boundary conditions are applied in such a way that; it consider the maximum pressure waves thatdistribute a load over the entire internal volume of the barrel.

RESULT

Induced stress MPa	Allowable stress MPa	Safety factor
130	152	8.84

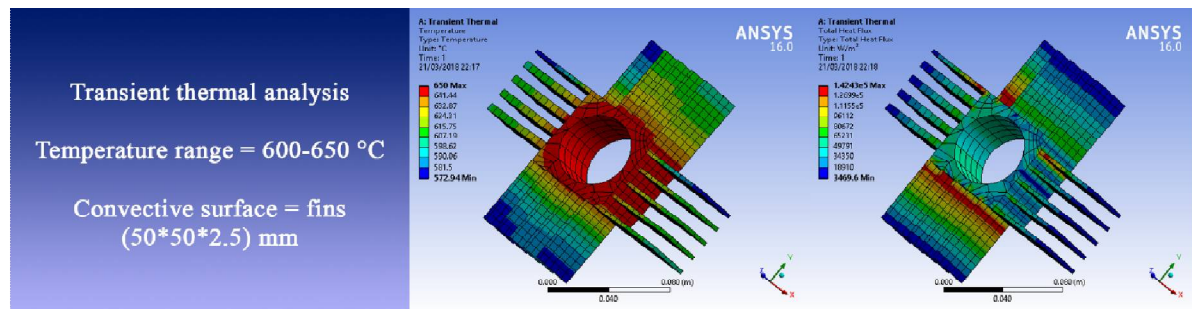
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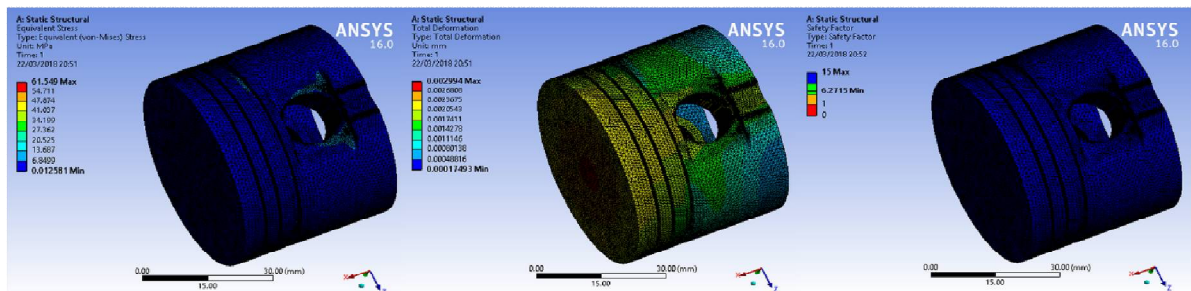
CYLINDER CASTING



Heat transfer analysis of cylinder casting with fins.

The maximum temperature inside barrel is considered to be 650 degree using convective surface as fins of (51*51*2.5) mm for the effective heat rejection from the cold cylinder, number of fins are 5. Situated each one side faces of cuboidal casting

PISTON



Piston = As per the manufacturing complexity taking standard OEM part, which was satisfying our dimensional requirements. The boundary condition applied during analysis process is, taking the displacement along x-y-z axes as zero, and maximum thrust pressure is applied on the top face of the piston.

Result-

Induced stress MPa	Allowable stress MPa	Safety factor
61.54	386	6.27

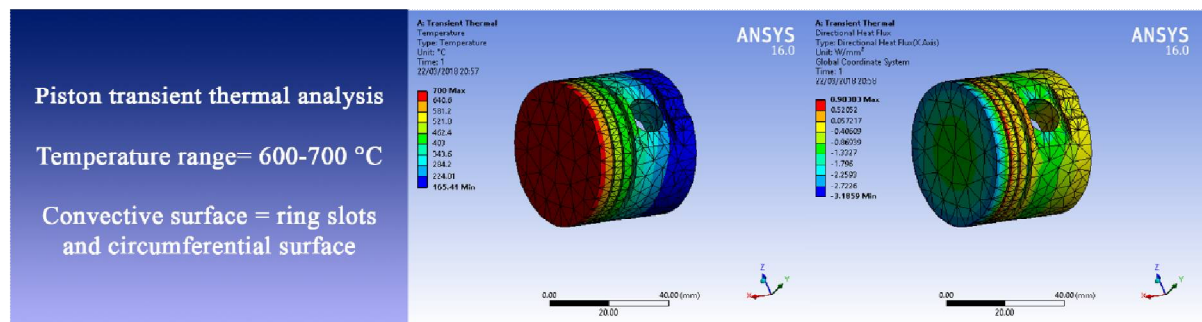
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PISTON

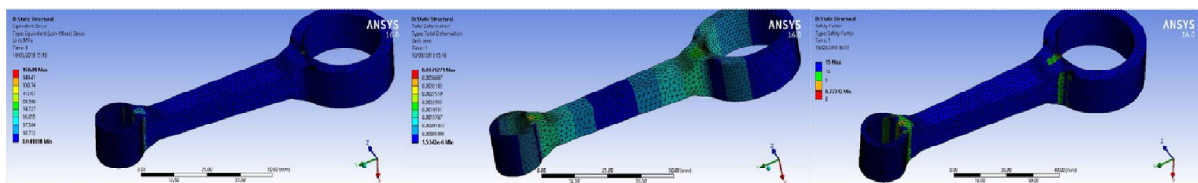


Transient thermal analysis of piston structure

Consider the piston top face is at maximum temperature i.e., 700 degree .and here we have to identify heat flux generation and flow of heat through the material structure within 1sec.

The convective surface are ring glands and the circumferential faces and bottom portion.

CONNECTING ROD



Two connecting links are used to actuate the piston for effective rotation of crankshaft.

The boundary conditions are such i.e., the displacement along X-Y-Z axes would be taken as zero and the forces are applied along a longitudinal axis of shorter end of connecting link,the force are radially inward opposed through the material.

RESULT

Induced stress MPa	Allowable stress MPa	Safety factor
168	180	1.73

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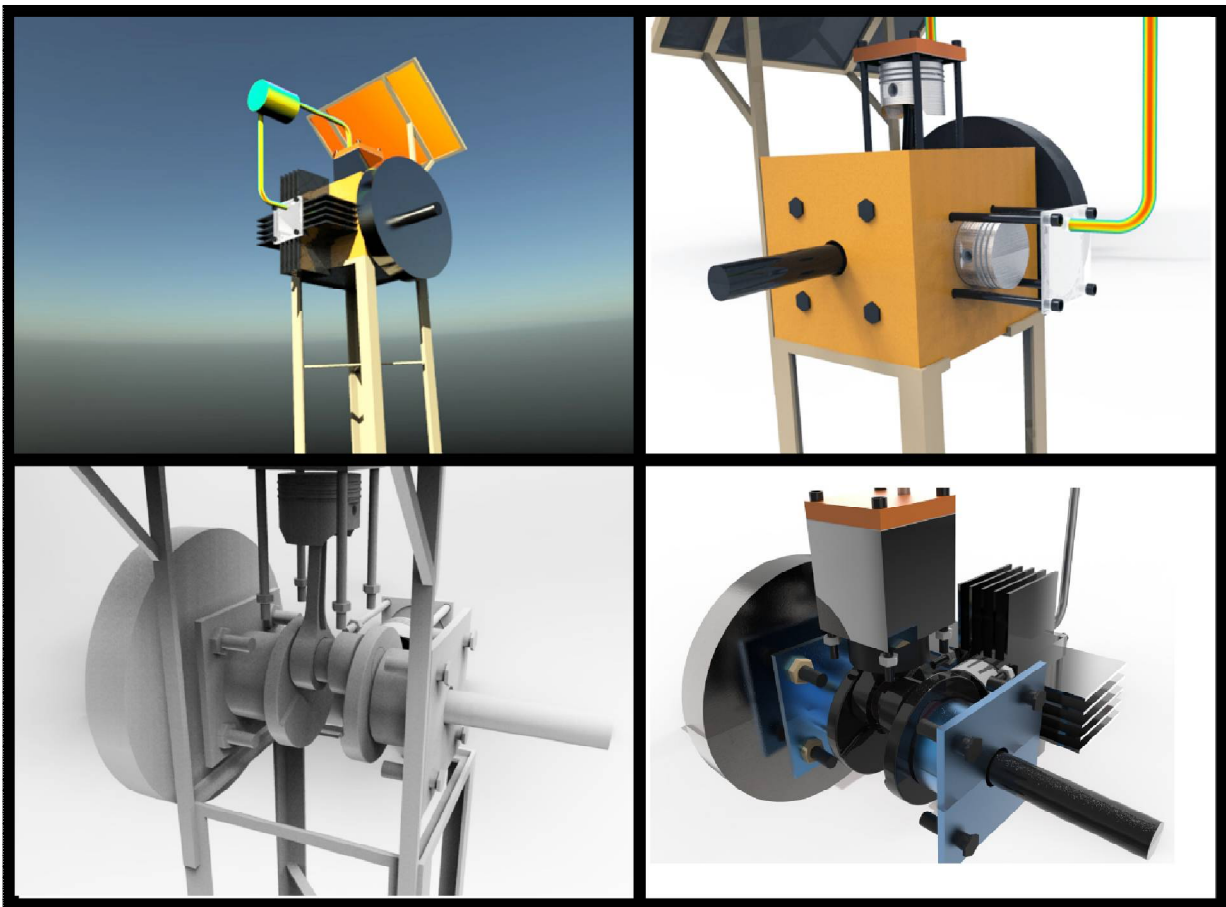
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VI. RENDERED FILES

RENDERINGS



VII. CONCLUSION

The objective of designing an alpha type Stirling engine using input heat from solar power to minimize usage of fuel and reduce air pollution was successful.

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