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# Sun-Powered Stirling Engine: Design and Feasibility Study

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**ABSTRACT:** The aim of this paper is to explore the utilization of the Stirling engine, which operates by heating and cooling a gas within a piston/cylinder device utilizing an external heat source, specifically the power of the sun. This unique engine has the ability to use air as the working medium, promoting the use of clean and green energy sources. Due to their high theoretical efficiencies, Stirling engines are of great importance for future solar energy generation research. In this paper, we estimate the heat flux provided by a solar concentrator and its effect on producing the necessary working temperature ratio of the Stirling engine. The remaining analysis is accomplished both theoretically and empirically. Additionally, critical components of the Stirling engine are analyzed to ensure safe operation.

**KEYWORDS:** Concentrator, analysis, design, solar, renewable energy.

## I. INTRODUCTION

We created a model of Stirling engine which generate electricity by heating through with wood waste, biomass and solar heating by solar concentrator. This inventive concept would capitalize on both available energy sources, promoting environmental sustainability. We called this the HYBRID CONCEPT. The privilege of this engine is that it can be easily manufactured and therefore buying cost of a product is not a big deal for individuals. Initially during design stage, our goal was to achieve an engine arrangement that could reach about 150 rpm and generate a potential of approximately 40 Watts.(Approximately). We believed that this output would be sufficient to power a few energy-saving bulbs, and also charging and operating a few android device and other electronic devices. It does have significant advantages such as operating house light, grocery store services and providing energy to other important places. The impact on the community would be significant, as this initiative would provide a reliable and sustainable power.

- **Extracting the sun's energy**

We integrated a parabolic solar concentrator into our solar heating system, which is designed to work in conjunction with a Stirling engine. The solar concentrator is a equipment that focus solar energy at one point by using reflective dish by this intensity of solar radiation can be aggrandize at sufficient level in order to achieve high temperature to heat container or chamber which in turn going to convert this energy in to electricity. Proper functioning of these concentrators requires the tracking of the sun. In our case, we employed a parabolic dish as the concentrator, which is same as used in solar cookers. When the sun is directed towards a three-dimensional parabola, all the light that comes into contact with its mirrored surface is reflected towards a focal point. By placing a black cooking pot or container at this focal point, it is able to absorb the energy from the light and become very hot.

## II. RELATED WORK

The Stirling cycle is a well-established air cycle for heat engines that has been shown to have high efficiency and the ability to utilize a wide range of fuels for heating. Previous studies have recognized the potential of Stirling engines in order to provide relentless energy as a form of power from 6 to 20 kW for water pumps and electricity generation in countries [5,6]. Compared to similar Otto and Diesel engines, Stirling engines have a higher thermal efficiency of 40% [1,2].

The cycle in Stirling is basically cycling expansion and compression of working medium at various temperatures [7-11]. A direct method for estimating power dissipation of Stirling engine was developed within TFS framework [12-16], and has been validated on the top 12 performing world's Stirling engine [12,13,17].

By this estimation, a unique appraisal artifice for effective working of Stirling Engine settled in addition considering external and internal irreversibilities. [12,13,18-21]. These developments have a potential to aggrandize substantially both power output and efficiency of the engine, making them even more viable for practical applications. The purpose of this paper is to review and discuss these recent advancements in Stirling engine performance computation, with a focus on the TFS framework and its implications for Solar Stirling engine technology.

### III. METHODOLOGY

- Design

#### First revision design

The design, which had superior kinematics and provided the most accurate simulation on a computer, is shown in the figure below with the specific dimensions given. However, it is important to note that this first version of the design was not implemented because the connectors used in the design were deemed too complex to manufacture. Design changes to the heating components were also required to prevent the system from overheating.

Specification:

- Bore Diameter = 4 cm  
(Used for calculation of maximum axial thrust)
- Piston rod diameter = 5 mm  
(To find factor of safety of piston rod subjected to maximum pressure)
- Length of cylinder = 13 cm

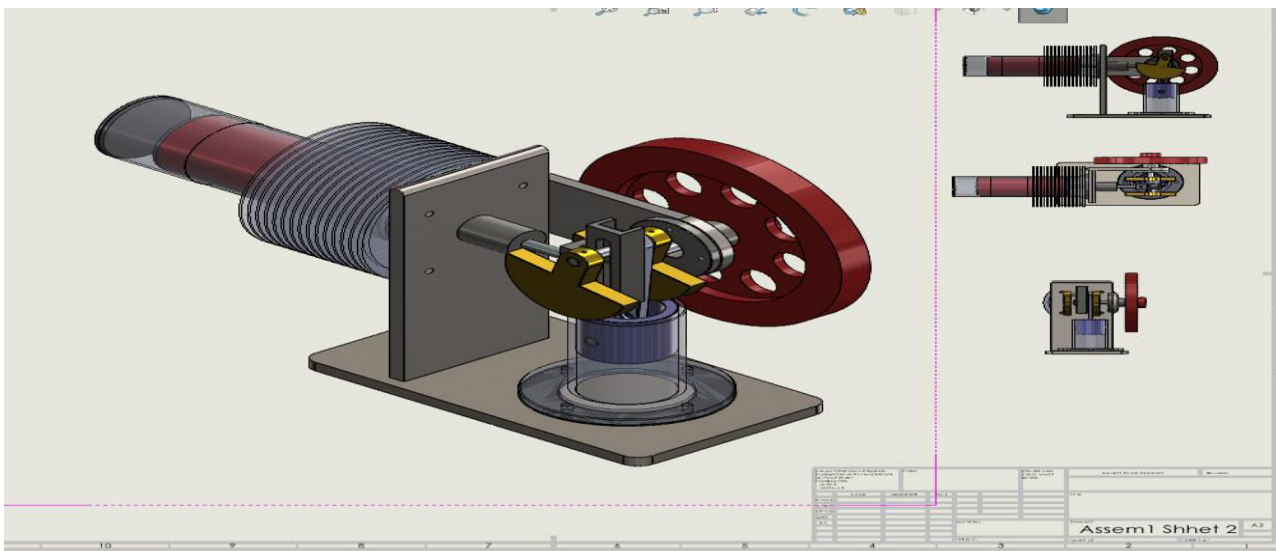


Fig 1: CAD Model of Stirling Engine

**Second revision** - Final design Integrated with Solar Concentrator, which is perfectly aligned such that the sun rays directly emerges on the front plate made of thermally conductive material.

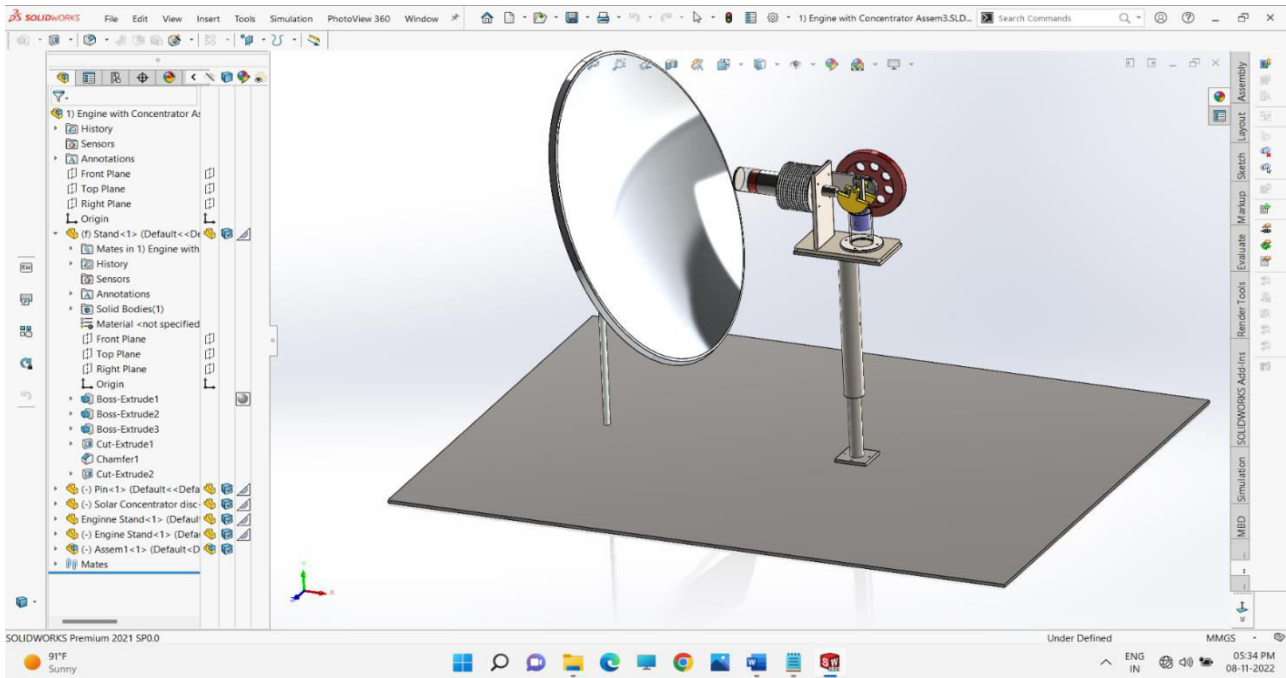


Fig 2: CAD Model of Stirling Engine with Concentrator

IV. CALCULATION AND RESULTS

• Calculations for Concentrator Efficiency

For calculation of incoming heat flux and concentrator efficiency; For the purpose of this study, a parabolic reflecting mirror with a 50 cm diameter and a 6 cm depth has been selected. The dish is shaped using a parabola on a rectangular coordinate system, where the vertex is positioned at the origin and the focus is located on the positive y-axis. By mathematical relations,

The form of the equation of the parabola is  $x^2 = 4ay$  and its focus is at (0, a). Since (25, 6) is a point on the graph, the equation is

$$25^2 = 4 a(6)$$

$$625 = 24a$$

Hence, the heat source will be 26 cm from centre vertex of the dish in direct line of sight toward the sun.

Now, for the calculation of **Concentration ratio**

$C/R = \frac{\text{Aperture Area } A1}{\text{Receiver Area } A2}$ . Approximate Aperture area  $A1 = \pi R^2$ , where R = 25cm (radius of concentrator). Receiver Area  $A = \pi r^2$  where r= 2cm (radius of bore or receiver of engine) Concentration ration to be **C/R = 156** (approximately).

**Parabolic concentrator Performance :**

Firstly a general range of working temperatures are estimated let the Solar receiving end provides a  $T_H = 650- 700$  K(High temperature Source) and a heat sink at temperature  $T^0 = 300-350$ K ,  $\eta = \eta_{\text{receiver}} - \eta_{\text{Carnot}}$ .

Where,  $\eta_{\text{Carnot}} = 1 - T^0 / T_H$  and,  $\eta_{\text{Receiver}} = (Q_{\text{Absorbed}} - Q_{\text{Lost}}) / Q_{\text{Solar}}$ .

Where  $Q_{\text{solar}}$  = incoming solar flux,

$Q_{\text{Absorbed}}$  = Fluxes absorbed,

$Q_{\text{Lost}}$  = heat lost by receiver.

Estimating peak solar heat flux  $I = 1300 \text{ W/m}^2$  which is concentrated by 156 times with an Optical efficiency  $\eta_{\text{optics}}$  on





the solar receiver ,

$$\begin{aligned} \text{(solar heat flux)} Q_{\text{solar}} &= \eta_{\text{optics}} ICA. \\ \text{(heat flux absorbed)} Q_{\text{Absorbed}} &= aQ_{\text{solar}}. \end{aligned}$$

Here, a = Absorptivity of the Steady receiver (standard value =0.15),  $\xi$  = Emissivity = 0.05.

For the calculation purpose of efficiency We assumed the Source temperature to be 700K and the sink temperature to be 300K , Later by getting value of efficiency We can Estimate the net heat flux inlet at the Receiver which is ,

$$Q(\text{Flux}) = Q(\text{absorbed}) - Q(\text{lost}) = \text{Efficiency} \times Q(\text{solar}) .$$

Where,

$$\text{Max Solar heat flux } Q(\text{solar}) = \text{concentration Ratio} \times \text{Max Solar Intensity on earth's surface } (1300\text{W/m}^2)$$

Here in Calculations, I = Intensity of radiation, C = Concentration Ratio,  $\sigma$ = Stefan Boltzmann Constant

Assumptions are made for the heat losses and other modes of heat transfer are neglected with compared to radiation heat transfer , By Stefan-Boltzmann law :  $Q_{\text{lost}} = A\xi\sigma T_H^4$

Substituting these equations to the overall efficiency equation and assuming perfect optics for simplicity ( $\eta_{\text{optics}} = 1$ )

$$\begin{aligned} \eta &= (\sigma - \xi\sigma T_H^4 / IC) (\eta_{\text{Carnot}}). \\ \eta &= 8.37\% \end{aligned}$$

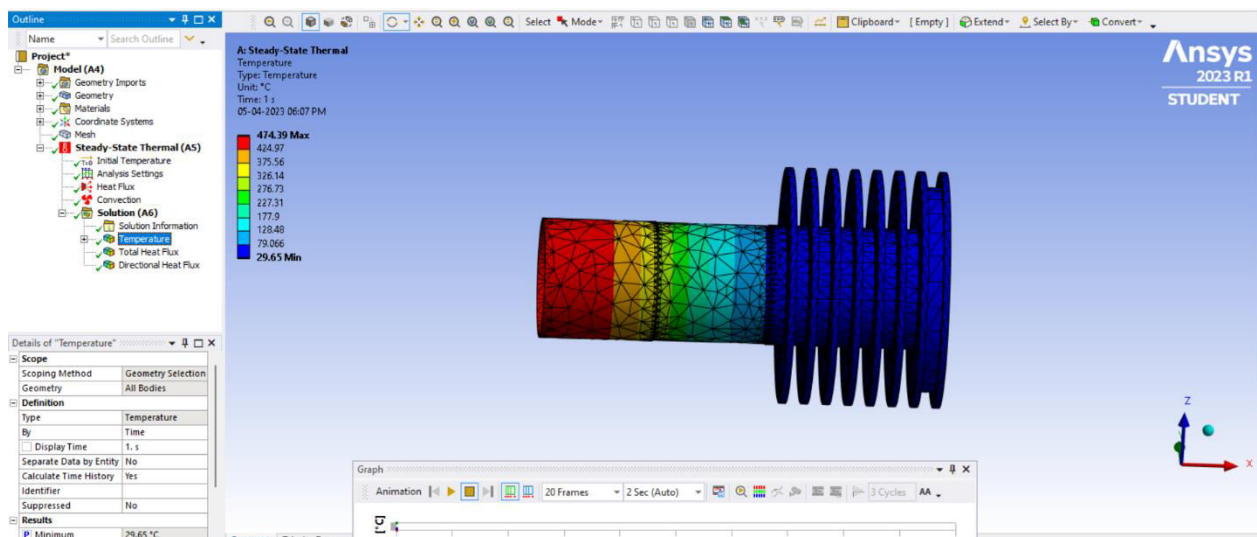
Now, we have got efficiency and we can estimate steady state heat flux at receiving end,

$$Q(\text{flux}) = 0.0837 \times 156 \times 1300 = 16974.36 = 17000 \text{ W/m}^2 \text{ (approximately).}$$

Heat flux analysis can be seen in figure 3 and figure 4.

This incoming heat flux can be used to estimate cylinder temperatures by using **Steady state thermal analysis using ANSYS STUDENT** , this temperature limits approximates actual working temperature limits of Stirling Engine and the Further Calculations Will be done by using this temperatures only.

- **Thermal analysis of cylinder and the piston using ANSYS**



**Fig (3);** Here As we can see temperature distribution for the known heat flux and we get approximately same results as we were expecting from mathematical analysis. Here high temperature end has temperature of **474.4** degree Celsius (=747.4K) and the low temperature end has temperature of **29.65** degree Celsius (=302.65K) . In our Analysis Convective film Coefficient is taken to be **h= 20 W/m2K** (Standard value of air in open environment where mild flow of air is considered)

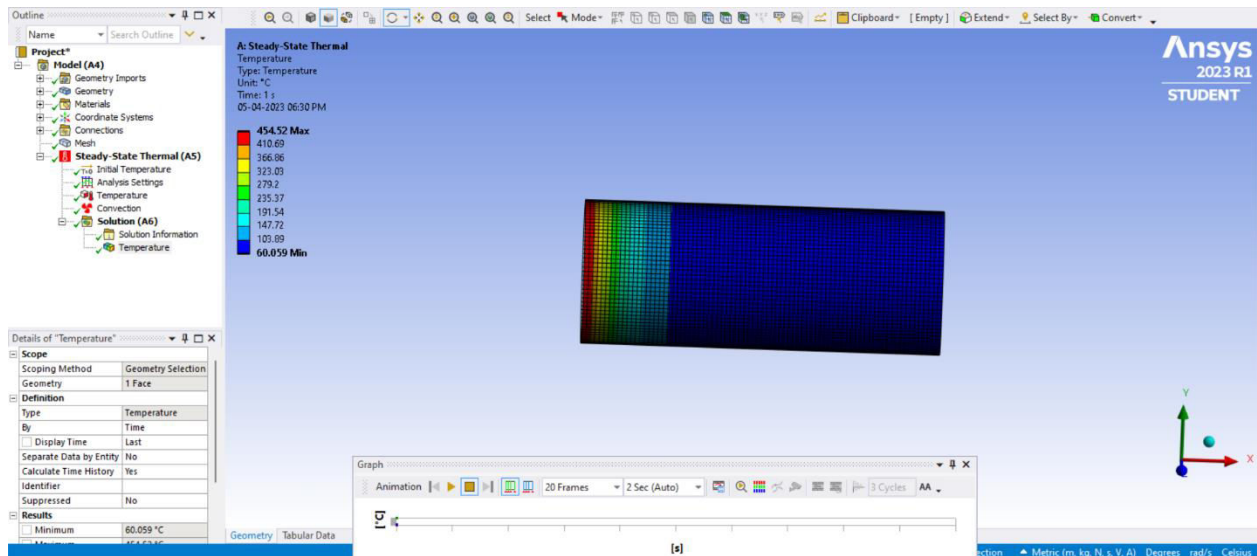


Fig (4); Thermal analysis of piston material also shows that the air at colder end of piston is well insulated from the air at colder than , which will ensure the efficient working of Stirling Engine.

• **Calculation of Power Output and RPM of Our Model.**

From reference book we used mean effective pressure analogy to estimate power output from the temperature ratio and the compression ratio, the value of compression ratio is approximated to be 6 in our model.

Assuming we achieved a temperature ratio of 474 °C:30 °C (hot to cold)

$$W_o = (1 - (rt)(rv) \ln|rv| / |rt|(Y-1))$$

$$W_o = |1 - 0.405| \times 6 \times \ln |6| / (0.405 \times 0.4) = 40 \text{ Watts.}$$

Based on the temperature and compression ratio assumptions, it is projected that the Stirling engine being studied will produce an output of roughly 40 Watts. Notably, the volume values are derived from the model parameters, whereas the temperature values align with the desired specifications..

The feasibility of using the Beale equation to analyze the performance of a Stirling engine is demonstrated in a reference book:

The power output from Stirling engine can also be estimated in theory by Beale equation.

$$\text{Power output } |W| = N_b \times P_{\text{mean}} (\text{Mean effective Pressure}) (\text{Mpa}) \times \text{Swept volume } (\text{cm}^3) \times R \text{ rotational speed } (\text{Hz})$$

Where,  $N_b$  is the Baele number = 0.1112. with the swept volume of 13 cm long and 2 cm radius, By calculating Swept volume will be = 163.36  $\text{cm}^3$  .

According to empirical research conducted on Stirling engines, assuming an internal mean effective pressure of 1 MPa in the power cylinder, and the power output projected is 40 W.

Now ,It's Rotational Speed will be ;

$$40 = 0.1112 \times (1 \times 10^6) \times (125.7 \times 10^{-6}) \times R.$$

Therefore  $R=2.86\text{Hz}$  which gives  $N = 171.6 \text{ RPM}$ .

• **Stress analysis of Engine Components**

To obtain Stirling Engine output power by using empirical relations and CAE results has been accomplished. Given that the mean effective pressure is 1 Mpa, we have analysed the impact of this pressure on the critical components of our engine using Static structural analysis in ANSYS Mechanical. Our aim was to determine whether these components would operate safely within the specified limits.

Maximum Stress Induced = 54 Mpa. Allowable Stress = 380, Factory of Safety=7

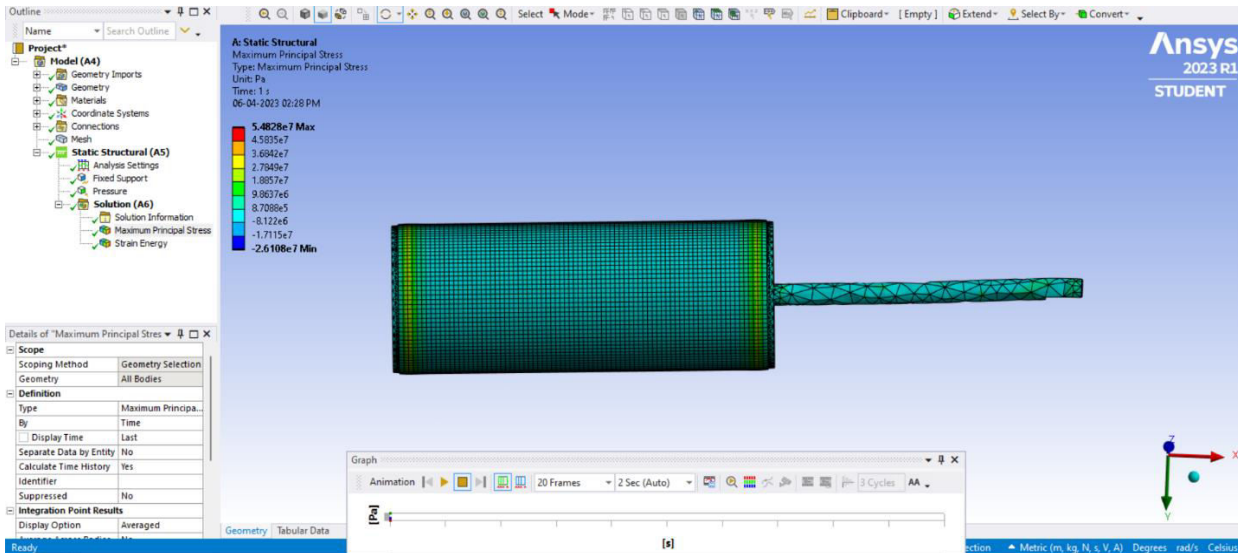


Fig 5: Static structural analysis over engine components.

Here is the more accurate analysis Of piston rod bearing the pressure load from the piston, Maximum stress = 157 Mpa, Allowable Stress = 210, Average Stress = 63 Mpa, Factory of Safety=1.34

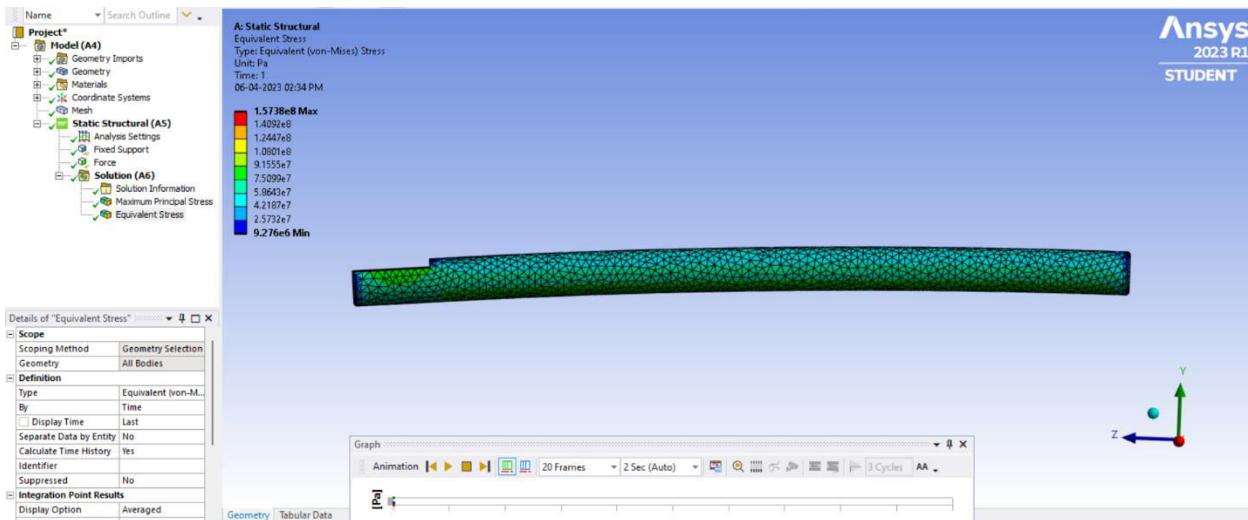


Fig 6: Static structural analysis over engine components.

## V. EXPERIMENTAL RESULTS

Our model has an engine swept volume of 168.36 cm<sup>3</sup>, with a hot-to-cold temperature ratio of 474:30 (in degrees Celsius). The mean effective pressure in the power cylinder is estimated to be 1 MPa, and the engine is expected to generate a power output of 40 Watts while operating at 148.63 RPM

From the above findings the suction flow rate of air in the cylinder will be approximately,  $V = 1000e-6$  m<sup>3</sup>/sec .

Efficiency = Work output /Energy input. (The formula of engine efficiency). The power absorbed by the system was estimated by using temperature difference between the heated part and the thermal energy input per second = air mass x air Cp x delta T. For Air mass calculation:

(M) Mass = Density ( $\rho$ ) x volume ( $v$ ) .

Hence, taking  $\rho = 1.2 \text{ kg/m}^3$ , Specific heat capacity,  $C_p = 1005 \text{ J/kgK}$  ,

$v = 1000 \times 10^6 \text{ m}^3$ , temperature change,  $\Delta T = |474-30| = 444\text{K}$ .

As we know , the  $P = 40 \text{ Watts}$ . Therefore, the efficiency is:

Engine Efficiency  $= 40 / 535.46 \times 100 = 7.47\%$

## VI. CONCLUSION

The proposed work is environmental friendly and cost effective. The heat flux provided by the solar concentrator and the analysis of operating temperature ratio of the Stirling engine is successfully done and a corresponding theoretical and empirical results of the engine are also taken into consideration to perform the stress analysis of the components of stirling engine to ensure its safe working.

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