# Design And Analysis Of Stirling Engine For Underwater Application

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**Abstract -** Selection of power systems for underwater vehicles is an important task. The power system must be compact enough to fit inside the vehicle and it should supply sufficient power. *This paper presents thermodynamic analysis of the Stirling engine based on schmidt analysis for underwater application. Alpha type engine with opposed cylinder configuration is selected. After the analysis, Dimensions for each component are selected followed by structural analysis of engine components.*

***Key Words*: Stirling Engine, thermodynamic analysis, underwater application, cooler, Regenerator, Unmanned vehicle.**

## 1. INTRODUCTION

Stirling Engine is a closed cycle heat engine in which no external air is required which makes it ideal for underwater application. The silent operation of it makes the vehicle more stealthy which makes the engine attractive for military applications. In the 2005 war games, USS *Ronald Reagan*, a newly constructed $6.2 billion dollar aircraft carrier, was sunk after being hit by multiple torpedoes. This torpedo was launched by Sweden's submarine named "Gotland". Gotland snuck past uss ronald reagan defenses. Americans never saw it coming and Yet despite making multiple attack runs on the *Reagan*, never saw it leave. Previously, diesel submarines could only navigate with noisy diesel engines powered by air and stay underwater for a few days. As a result, diesel submarines were most vulnerable while snorkeling and could be easily tracked. On the other hand, submarines fueled by nuclear reactors require large amounts of coolant to prevent a meltdown. Hence pumping of coolant creates noises and vibrations which can be easily detected by SONAR. The Swedish Gotlands uses a 75 KW stirling engine which is an External combustion engine. Therefore frequent combustion does not take place while operation and there is gradual compression and expansion of working gas which makes it more silent.

Stirling Engines can be used for the underwater vechicles that can operate underwater with or without a human occupant. They can be used for surveillance and other missions that require very quiet operation. A closed-cycle heat engine has potentially better overall energy density than available battery systems. For example, 100 mile range, Submersible with 2m Diameter and 10m Length operating at 10 Knots for 1 hour requires 200 KW-Hr of energy. If we use a 35W-hr/Kg lead acid battery, We would require 6 tons of it. Above requirement can be fulfilled by the 15 kW, 100 kg stirling engine. Although the weight of the reactant storage must be added to this, the total propulsion package with a Stirling could be lighter than the propulsion package with advanced batteries.

Among Alpha, Beta, Gamma type stirling engines, Alpha type is more efficient and has more power density. So that, Alpha type stirling engine with opposed cylinder configuration is designed. In this type of configuration, Instead of displacer, Two separate cylinders are used. One is connected to the heater and the other is connected to the cooler. Regenerator between heater and cooler acts as a heat reservoir.

### 1.1 Aim Of The Work

The purpose of this article is to design the Stirling engine and its various components as well as the analysis of the engine (strain, stress, deformation). Theoretical thermodynamic analysis was also performed for the engine.

## 2. METHODOLOGY

Work took place in three stages, first the Stirling engine was modeled by Schmidt analysis using ratings taken from various references. Then it was modeled and then partially imported in analysis software where structural analysis is performed.

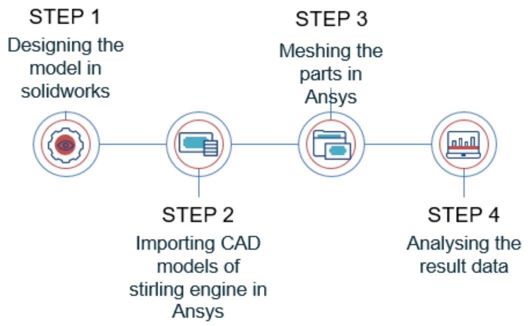

**Fig -1**: Mind Map

## 2.1 Theoretical Analysis

Opposite cylinder configuration type is selected for the design for the optimum use of volume inside the vehicle. Schmidt's analysis is used to model the system. This analysis is still used today as the classical analysis of the Stirling cycle.

Following are the assumptions for this analysis:

- working fluid obeys ideal gas law
- Engine is perfectly sealed and there is no working fluid leakage. Thus total mass of working fluid is constant
- Temperature in each working space (compression, Expansion) is known and there is no temperature gradient
- Engine is running at constant speed
- Uniform instantaneous pressure in the working space

Following are some of the parameters selected for the engine:

Stroke = 60mm
Crank radius (r) = 30mm
Clearance length = 4 mm
Bore Diameter (D) = 52.4 mm
$T_c$ =350K
$T_h$ = 923 K
n = 1200 rpm

$V_{regen}$ = 154 cm$^3$
$D_{regen}$ = 60 mm
$L_{regen}$ = 4 $V_{regen}$ / π $D^2_{regen}$
$L_{regen}$ = 54.46mm

Now, Let's find out variation of working volumes with crank angles

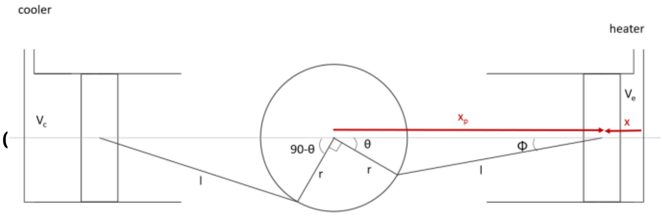

**Fig -2**: Engine system Configuration

$$Xp = r\,cos(\Theta) + l\,cos(\phi)$$

$$sin\phi = r\,sin\Theta / l$$

$$cos\phi = \frac{\sqrt{n^2 - sin^2\theta}}{n}$$

$$x = r(1 - cos\theta) + r(n - \sqrt{n^2 - sin^2\theta})$$

$$Ve = \frac{\Pi}{4} D^2 r(1 - cos\theta) + r(n - \sqrt{n^2 - sin^2\theta})$$

Similarly, we can find out variation of compression volume with crank angle

$$Vc = \frac{\Pi}{4} D^2 r(1 - sin\theta) + r(n - \sqrt{n^2 - cos^2\theta})$$

Mass of the gas

$M = (P_{atm} V_{total\,(max)}) \div (R\,T_{initial})$

Where,
$P_{atm}$ = 101325 N/m$^2$
$V_{total\,(max)}$ = 372.63 cm$^3$
$T_{initial}$ = 293.15 k
R =287 J/kg-k

M = 0.4375 g

$M_{total} = M_e + M_c + M_{regen}$
$M_{total} = P/R\,(V_e / T_e + V_r / T_r + V_c / T_c)$

$P = M_{total} R / (V_e / T_e + V_r / T_r + V_c / T_c)$

$T_r = (T_h - T_c) / \ln(T_h / T_c)$
$T_r$ = 590.9 K

## 2.2 Flywheel Design

Torque developed by expansion piston on crank will be given by-

$T_e = r\,F_p\,[\sin\theta + \sin(2\theta) / 2\sqrt{[(n^2 - \sin^2\theta)]}]$
Where,
$F_p = \pi/4\, D^2\, P$

Torque developed by compression piston on crank will be given by-
$T_c = r\,F_p\,[\cos\theta + \sin(2\theta) / 2\sqrt{(n^2 - \cos^2\theta)}]$

Total torque (T) $= T_e + T_c$

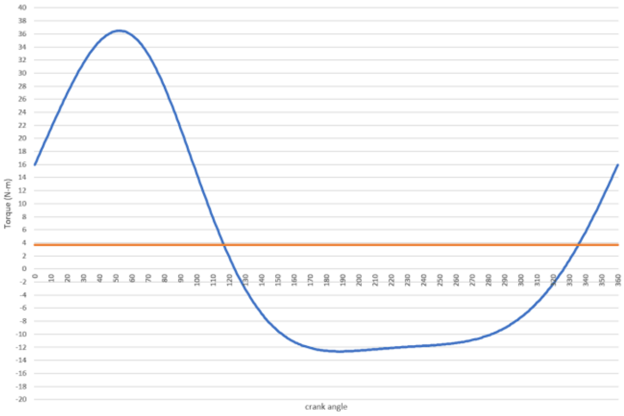

**Chart -1**: Turning moment diagram

Work developed by the engine = work require for an application

Area of turning moment diagram = $T_{mean}$ 2pi

$T_{mean}$ =Area of turning moment diagram/2pi
$T_{mean}$ =22.88/2pi = 3.64 Nm

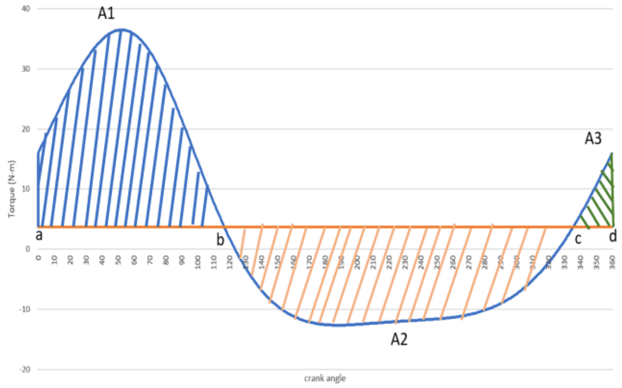

**Chart -2**: Turning Moment with Area

A1 = 45 Nm
A2 = 46.85 Nm
A3 = 2.5 Nm

Let energy at point a be E
A : E
b : E + A1
c : E + A1 - A2
d : E + A1 - A2 + A3 = E

Maximum fluctuation of energy -
ΔE = maximum energy - Minimum energy
ΔE = energy at b - energy at c
ΔE = (E + A1) - (E + A1 - A2)
ΔE = A2 = 46.85 Nm

Coefficient of fluctuation of speed($C_s$) = 0.03
Solid disk type flywheel is selected
Maximum fluctuation of energy in flywheel = $\frac{1}{2} I w^2 C_s$
$\Delta E = \frac{1}{2} I w^2 C_s$

Where,
W = 2 pi n / 60 = 125.66 rad/s

I = 0.098 Kg-m²

$I = M (R_o^2 - R_i^2) / 2$
$M = \rho\, \pi\, (R_o^2 - R_i^2)\, t$

$I = \rho\, \pi\, (R_o^2 - R_i^2)^2\, t / 2$

ρ = 7800 kg/m³ (carbon steel)
$R_i$ = shaft radius = 10mm
t = 10 mm

$R_o$ = 31.53 mm

## 2.3 Cooler

For cooler, Equivalent model was designed using ansys and the analysis is carried out. Taking the regenerator temperature as the inlet, We must achieve the temperature of 350K. The surface area is calculated which can produce that much temperature difference. Following parameters are taken for the analysis:

**Table -1: Specifications**

| Parameters | Specifications |
|---|---|
| Cooler temperature | 20-30⁰C, Average : 25⁰C |
| Heater temperature | 923K=650⁰C |
| Heating method | liquid oxygen and diesel to create the heating of the engine in the |

| | |
|---|---|
| | combustion chamber. |
| Cooling method | cold seawater |
| material | copper |
| tube diameter | 300 mm |
| shell diameter | 1000 mm |
| length | 4000 mm |

It was observed that surface area of 0.2827 $m^2$ is sufficient to produce the temperature difference

## 2.4 CAD Modelling

### Piston

The pistons of the Stirling engine are hermetically sealed and are driven to move up and down as the gas inside expands. We use gray cast iron material for piston.

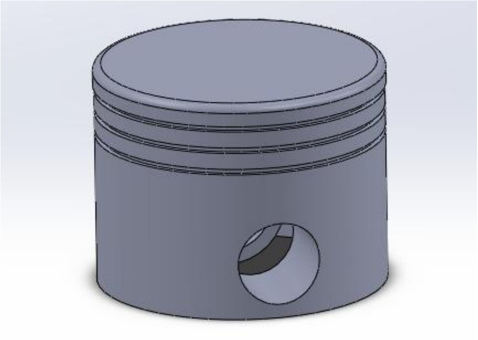

**Fig -2**: Piston CAD Model

### Connecting Rod

A device used to connect two moving parts, where it is used between the crankshaft and the piston. Here we have used carbon steel material for it.

**Fig -3**: Connecting Rod CAD Model

### Flywheel

The design of the flywheel is done in the previous section. It is used to minimize the fluctuations in the output power. Carbon steel is used as a material

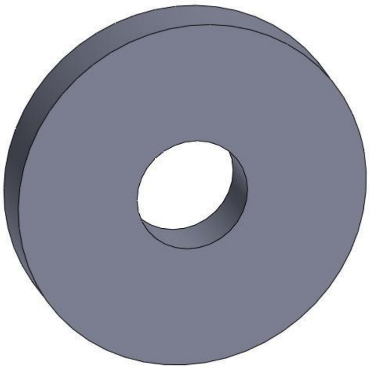

**Fig -4**: Flywheel CAD Model

### Gudgeon pin

The Gudgeon/piston pin is used to connect the piston to the connecting rod. It also provides a bearing on which the connecting rod rotates as the piston moves.

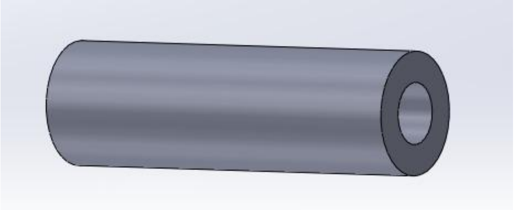

**Fig -5**: Gudgeon Pin CAD Model

### Regenerator

In a Stirling engine, the regenerative is an internal heat exchanger and a heat reservoir temporarily placed between the hot and cold spaces so that the working fluid passes through it first in one direction and then in the other. Its function is to retain in the system heat that would otherwise be exchanged with the intermediate temperature medium at the maximum and minimum cycle temperatures. Copper is used as a material.

**Fig -6**: Regenerator CAD Model

### Engine housing

An engine house is a structure that holds the moving parts.

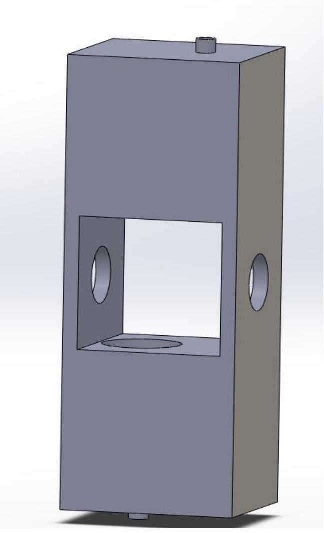

**Fig -7**: Engine housing CAD Model

### Spur Gear

Spur/Cylindrical gears are used in mechanical applications to increase or decrease the speed of equipment or multiply torque by transmitting motion and power via a belt drive.

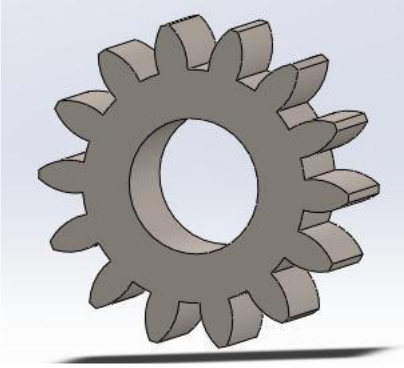

**Fig -8**: Spur gear CAD Model

### Crankshaft

The shaft through which the mechanical work is transferred from the piston to the flywheel.

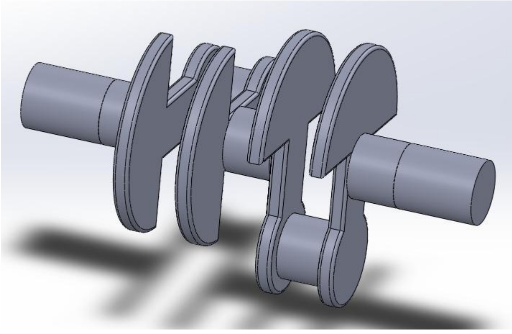

**Fig -9**: Crankshaft CAD Model

### Bearing

A bearing is a part of machinery that limits motion relative to only the desired motion and reduces friction between moving parts.

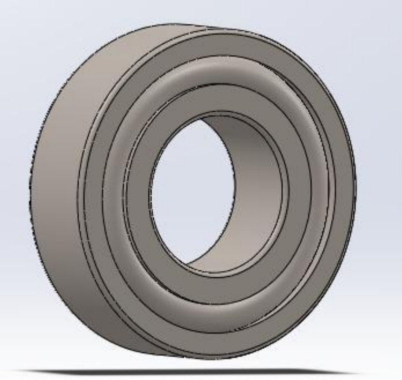

**Fig -10**: Bearing CAD Model

### Pipe

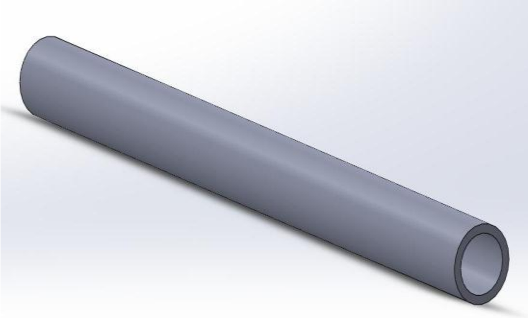

**Fig -11**: Pipe CAD Model

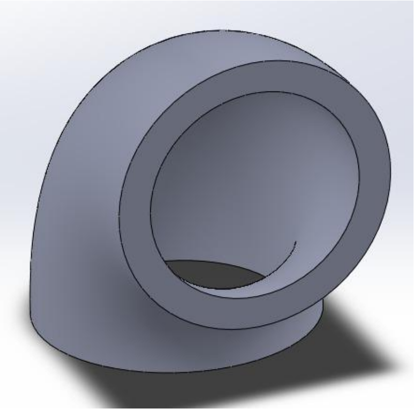

**Fig -12**: Pipe bend CAD Model

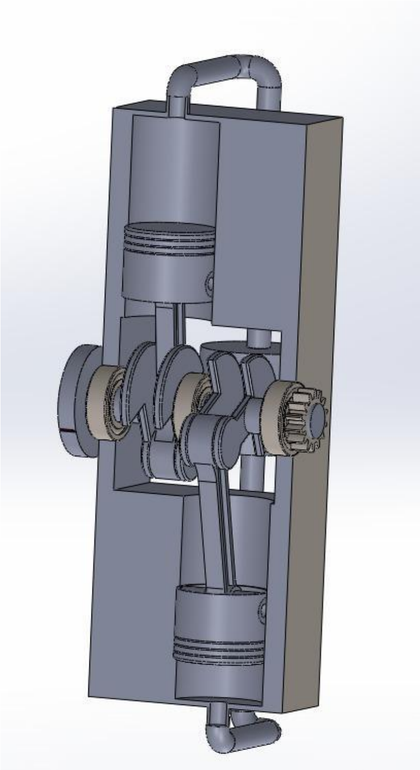

**Fig -13**: Assembly Section View

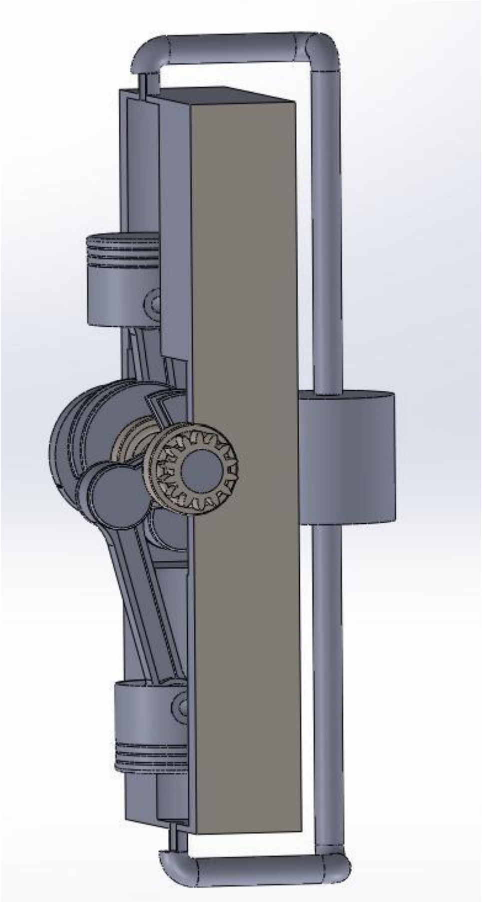

**Fig -14**: Assembly side view

## 3. RESULT

### 3.1 Theoretical Thermodynamic Results

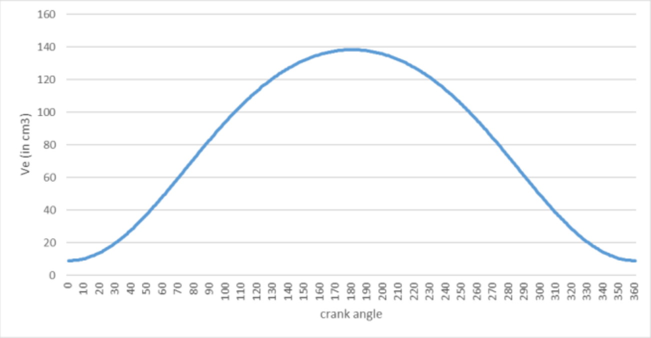

**Chart -3**: Variation of Expansion Volume with Crank Angle

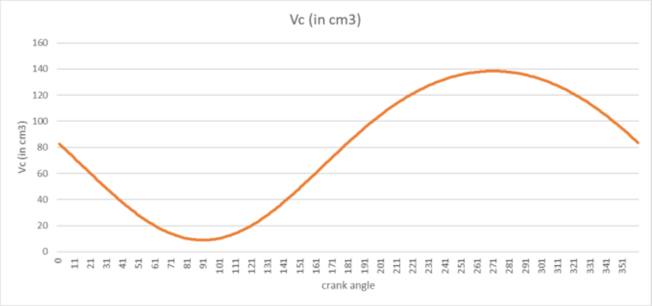

**Chart -4**: Variation of Compression Volume with Crank Angle

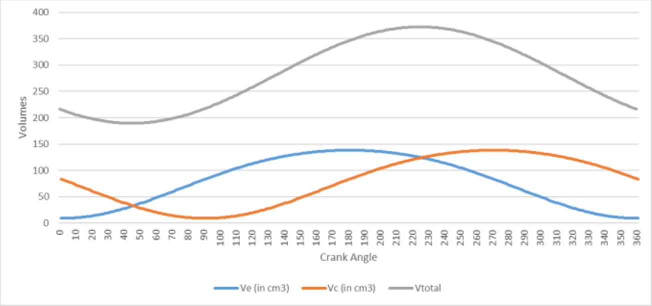

**Chart -5**: Variation of Total Volume with Crank Angle

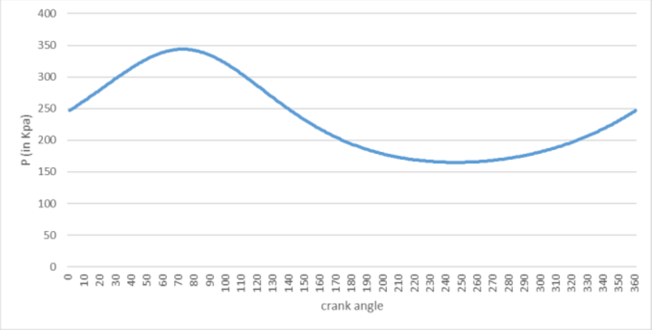

**Chart -6**: Variation of Pressure with Crank Angle

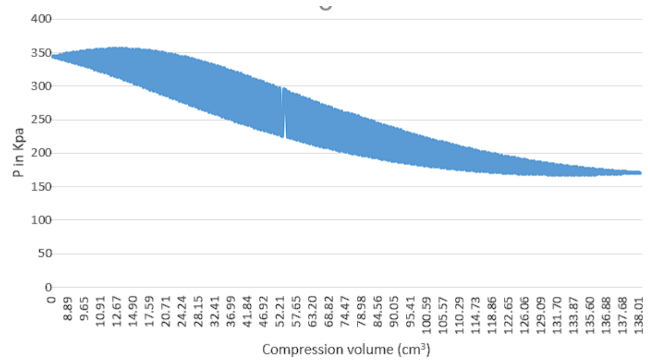

**Chart -7**: Variation of Pressure with Compression Volume

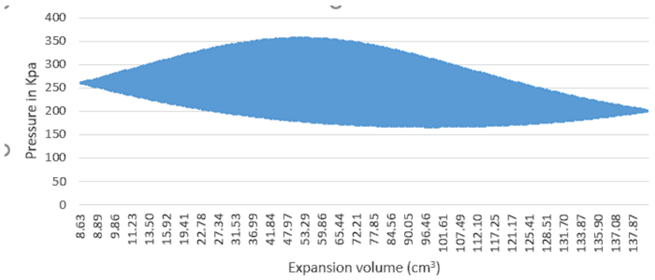

**Chart -8**: Variation of Pressure with Expansion Volume

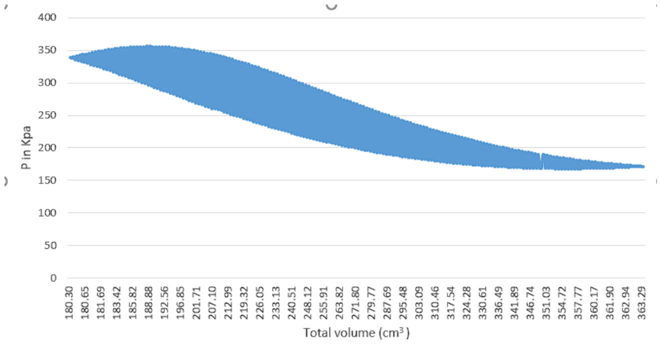

**Chart -9**: Variation of Pressure with Total Volume

## 3.2 Structural Analysis

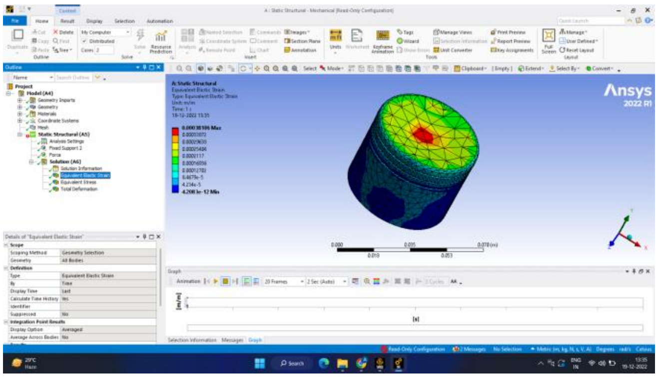

**Fig -15**: Piston - Equivalent Elastic Strain

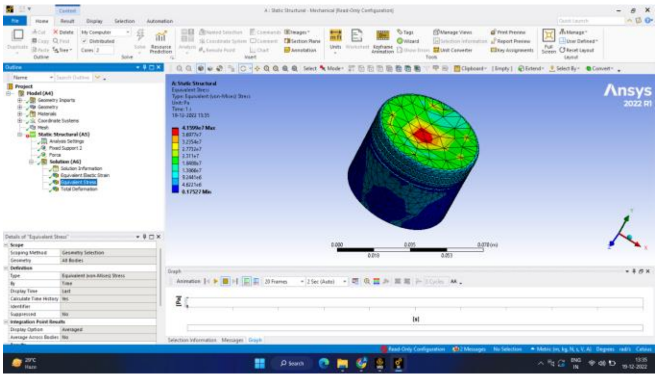

**Fig -16**: Piston - Equivalent stress

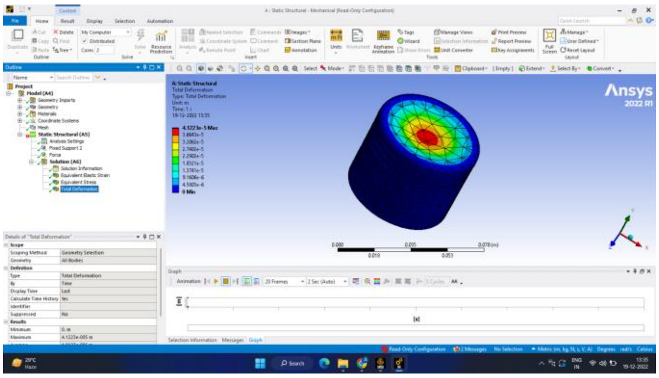

**Fig -17**: Piston - Total Deformation

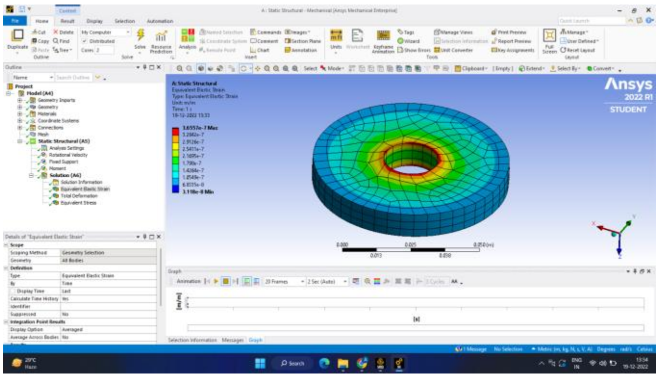

**Fig -18**: Flywheel- Equivalent Elastic Strain

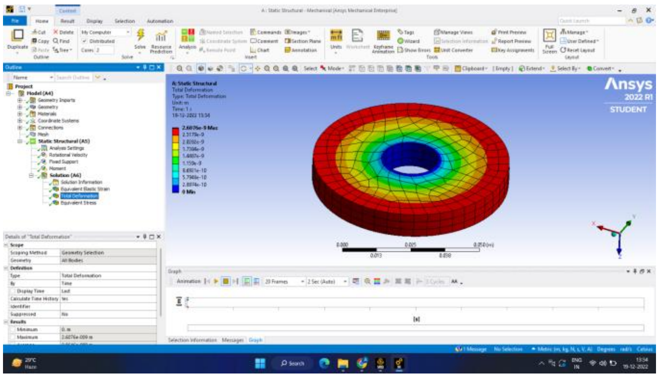

**Fig -19**: Flywheel- Total Deformation

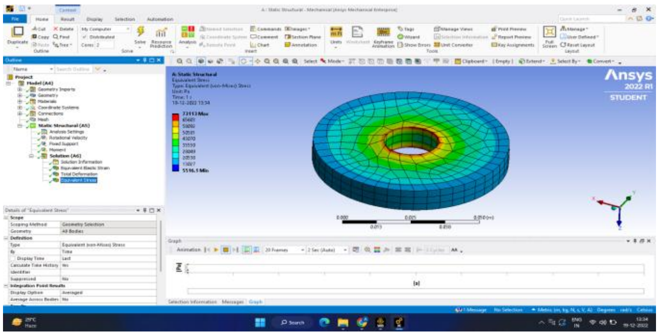

**Fig -20**: Flywheel- Equivalent stress

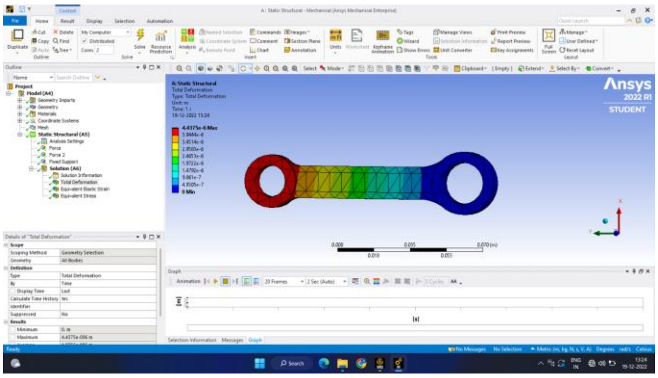

**Fig -21**: Connecting Rod - Total Deformation

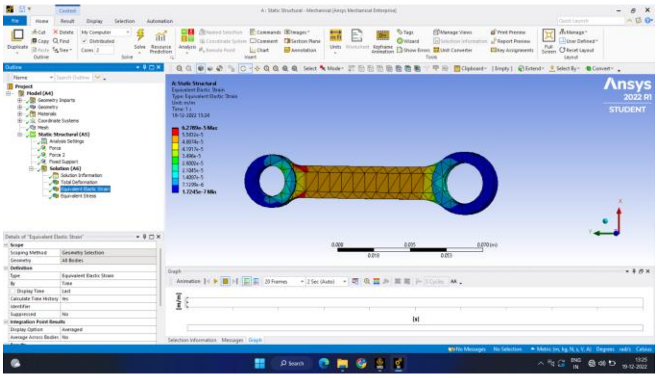

**Fig -22**: Connecting Rod - Equivalent Elastic Strain

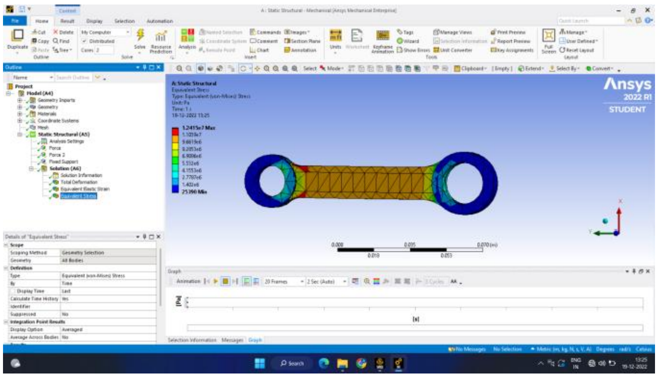

**Fig -23**: Connecting Rod - Equivalent stress

### 3.3 CFD Analysis

The equivalent model was used to determine the surface area required to achieve the required temperature difference. The surface is found to be 0.2827 $m^2$.

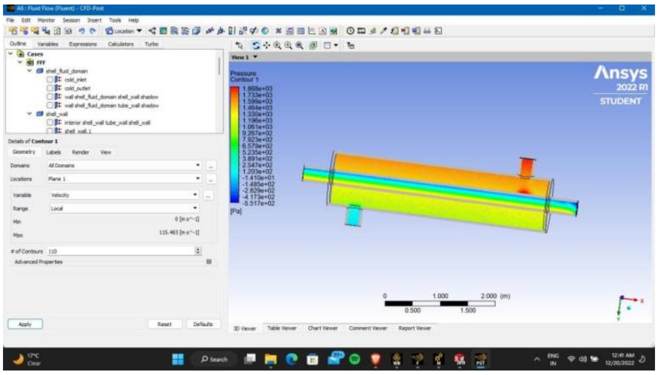
Details of Contour 1
Domains: All Domains
Locations: Plane 1
Variable: Velocity
Range: Local
Min: 0 [m s^-1]
Max: 115.483 [m s^-1]
# of Contours: 110

**Fig -24**: Pressure Contour

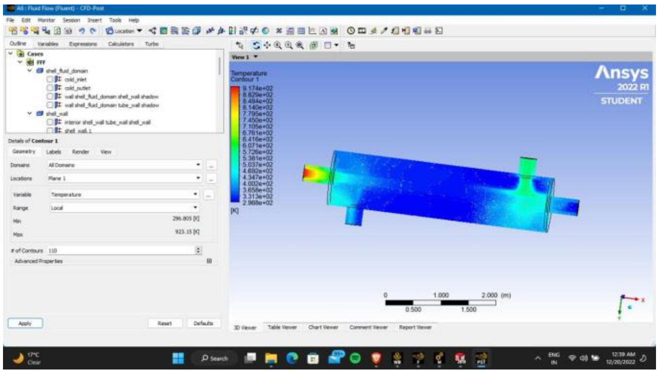
Details of Contour 1
Domains: All Domains
Locations: Plane 1
Variable: Temperature
Range: Local
Min: 296.805 [K]
Max: 923.15 [K]
# of Contours: 110

**Fig -25**: Temperature Contour

## 4. CONCLUSION

By doing the thermodynamic analysis, It is concluded that work done for compression is smaller than work obtained in the expansion stroke. So that net work of 10.735 Joule is obtained. considering 1200 rpm speed, cycle completed in 1 second will be 20 hence power obtained is 214.7 Watts. Structural analysis is done in ansys and the deformation, Von mises stress, strain is calculated. Stress induced in the piston was 41 Mpa and 21 Mpa for the connecting rod which are well within the permissible limits.

## 5. FUTURE SCOPE

Effect of pressure drop due to friction can be taken into consideration to correctly model thermodynamic analysis Working fluid like helium can be used for the efficient operation due to its high conduction coefficient and low drag coefficient.

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