

Design and Analysis of a Mini Setup of Steam Power Plant

Rohan Desai¹, Vivek Mane², Yash Sahindrakar³, Pooja Patkar⁴, Dr. Anilkumar Sathe⁵

¹⁻⁴UG Students, Dept. of Mechanical Engineering, MIT School of Engineering, MIT ADT University, Pune, Maharashtra, India

⁵Asst. Professor, Dept. of Mechanical Engineering, MIT School of Engineering, MIT ADT University, Pune, Maharashtra, India

Abstract - Steam is being used as a popular mode of generating power since the industrial revolution. It is because water is available free of cost and the fuel required to convert water into steam is usually cheap. Steam power plants are compact, easy to handle and require low initial cost and maintenance. The aim of this project is to design and analyze a mini setup of steam power plant for laboratory purpose, which uses saturated steam at 2 bar gauge pressure and 145°C temperature. The fundamental operating cycle of all steam power plants is a thermodynamic cycle known as the Rankine Cycle. A MATLAB code has been developed here, which has proved to be an innovative solution to carry out the performance calculations related to the Rankine Cycle with ease.

Key Words: CAD Modelling, MATLAB Code, Rankine Cycle, Finite Element Analysis, Structural Analysis, Thermal Analysis, Modal Analysis

1. INTRODUCTION

Majority of the electricity produced now comes from steam power plants all around the world. Steam is used in power plants to generate over 80% of the world's total electricity. India's electricity usage accounts for around 4% of the total global electricity consumption and is increasing at an annual pace of 8–10%. In India as well, steam power plants, which mostly use coal as a fuel, produce the majority of the electricity. Hence, it is important to learn about steam power plants.

Steam power plants are those in which steam is used to drive the electric generator. A steam power plant consists of major components such as boiler, steam turbine, generator, condenser and pump, as well as other auxiliaries such as pipe, nozzle, valves, etc. The combustion of a fuel at high pressure within a boiler produces steam in power plants. Steam is generated in coal-fired power plants, in nuclear reactors by atomic fission, and even in solar thermal power plants by sunlight. Since it is utilized to spin a turbine, steam plays a critical role in the generation of power. When high-pressure steam hits the turbine, it expands and emerges at a faster speed but lower pressure. On collision, the kinetic energy of the steam is transferred to the turbine. As a result, the turbine rotates at an increasing speed, and the

generator attached to the turbine's rotor also rotates at a high speed. The generator thus converts the mechanical energy of the turbine into electrical energy. In most cases, the used steam coming out from the turbine is condensed to form water again with the help of a condenser and pumped back to the boiler to generate steam.

2. METHODOLOGY

2.1 Design Calculations

A standard design procedure is to be followed while designing a product, the formulae for which are derived from the standard tables in empirical relation form. Design calculations are not only used for finding out dimensions but they are also used for finding out the forces, stresses and factor of safety theoretically. The values obtained from the design calculations are then used in 3D CAD modelling, drafting and analysis.

2.1.1 Design Calculations for Pressure Vessel

Selection of design parameters:

1. Maximum working pressure (P_{max}) = **2 bar**

2. Design pressure (P_i):

$$P_i = 1.05 P_{max}$$

$$P_i = 1.05 \times 2 = \mathbf{2.1 \text{ bar}}$$

3. Hydrostatic pressure (P_b):

$$P_b = 1.3 P_i$$

$$P_b = 1.3 \times 2.1 = \mathbf{2.73 \text{ bar}}$$

4. Allowable stress (σ_{all}):

$$\text{For Material 20C8} = 450 \text{ N/mm}^2$$

$$\sigma_{all} = 450/4 \text{ (as per ASME code)}$$

$$\sigma_{all} = \mathbf{112.5 \text{ N/mm}^2}$$

5. Cylindrical pressure vessel subjected to internal pressure:

$$\sigma_{all} = \frac{P_i d}{2} \times t \times n_t$$

$$t = \frac{P_i d}{2 \times \sigma_{all} \times n_t - P_i}$$

$$t = \frac{2.1 \times 250}{2 \times 112.5 \times 0.7 - 2.1}$$

$$t = \frac{525}{155.4}$$

$$t = 3.378 \approx \mathbf{3.40 \text{ mm}}$$
 ... (without corrosion allowance)

$$t = 3.378 + c$$
 ... (c is corrosion allowance)

$$t = 3.378 + 1.5$$

$$t = 4.878 \approx \mathbf{5 \text{ mm}}$$
 ... (with corrosion allowance)

6. Pressure vessel under combined loading:

a) Stress in circumferential direction (σ_t):

$$\sigma_t = \frac{P_i(d_i+t)}{2t}$$

$$\sigma_t = \frac{2.1(250+3.40)}{2 \times 3.40}$$

$$\sigma_t = \mathbf{78.255 \text{ N/mm}^2 \text{ (tensile)}}$$

b) Stress in longitudinal direction (σ_l):

$$\sigma_l = \frac{P_i d_i}{4t}$$

$$\sigma_l = \frac{2.1 \times 250}{4 \times 3.40}$$

$$\sigma_l = \mathbf{38.6029 \text{ N/mm}^2}$$

c) Resultant stress:

$$\sigma_R = \sqrt{(\sigma_t^2 - \sigma_l^2) + 3\tau^2}$$

$$\sigma_R = \sqrt{[78.255^2 - 38.6029^2] + [55 + 55^2]}$$

$$\sigma_R = \mathbf{69.60 \text{ N/mm}^2}$$

Allowable stress (σ_{all}) is 112.5 N/mm², which is greater than the resultant stress (σ_R), i.e., 69.60 N/mm². Therefore, the pressure vessel design is considered to be within the allowable limit.

d) Torispherical dished head (End closure design)
 'R_c' is the crown radius and 'r_{ic}' is the knuckle radius or inner radius.

$$R_c = 0.75 \times d_i = 0.75 \times 250 = 187.5 \text{ mm}$$

$$r_{ic} = 0.06 \times d_i = 0.06 \times 250 = 15 \text{ mm}$$

Working gauge pressure = 2.0 – 1.01325
 = 0.98675 bar

$$0.5d_i < R_c \leq d_i$$

$$0.5 \times 250 < R_c \leq 250$$

$$R_c = \mathbf{125 \text{ mm}}$$

$$r_{ic} = 0.06 \times 125 = \mathbf{7.5 \text{ mm}}$$

Stress intensification factor:

$$K_f = \frac{1}{4} \left[3 + \sqrt{\frac{R_c}{r_{ic}}} \right]$$

$$K_f = \frac{1}{4} \left[3 + \sqrt{\frac{125}{7.5}} \right]$$

$$K_f = \frac{1}{4} \times 7.082$$

$$K_f = \mathbf{1.7706}$$

Torispherical dished head thickness:

$$T_h = \frac{K_f P_i R_c}{\sigma_{all} \eta} - 0.2P_i + c$$

... (η is the welded joint efficiency = 0.7)

$$= \frac{1.77 \times 2.1 \times 125}{2 \times 112.5 \times 0.7} - (0.2 \times 2.1) + 1.5$$

$$= \frac{464.625}{157.08} + 1.5$$

$$= 2.95 + 1.5$$

$$T_h = \mathbf{4.45 \text{ mm}}$$

e) Straight Flange Length (S_f):

$$S_f = 3 \times T_h = 3 \times 4.45 = \mathbf{13.35 \text{ mm}}$$

f) Factor of safety:

The factor of safety based on yield strength should be greater than 1.5 and the factor of safety based on ultimate tensile strength should be greater than 3.0.

Factor of safety based on yield strength

$$= \frac{S_{yt}}{\sigma_t}$$

$$= \frac{250}{78.255}$$

$$= \mathbf{3.19 > 1.5}$$

Factor of safety based on ultimate tensile strength

$$= \frac{S_{ut}}{\sigma_t}$$

$$= \frac{450}{78.255}$$

$$= \mathbf{5.7 > 3.0}$$

Hence, the design of pressure vessel is considered to be safe.

2.1.2 Design Calculations for Pipe

Input Data Units: SI(bar) ▾

Pipe Grade: ▾

Steam Pressure: ▾

Steam Flow Rate: ▾

Maximum Allowable Velocity [?]: ▾

Pipe Length [?]: ▾

[Show Advanced Options](#)

Result

Pipe Size	NPS1/2	
Pipe Inner Diameter	15.7988	<input type="text" value="mm"/> ▾
Steam Velocity	24.7903	<input type="text" value="m/s"/> ▾
Pressure Loss	0.00378574	<input type="text" value="bar"/> ▾
Equivalent Length of Straight Pipe	0.4	<input type="text" value="m"/> ▾

Fig.-1: Pipe Dimensions Calculator

Final dimensions of pipe:

Pipe Std: **ANSI SCH 40**

Pressure = **2 bar**

Steam Velocity = **25m/s**

Nominal diameter (N_d) = **15 mm**

Inner diameter (I_d) = **15.8 mm**

Wall thickness (t) = **2.77 mm**

Outer diameter (O_d) = **21.33 mm**

Length of pipe = **400 mm**

2.1.3 Design Calculations for Nozzle (convergent)

Mass flow rate of steam at 2 bar in ANSI SCH 40 pipe grade,

$\dot{m} = 29 \text{ kg/hr}$

Velocity of steam through pipe = 25 m/s

Inlet pressure = 2 bar (gauge)

1. Critical Pressure Ratio:

$$\frac{p_2}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$$

$$\frac{p_2}{p_1} = \left(\frac{2}{1.135+1}\right)^{\frac{1.135}{1.135-1}}$$

... (for saturated steam, n =

1.135)

$$\frac{p_2}{p_1} = 0.5774$$

$$p_2 = 0.5774 \times p_1$$

$$p_2 = 0.5774 \times 2$$

... (p₁ is the pressure at nozzle inlet, i.e., 2

bar)

$$p_2 = \mathbf{1.15 \text{ bar}}$$

... (pressure at nozzle

outlet)

2. Velocity of steam through nozzle:

$$C_2 = \sqrt{C_1^2 + 2(H_1 - H_2)}$$

... (C₁ is the velocity of steam at nozzle inlet)

$$C_2 = \sqrt{25^2 + 2(2706.24 - 2681.16)}$$

$$C_2 = \sqrt{675.16}$$

$$C_2 = \mathbf{26 \text{ m/s}}$$

... (C₂ is the velocity of steam at nozzle

outlet)

3. Area of cross section of nozzle (A):

$$\dot{m} = \frac{A v}{V}$$

$$A = \frac{\dot{m} V}{v}$$

$$A = \frac{0.0805 \times 1.4864}{26}$$

$$A = \mathbf{0.0046 \text{ m}^2}$$

4. Diameter of Nozzle (d):

For maximum power transmission,

$$d = \left(\frac{D^5}{8FL}\right)^{\frac{1}{4}}$$

where,

D = Inner diameter of pipe

F = Darcy's coefficient for pipe friction (0.01)

L = Length of pipe

$$d = \left(\frac{15.7988^5}{8 \times 0.01 \times 400}\right)^{\frac{1}{4}}$$

$$d = \mathbf{13.24 \text{ mm}}$$

(Note: The values of 'D' and 'L' are the standard values of pipe grade ANSI SCH 40.)

2.2 MATLAB Code

A MATLAB code has been developed to solve the equations of the Rankine Cycle. This code takes input as inlet pressure of turbine, inlet temperature of turbine and pressure inside the condenser and gives output as turbine work, pump work, net work, thermal efficiency and work ratio. For better understanding, T-S and H-S graphs are also plotted as an output by the code.

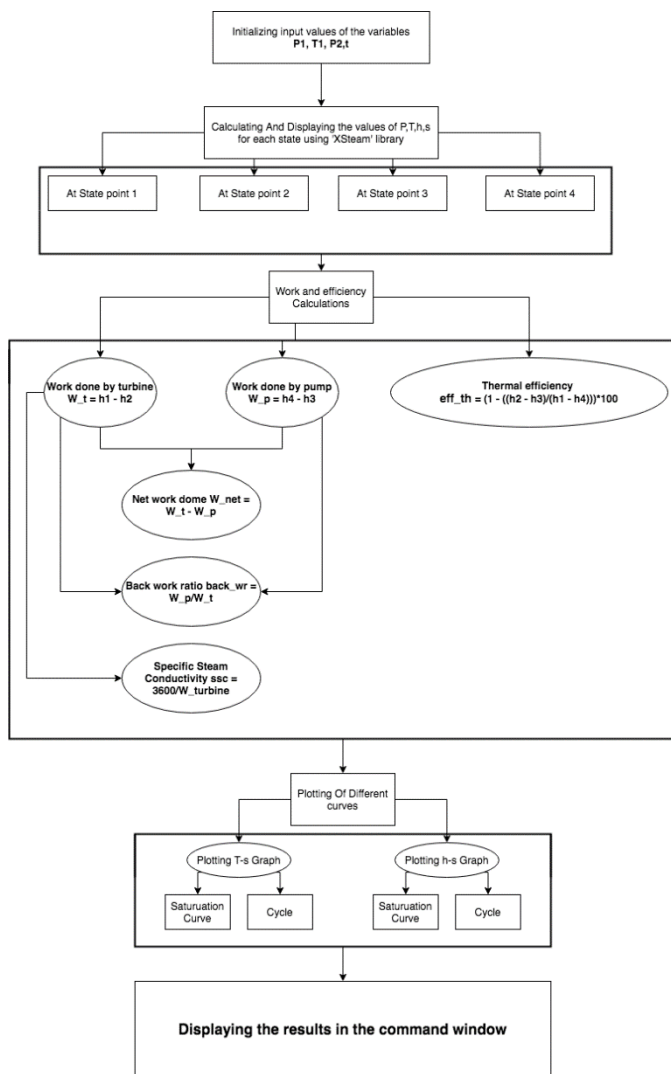


Fig.-2: Flowchart of the MATLAB Code

2.2.1 Input for the Code

```

RANKINE CYCLE SIMULATOR
1-2 is isentropic expansion in the turbine
2-3 is constant pressure heat rejection by condenser
3-4 is isentropic compression in the pump
4-1 is the constant pressure head addition by boiler
enter the pressure at turbine inlet:
2
enter the Temp. at turbine inlet:
145
enter the pressure at condenser:
0.1
COMMAND WINDOW
    
```

Fig.-3: MATLAB Code Input

2.2.2 Output of the Code

```

RESULTS
At state point 1:
P1 is 2.000000 bar
T1 is 145.000000 degree celcius
H1 is 2758.728972 KJ/kg
S1 is 7.256284 kj/kgk

At state point 2:
P2 is 0.100000 bar
T2 is 45.807548 degree celcius
H2 is 2299.182765 KJ/kg
S2 is 7.256284 kj/kgk
x2 is 0.880980

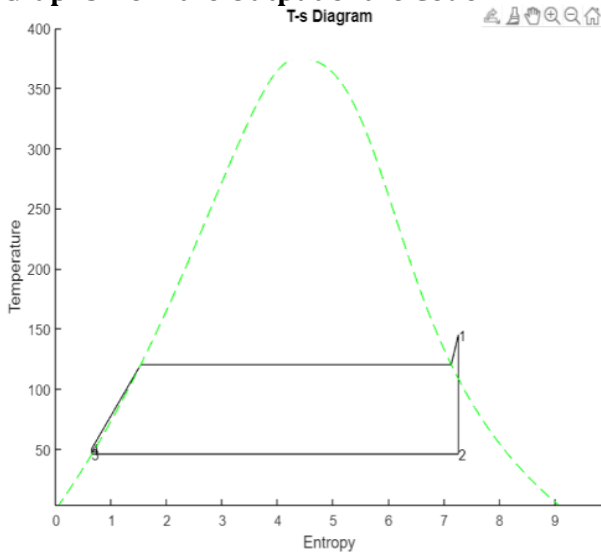
At state point 3:
P3 is 0.100000 bar
T3 is 45.807548 degree celcius
H3 is 191.812295 KJ/kg
S3 is 0.649218 kj/kgk

At state point 4:
P4 is 2.000000 bar
T4 is 50.432912 degree celcius
H4 is 191.814215 KJ/kg
S4 is 0.649218 kj/kgk

The turbine work is 459.546207 KJ/kg
The pump work is 0.001919 KJ/kg
The net work is 459.544288 KJ/kg
The thermal efficiency is 0.179026 percent
The Work ratio is is 0.999996
The SSC is is 7.833815
>>
    
```

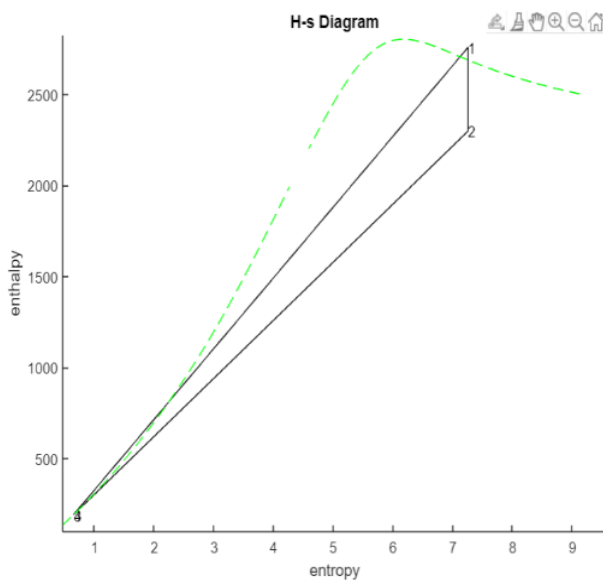
Fig.-4: MATLAB Code Output

2.2.3 Graphs from the Output of the Code



Graph-1: T-S Diagram

Graph-1 shows the Temperature vs. Entropy (T-S) diagram obtained as an output from the code based on the inputs provided. This graph resembles the standard T-S diagram of Rankine cycle, which shows that the code and the inputs provided are correct.



Graph-2: H-S Diagram

Graph-2 shows the Enthalpy vs. Entropy (H-S) diagram obtained as an output from the MATLAB Code. This graph is similar to the standard H-S diagram of Rankine cycle, which again proves that the code is correct and it gives correct output.

2.3 CAD Model

3-D CAD models of the pressure vessel, pipe and nozzle have been made in SolidWorks 2019 student version software. The dimensions for the models have been taken from the end results of the design calculations.

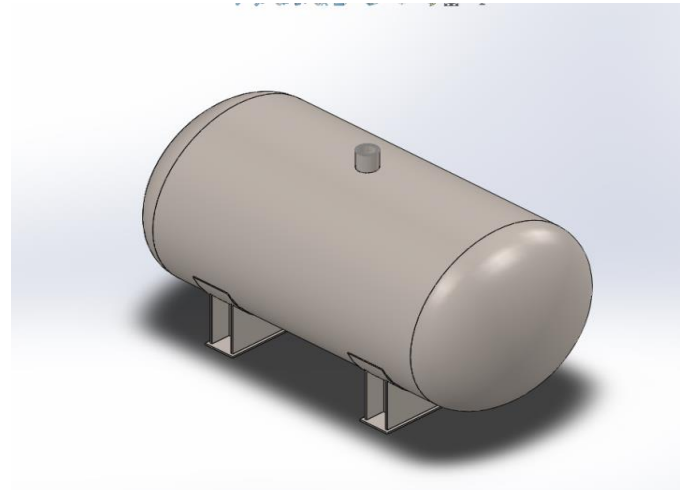


Fig.-5: CAD Model of Pressure Vessel

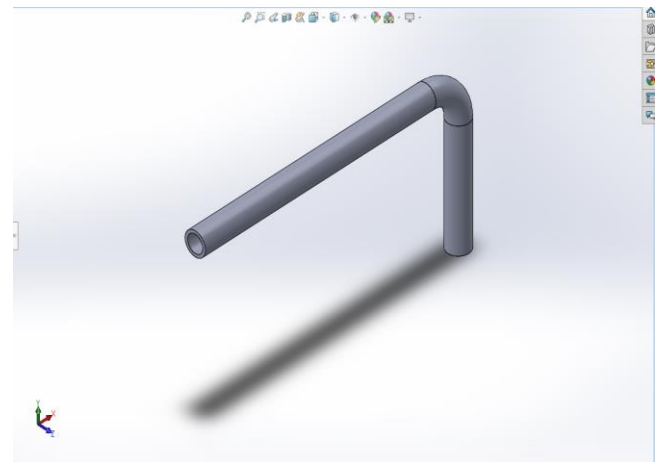


Fig.-6: CAD Model of Pipe

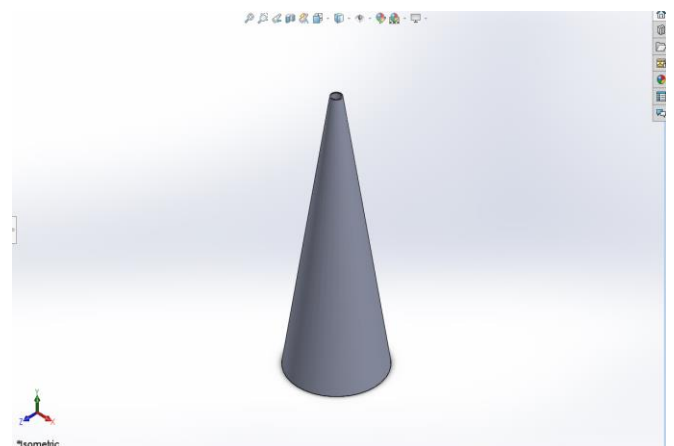


Fig.-7: CAD Model of Nozzle

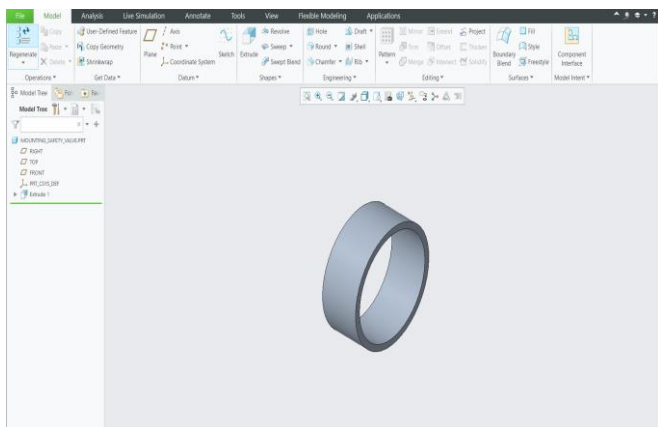


Fig.-8: CAD Model of Mounting for Safety Valve, Nozzle, etc.

Fig-8 shows the mounting for safety valve, pressure gauge, temperature indicator, nozzle and water inlet. It is further given internal threading of 1/2" BSP since these parts have external threading of 1/2" BSP.

Fig.-10 shows the mounting for level probe with 1" BSP internal threading as the level probe has 1" external threading. The dimensions for mountings have been referred from the BSP chart.

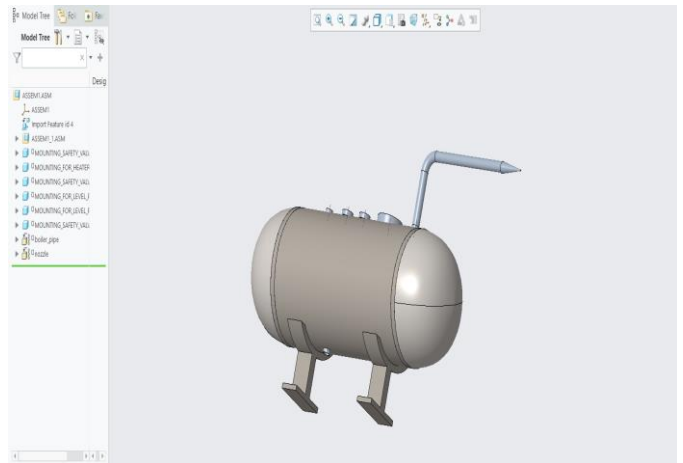


Fig.-11: Final assembly with mountings

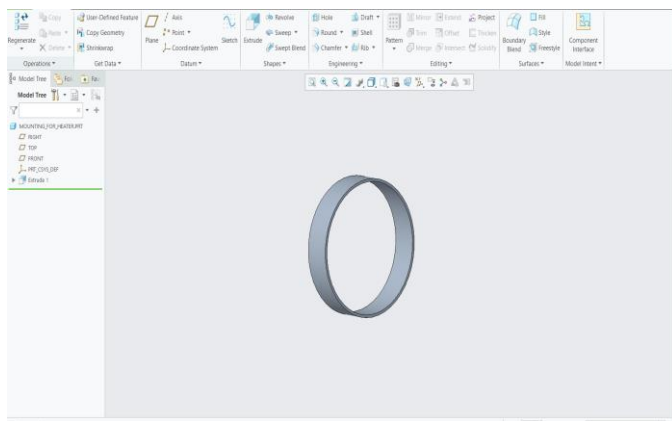


Fig.-9: CAD Model of Mounting for Heater

Fig-9 shows the mounting for heater with 2.5" BSP internal threading as the heater has 2.5" BSP external threading.

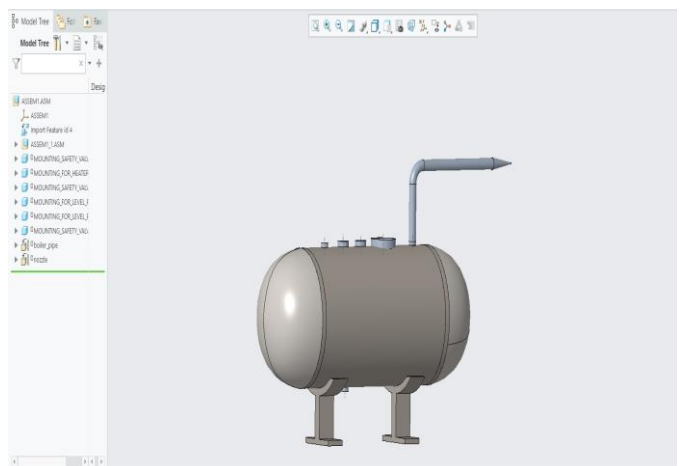


Fig.-12: Final assembly with mountings

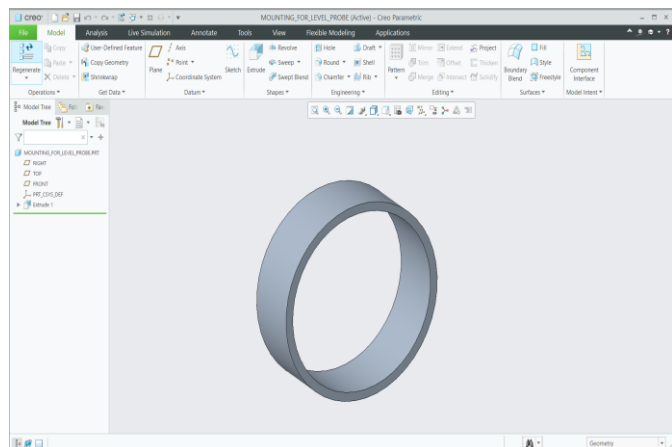


Fig.-10: CAD Model of Mounting for Level Probe

2.4 Finite Element Analysis

The analysis of pressure vessel has been performed on ANSYS R1 2021 student version. Three types of finite element analysis have been performed on the pressure vessel CAD model:

1. Thermal Analysis
2. Structural Analysis
3. Modal Analysis

2.4.1 Meshing

For the pressure vessel meshing, tetrahedron mesh has been used because of its curved shape. Tetrahedron mesh is generally used on curved surfaces.

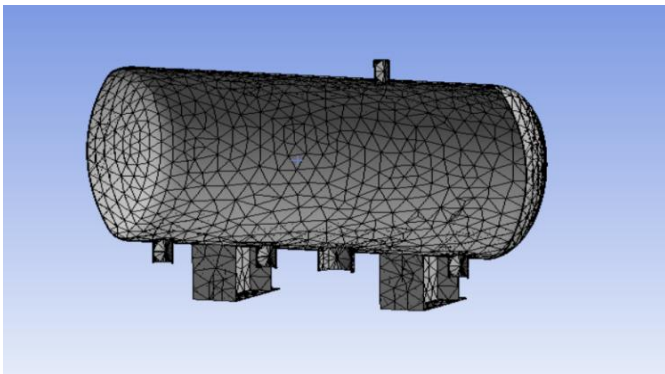


Fig.-13: Tetrahedron Mesh

2.4.2 Thermal Analysis of the Pressure Vessel:

In an object with thermal loads that do not change over time, the temperature distribution can be determined using steady-state thermal analysis.

Inputs for Thermal Analysis:

1. Temperature:
The temperature input is taken as 145°C at 2 bar gauge pressure.

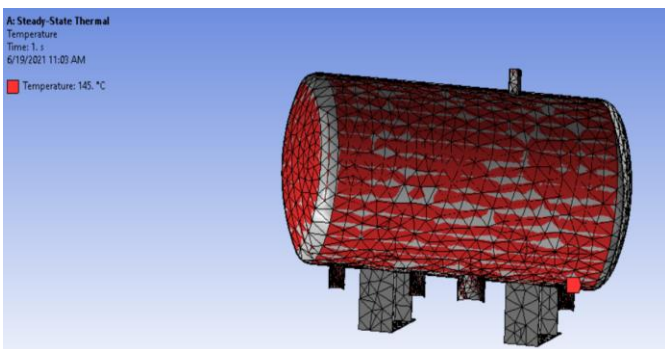


Fig.-14: Input: Temperature

2. Convection:
Convection at room temperature is taken as the second input.

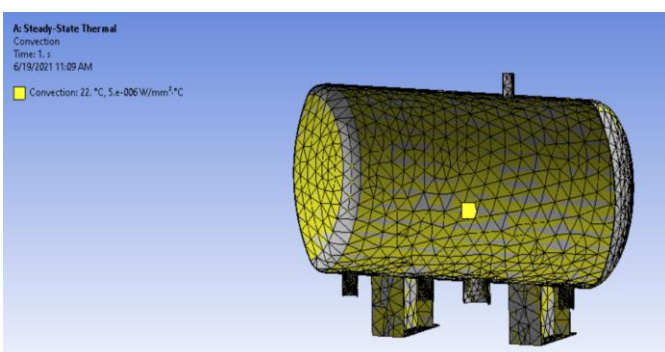


Fig.-15: Input: Convection

Outputs of Thermal Analysis:

1. Temperature Distribution:
Based on the inputs given, the temperature distribution in the vessel is shown in Fig. 16. It is seen that the maximum temperature 145°C will be inside the vessel (indicated in red colour) and the minimum temperature will be at the base which is 37.7°C (indicated in blue colour).

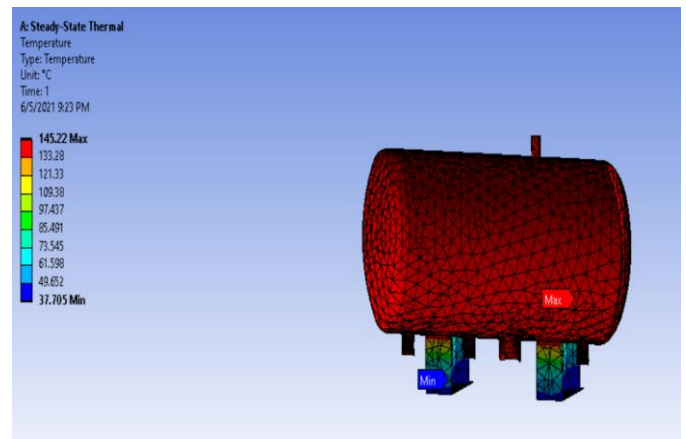


Fig.-16: Output: Temperature Distribution

2. Heat Flux:
According to the analysis, the maximum heat flux will be at the outer surface of the vessel which is 0.1381 W/mm².

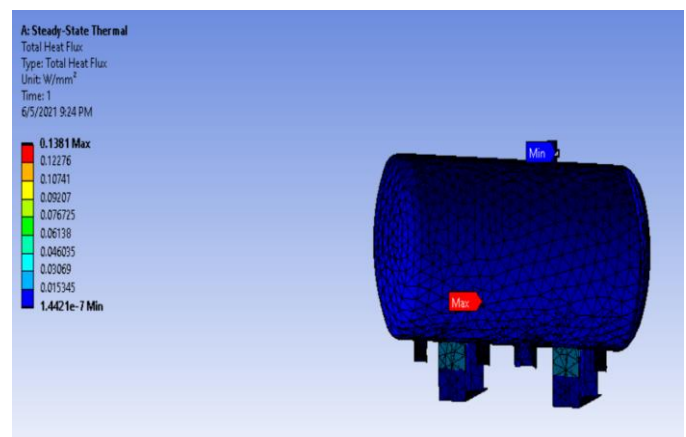


Fig.-17: Output: Total Heat Flux

2.4.3 Structural Analysis of the Pressure Vessel:

The process of determining the effect of load on a physical structure and its components is known as structural analysis. The results of structural analysis are then utilized to confirm a structure's suitability for usage, typically obviating the need for physical tests.

Inputs for Structural Analysis:

1. Pressure:

The first input for structural analysis is the pressure inside the vessel which is taken as 0.2 MPa (2 bar). It is indicated by red colour inside the vessel in Fig.-18.

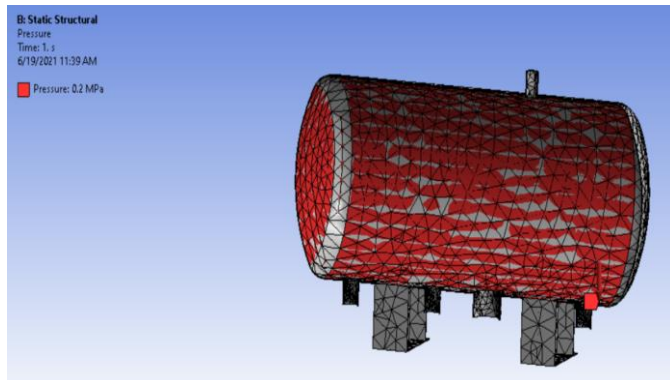


Fig.-18: Input: Pressure

2. Standard Earth Gravity:

The second input is taken as the standard earth gravity, which acts in -Y component or downward direction.

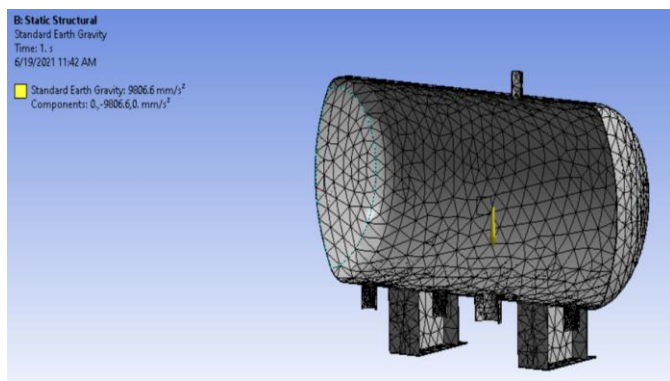


Fig.-19: Input: Standard Earth Gravity

3. Fixed Support:

The third input is a fixed support which is applied at the bottom of the stand.

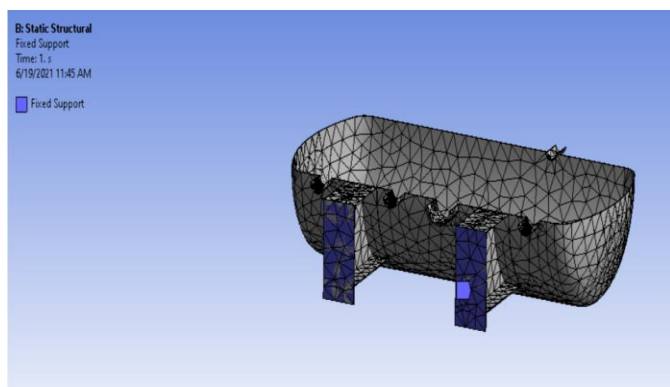


Fig.-20: Input: Fixed Support

Outputs of Structural Analysis:

1. Total Deformation:

The first output of structural analysis is the total deformation. According to the result, maximum deformation in the pressure vessel would be of 2.47 mm, indicated in red colour in Fig.-21.

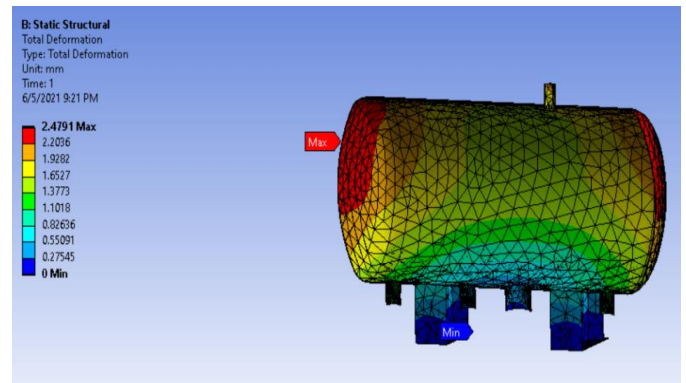


Fig.-21: Output: Total Deformation

2. Equivalent Stress:

The second output is the equivalent stress. An Equivalent stress considers different effects resulting from multiaxial residual stress states. According to the analysis, the maximum equivalent stress in the pressure vessel will be 186.89 MPa.

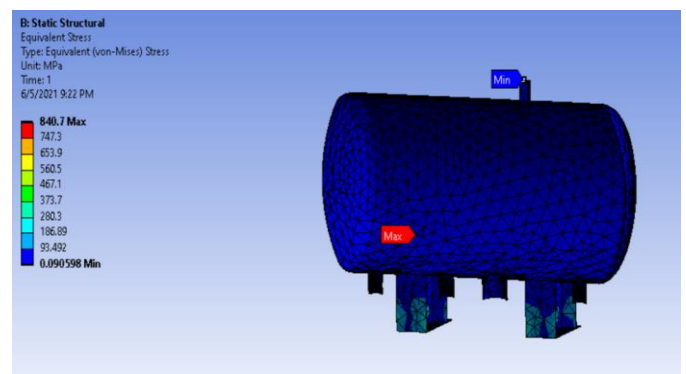


Fig.-22: Output: Equivalent Stress

2.4.4 Modal Analysis of the Pressure Vessel:

Modal analysis is carried out to determine the natural mode shapes and frequencies of an object or structure during free vibration. A physical object can also be tested to identify its natural frequencies and mode shapes. Quasi-Static type of modal analysis is performed over here. The term "quasi-static load" refers to a load that is delivered so slowly that the structure deforms slowly enough (low strain rate) that the inertia force is negligible and can be

ignored. For the pressure vessel, modal analysis has been performed 6 times.

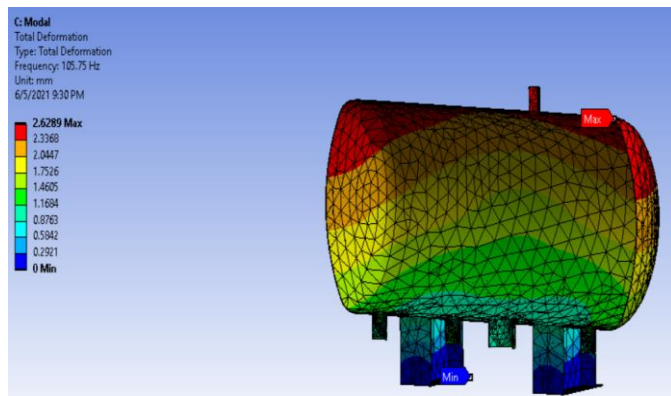


Fig-23: Total Deformation 1

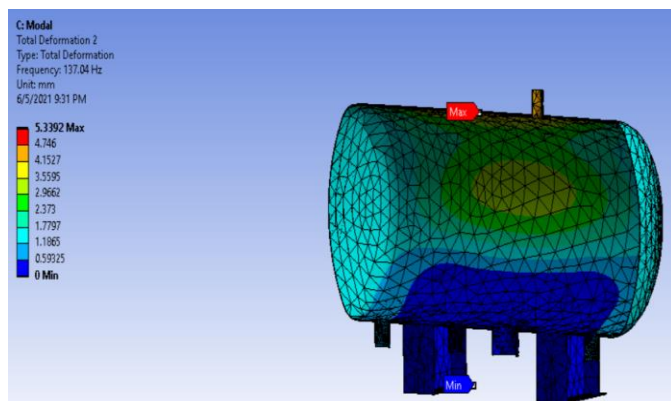


Fig-24: Total Deformation 2

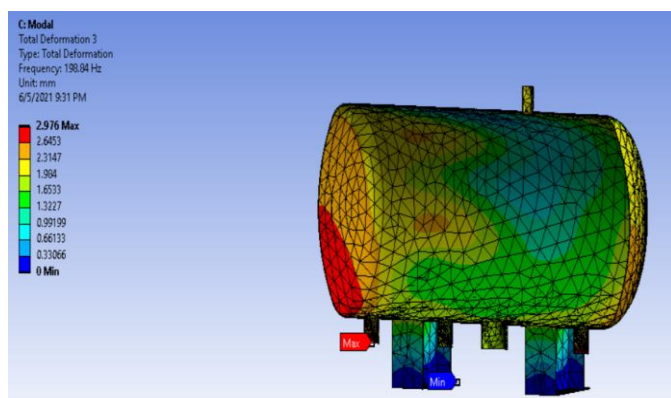


Fig-25: Total Deformation 3

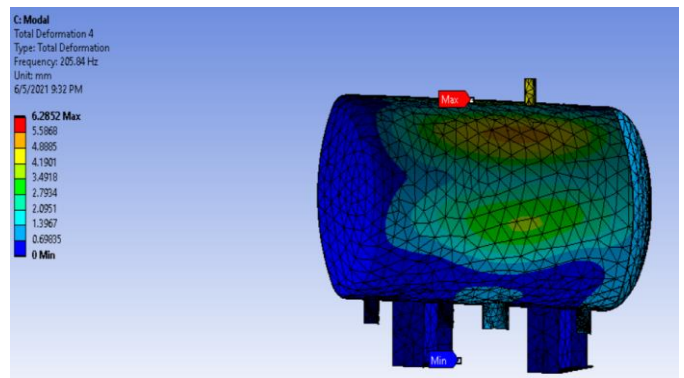


Fig-26: Total Deformation 4

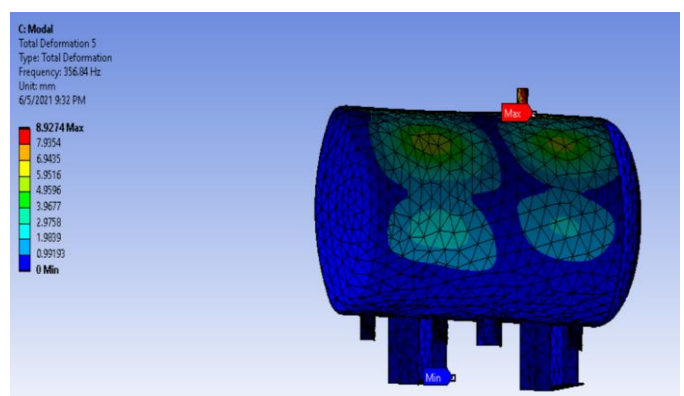


Fig-27: Total Deformation 5

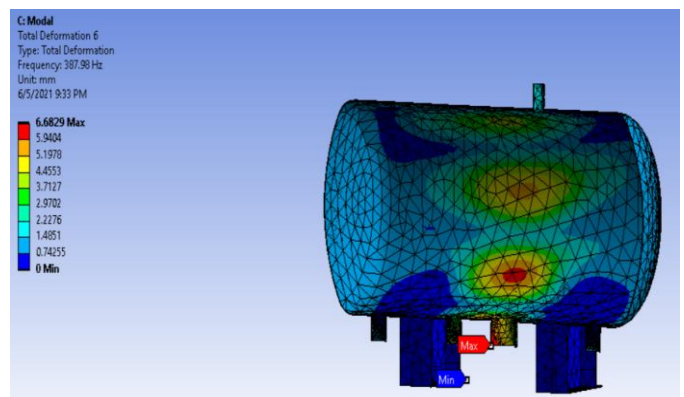
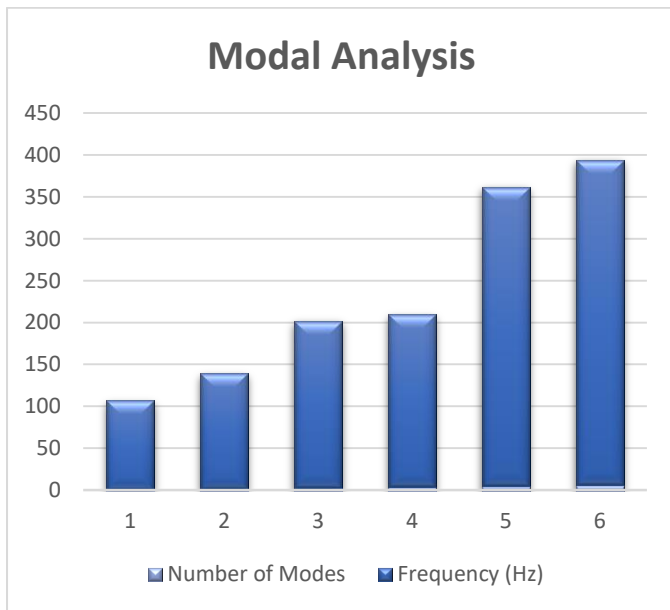


Fig-28: Total Deformation 6

Outputs of Modal Analysis:

The Bar graph (Graph-3) of the number of modes versus frequency can be obtained from the modal analysis performed.



Graph-3: Bar graph obtained from Modal Analysis

Output of the Modal Analysis	
Number of modes	Frequency (Hz)
1	105.75
2	137.04
3	198.84
4	205.84
5	356.84
6	387.92

3. RESULTS AND DISCUSSION

The MATLAB code solves all the Rankine cycle equations which are required to judge the performance of steam turbine. The steam is considered to be in saturated condition at 145°C and 2 bar pressure and the pressure at the inlet of the condenser is 0.1 bar. This was the input given to the code and the output received is as mentioned in Section 2.2. The graphs received as output are similar to the standard graphs of the Rankine cycle. Hence, it clearly shows that the code works properly and gives the desired output.

The design calculations performed for the pressure vessel and nozzle ensure safety and the required performance. Accordingly, the 3-D model has been developed. Finite Element Analysis performed on the pressure vessel helped in understanding the behavioral properties of the

component and also ensured that the design is safe for the operating conditions.

4. CONCLUSION

The MATLAB program serves as an innovative solution for carrying out the Rankine Cycle calculations. This design and analysis will help in developing a mini setup of steam power plant which can be used for laboratory demonstration purposes in colleges to provide the students with practical understanding of steam power plants and turbomachines.

5. REFERENCES

- [1] Sunil Chore, Pratik Kshirsagar and S.A Kulkarni, "Design & Manufacturing of Steam Power Plant" *International Journal of Advanced Industrial Engineering*, Vol.7, No.6, 2017.
- [2] T.G. Arul, N. Pramoath, R. Premkumar, S. Pravinkumar, A. Rameshkumar "Experiment and Fabrication of Miniature Steam Power Plant" *International Journal of Innovative Research in Science Engineering and Technology*, Vol.4, Special Issue, May 2015.
- [3] Wadhah H. Al-Tahal, Hassan A. Osman, "Performance Analysis of a Steam Power Plant: A Case Study" *MATEC Web of Conferences*, 225, 05023 (2018) UTP-UMP-VIT SES, 2018.
- [4] Bayu Rudiyantoa, Tri Ajeng Kusuma Wardanib, Saiful Anwar, Lutfi Al Jamalid, Totok Prasetyoe, Kukuh Mukti Wibowof, Nugroho Agung Pambudig, Lip Huat Sawh, "Energy and Exergy Analysis of Steam Power Plant in Paiton, Indonesia" *International Conference on Sustainable Energy and Green Technology*, 2018.
- [5] R K Rajput, "Heat and Mass Transfer" Tenth edition, S. Chand Publications, Co-operative Industrial Estate (MCIE), Mathura Road, New Delhi - 11004.
- [6] P K Nag, "Basic and Applied Thermodynamics", Eighth Edition, Tata McGraw-Hill Publishing Company, B-4, Sector 63, Dist. Gautam Buddha Nagar, Noida - 201301, Uttar Pradesh, India.
- [7] R K Rajput, "Engineering Thermodynamics" Third edition, Laxmi Publications Ltd., 113, Golden House,

Daryaganj, New Delhi - 110002.

- [8] R K Bansal, "Fluid Mechanics and Hydraulic Machines" Ninth Edition, Laxmi Publications Ltd., 113, Golden House, Daryaganj, New Delhi - 110002.

- [9] R B Patil, "Mechanical System Design" First Edition, Tech-Max Publications, Maniratna complex, Aranyeshwar Corner, Pune - 411009.