International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2015): 6.391

Structural Analysis and Cost Estimation of Reactor Pressure Vessel

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Abstract: ***A pressure vessel is a closed container which is used to hold gases or liquids at high pressures substantially different from the ambient pressure. Pressure can be caused by the reaction or it is created by an external source, like hydrogen in catalytic transfer hydrogenation. Shell, heads and nozzles are the main components of the reactor pressure vessel. In this work a reactor pressure vessel is to be created using CAD tool (creo-2) and then it is to be analyzed in ANSYS workbench. The analysis is to be carried out for materials of reactor pressure vessel with same boundary conditions. Deformations, stress, strain energy and safety factor values are to be found for different reactor pressure vessels. In this work an attempt has been made to estimate the cost of each reactor pressure vessel also. From this work, the efficient reactor pressure vessel is to found based on the values of strength to weight ratios and cost of the pressure vessel.***

Keywords: Reactor pressure vessel, external source, safety factor, strain energy, strength to weight ratio

1. Introduction

Generally the pressure vessels are designed to store reactive fluids and sustain chemical reactions that may occur in the vessel. The vessel is usually applied with refractory coating in order to avoid direct contact of reactive fluids with the shell and thus avoid the reaction with shell material. The applications of these pressure vessels are mostly found in oil and petroleum industry for storage purposes. The most common failure of pressure vessel is due to stress dependent, for this reason it becomes necessary to obtain the stress distribution in the pressure vessels. Patel Nikunj S and Ashwin Bhabhor [2013], designed new parts of reactor pressure vessel and then compared the design values with some experimental/ analytical values. Thermal analysis of reactor pressure vessel had been done by them using advanced CAE tool. Based on the analysis values they found the best designs among parts of reactor pressure vessels which are made of different material. Apurva R. Pendbhaje et al [2011], presented the design and analysis of a pressure vessel which is effected with high pressure rise. They mainly focused on safety parameters for allowable working pressure. Using pressure vessel design manual by Dennis Moss, they calculated the design calculations. Apsara C. Gedam and Dr. D. V. Bhope [2015], analyzed the thin cylindrical pressure vessel for different end connections using analytical and finite element analysis. They compared the stress distribution for various end connection shapes of pressure vessel viz. hemispherical, flat circular, standard ellipsoidal and dished shape. They used analytical design for calculating the inner diameter, thickness of vessel and end connections. Zahiruddin Mohammed Farooque Khateeb, Dr. Dhanraj P. Tambuskar [2016], investigated failure of half pipe jacket (limpet coil) on the basis of thermal analysis. They designed the pressure vessel as per the ASME section VIII, division 1 for given design conditions for various parameters. They designed the model in creo-3 based on the dimensions obtained from analytical calculations and validation is done on PV-ELLITE software. Based on thermal analysis values they suggested the material for limpet coil. M. A. Khattak et al [2016], presented an brief overview on the unique features of pressure vessels, such as material used for their preparation, design and construction along with various aspects of pressure vessel. They reviewed about 32 published journals in the area of pressure vessels. From studies they found that A516 material is mostly used for designing and construction of pressure vessels. Myung Jo Jhung1 et al [2008], performed comparative assessment for the deterministic fracture mechanics approach of the pressurized thermal shock of a reactor pressure vessel. They solved the round robin problems which consist of two transients and two defects. They suggested some recommendations based on the results obtained by them for understanding the key parameters. Jerzy Lewinski [2015], described the advantageous shape and configuration of a manhole located at the upper part of the cylindrical pressure vessel. To find out the best shape of manhole he considered circular and elliptical cross sections. Hiroyuki Kaneko et al [2013], conducted an accelerated corrosion test on SA533B low alloy steel and Inconel 600 to estimate corrosive characteristics of the pressure vessels. They discussed validity of the extreme experimental condition for accelerated corrosion tests and further investigations are proposed. Adithya M and M. M. M. Patnaik [2013], analyzed the horizontal pressure vessel supported on saddles according to the guidelines given in ASME Division 1 and Division 2. They analyzed the stress intensities for the saddles which are placed away from the heads and found the most suitable design for the large horizontal vessels. They also optimized the thickness of pressure vessel which has resulted in huge reduction of weight. Ya-Jin Liu et al [2011], introduced an aging and life management system for an operating of reactor pressure vessel that can be used as a reference of the lifetime extension. They developed aging and life management system which integrates decentralized information and serves as a valuable data center. The developed system by them can be used as an efficient tool for aging and life estimation of reactor pressure vessel.

2. Modeling of Pressure Vessel

The pressure vessel is made of special fine-grained low alloy ferritic steel, well suited for welding and with a high toughness while showing low porosity under neutron irradiation. The inside of vessel is lined with austenitic steel cladding for protection against corrosion.

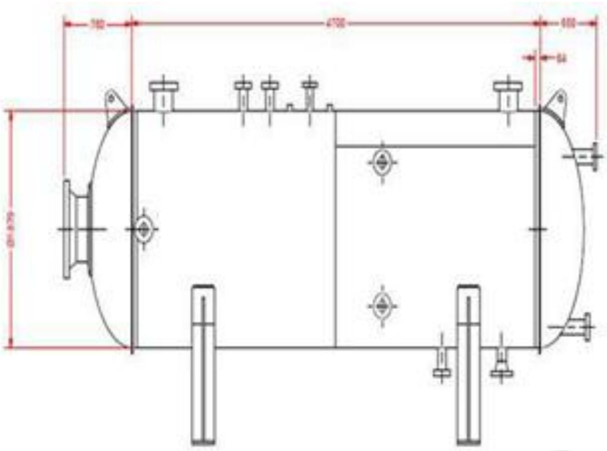

Figure 1: Sketch of reactor pressure vessel

Figure 2: 3D model of reactor pressure vessel

The pressure vessel is about 6 m high, the inner diameter is 1.925 m, and the wall of the cylindrical shell is about 125 mm thick. The overall weight of the vessel is approximately 7.9 tonnes without internals. In this work the vessel is designed for a pressure of 5 MPa (50 bar) and a temperature of 350 °C. The modeling of reactor pressure vessel is to be done in CAD tool creo – 2. CREO is a suite of programs that are used in the design, analysis, and manufacturing of a virtually unlimited range of product. The line diagram of reactor pressure vessel is shown in Fig. 1. The 3D model of reactor pressure vessel created in creo - 2 is shown in Fig. 2.

3. Structural Analysis of Pressure Vessel

Structural analysis is the common application of the finite element method. With the stress analysis the response of the pressure vessel in terms of the deflections, stresses, and strains for the applied loads. Assumptions that are made in the structural analysis of pressure vessel are:

a) The deformed configuration can be approximated by the un-deformed configuration under the applied loads in satisfying the equilibrium equations.
b) The relationship between strain and displacement remains linear.
c) The material of the structural member is linear elastic, isotropic and homogeneous.

The material properties of various materials with which the pressure vessel is made are:

Steel:
Young's Modulus (Ex): 2 x 10^{11} Pa, Poison ratio: 0.3, Density: 7850 Kg/m^3, Yield strength: 250 Mpa

Al-6061-t6:
Young's Modulus (Ex): 68.9 x 10^9 Pa, Poison ratio: 0.33, Density: 2700 Kg/m^3, Yield strength: 276 Mpa

Stainless steel 316:
Young's Modulus (Ex): 1.93 x 10^{11} Pa, Poison ratio: 0.275, Density: 8000 Kg/m^3, Yield strength: 290 Mpa

Stainless steel 304:
Young's Modulus (Ex): 1.93 x 10^{11} Pa, Poison ratio: 0.29, Density: 8000 Kg/m^3, Yield strength: 215 Mpa

The 3D meshed model of reactor pressure vessel is shown in Fig. 3. The deformation, stress, strain energy and safety factor values obtained for steel materials are shown in Fig. 4 to Fig. 7.

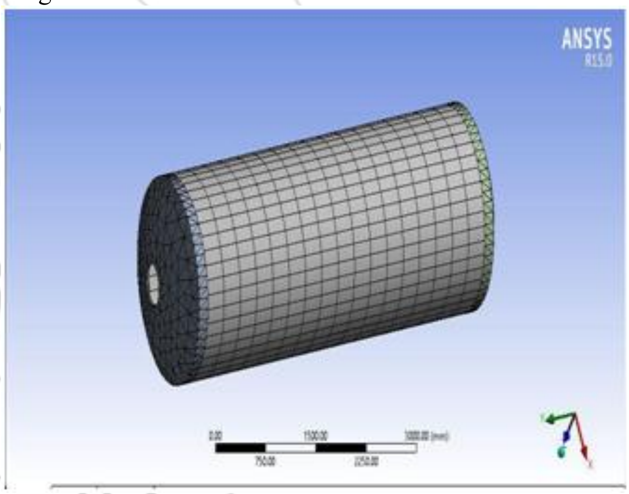

Figure 3: Meshed model of reactor pressure vessel

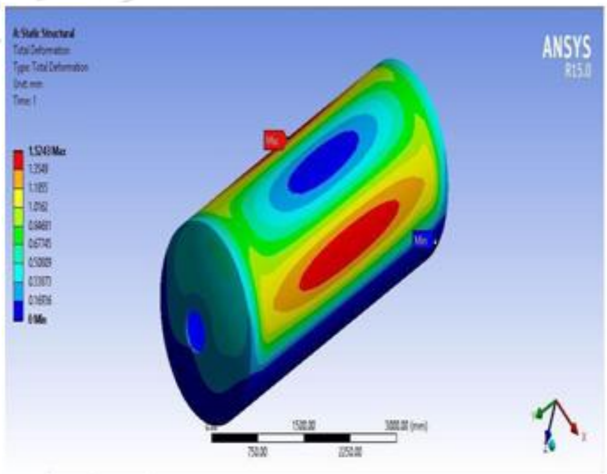

Figure 4: Deformation of Reactor pressure vessel made of steel

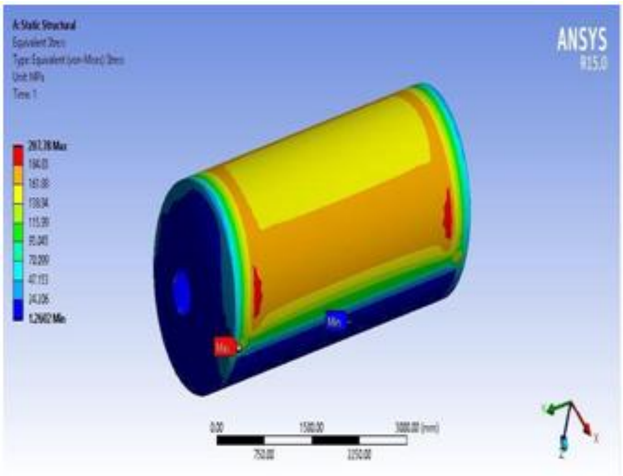

Figure 5: Stress of Reactor pressure vessel made of steel

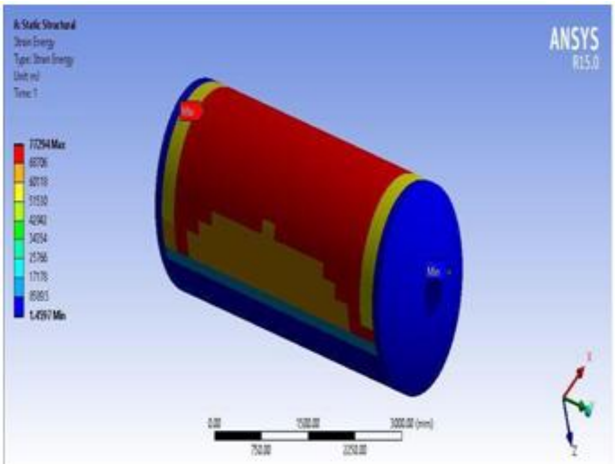

Figure 6: Strain energy of Reactor pressure vessel made of steel

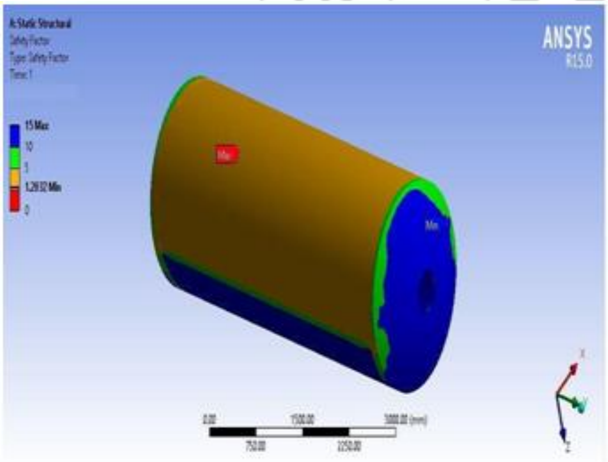

Figure 7: Safety factor of Reactor pressure vessel made of steel

From Fig. 4 to Fig. 7 it is observed that for an applied pressure on the reactor pressure vessel it produces 207.78MPa stress and it is the maximum limit of the object because the safety factor has shown 1.2032. If the pressure increase then stress exceeds the yield limit of the material then it will going to break the total vessel.

To avoid such type of failure we have to reduce the stresses on the body, generally we may not eliminate total stresses on the body. But we can reduce it some extent by following methods

1) Changing material
2) Changing design
3) Changing design and material both

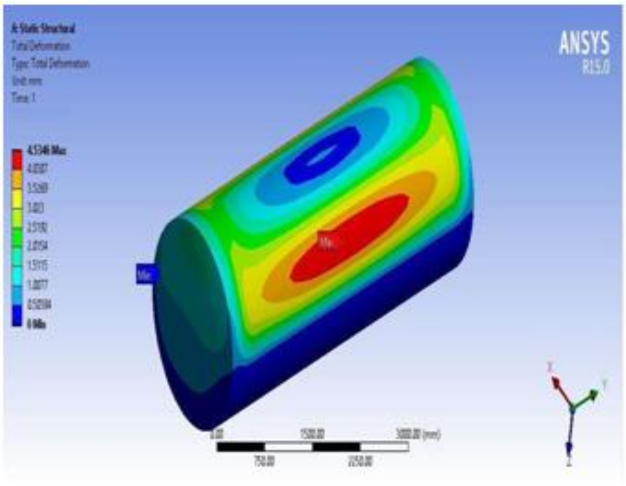

Figure 8: Deformation of Reactor pressure vessel made of al-6061-t6

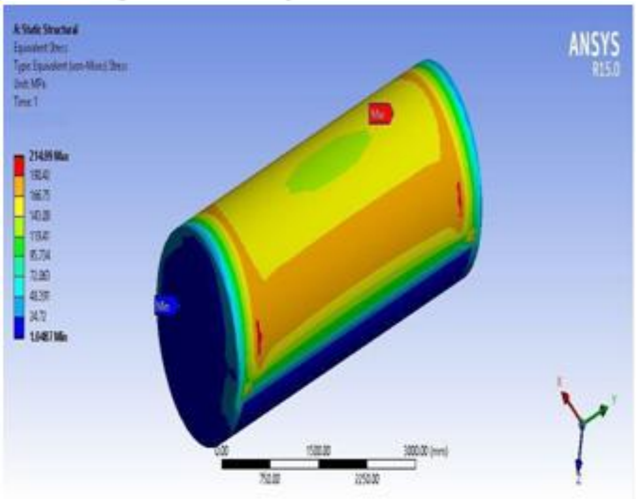

Figure 9: Stress of Reactor pressure vessel made of al-6061-t6

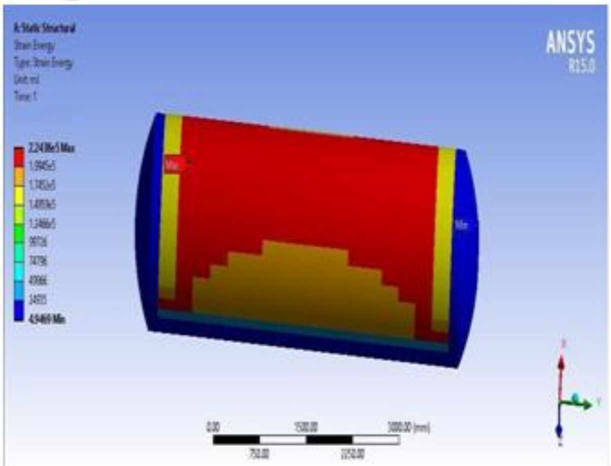

Figure 10: Strain energy of Reactor pressure vessel made of al-6061-t6

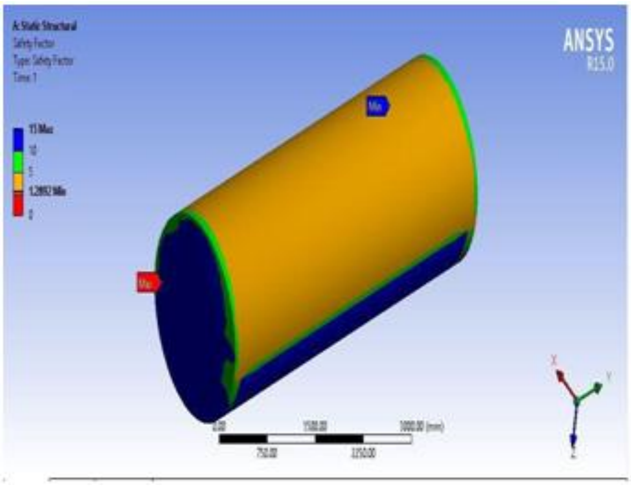

Figure 11: Safety factor of Reactor pressure vessel made of al-606-t6

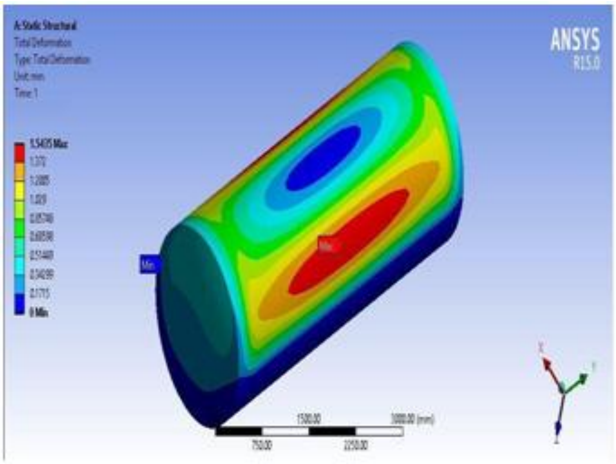

Figure 12: Deformation of Reactor pressure vessel made of ss-316

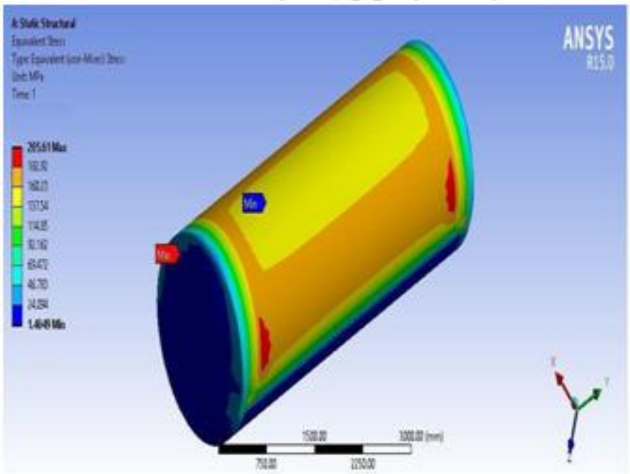

Figure 13: Stress of Reactor pressure vessel made of ss - 316

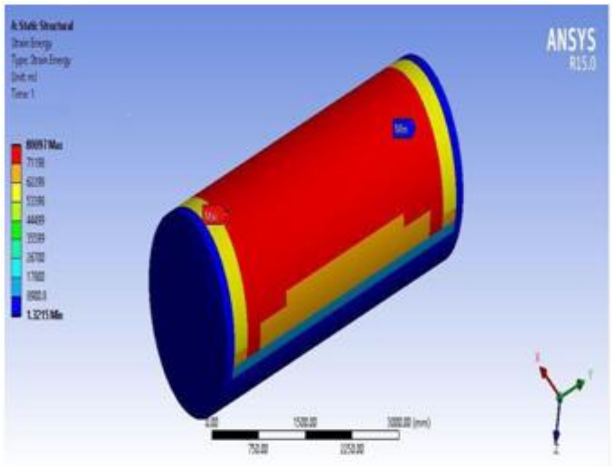

Figure 14: Strain energy of Reactor pressure vessel made of ss-316

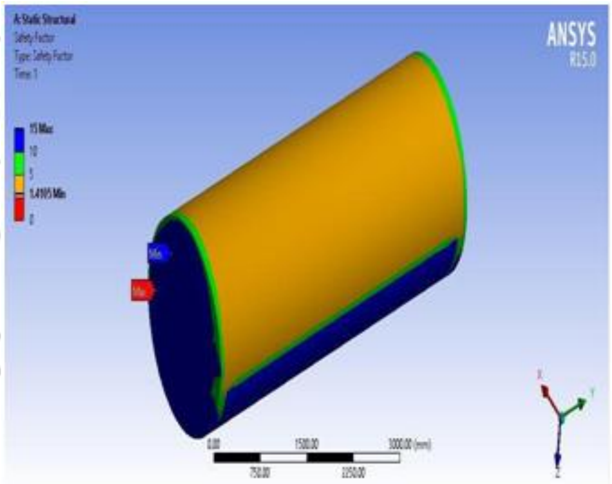

Figure 15: Safety factor of Reactor pressure vessel made of ss-316

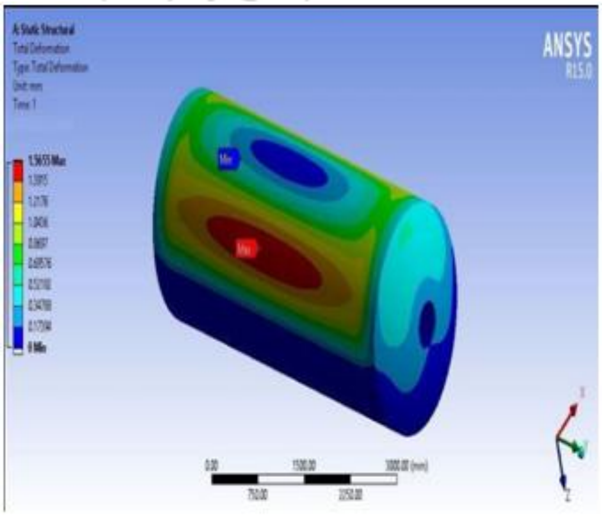

Figure 16: Deformation of Reactor pressure vessel made of ss-304

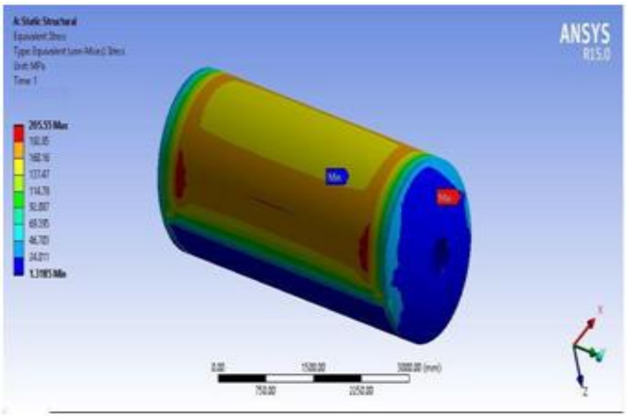

Figure 17: Stress of Reactor pressure vessel made of ss - 304

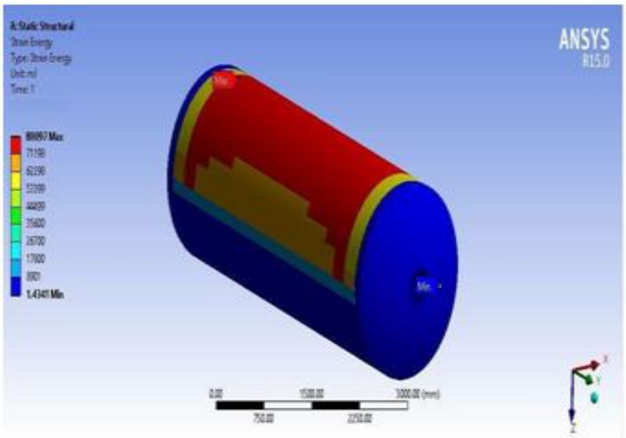

Figure 18: Strain energy of Reactor pressure vessel made of ss-304

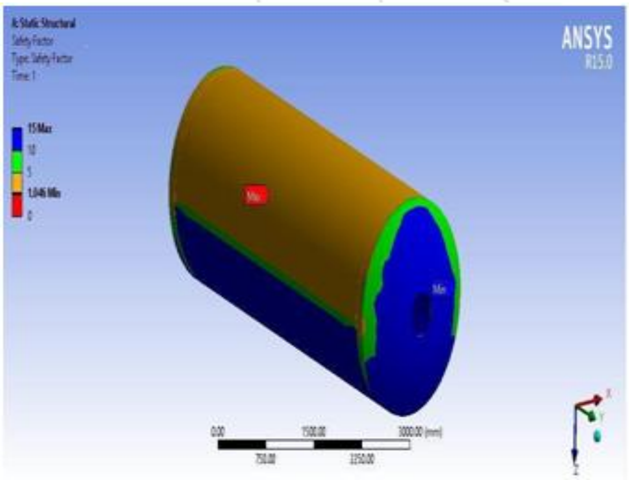

Figure 19: Safety factor of Reactor pressure vessel made of ss-306

Table 1: Deformation, stress, strain energy and safety factor values for different materials

Material	Deformation (mm)	Stress (Mpa)	Strain Energy (MJ)	Safety factor
Steel	1.3189	200.04	71424	1.2497
Al – 6061-t6	3.9154	206.26	207290	1.3381
SS -316	1.338	194.44	74028	1.4914
SS - 304	1.3556	197.84	74020	1.0867

Table 2: Weight estimation for 60mm thickness vessel

Material	Volume (mm^3)	Mass (Ton)
Steel	1.0156×10^9	7.9724
Al – 6061-t6	1.0156×10^9	2.4875
SS - 316	1.0156×10^9	8.1248
SS - 304	1.0156×10^9	8.1248

Table 3: Weight estimation for 80mm thickness vessel

Material	Volume (mm^3)	Mass (Ton)
Steel	1.1288×10^9	8.8611
Al – 6061-t6	1.1288×10^9	2.76491
SS - 316	1.0156×10^9	9.0304
SS - 304	1.0156×10^9	9.0304

Table 4: Cost estimation for 60mm thickness vessel

Material	Weight x Cost per ton ($)	Total Cost ($)
Steel	7.9724 x 800	5580.680
Al – 6061-t6	2.4875 x 2250	5596.875
SS - 316	8.1248 x 1400	11374.72
SS - 304	8.1248 x 2600	21124.48

Table 5: Cost estimation for 80mm thickness vessel

Material	Weight x Cost per ton ($)	Total Cost ($)
Steel	8.8611 x 800	7088.88
Al – 6061-t6	2.76491 x 2250	6180.5475
SS - 316	9.0304 x 1400	12642.56
SS- 304	9.0304 x 2600	23479.04

The deformation, stress, strain energy and safety factor values obtained for Al – 6061, ss-316, ss-304 materials are shown from Fig. 8 to Fig. 19. The results obtained from Fig. 4 to Fig. 19 are shown in Table 1. The weight estimation for 60 mm and 80 mm thickness reactor pressure vessel made of different materials is shown in Table. 2 and Table. 3. Results obtained for reactor pressure vessel made of different materials with thickness 60 mm and 80 mm are shown in Table 4 and Table 5.

4. Conclusion

In this work RPV (reactor pressure vessel) model is created using cad tool creo-2 and then it is analyzed with CAE tool ANSYS workbench. First reactor pressure vessel made with structural steel of 60 mm and 80 mm thickness is modeled and analyzed with the boundary conditions. With increase in thickness the pressure vessel gains more weight and reduces stress but it also increases cost due to increasing the weight. In order to reduce the cost of pressure vessel it is made with different materials such as aluminum alloy – 6061-t6, stainless steel - 316 and stainless steel - 304 and then these are analyzed in ANSYS workbench with the same boundary conditions. From the results pressure vessel made of stainless steel 316 produces less stress values but when cost estimation also is considered al-6061-t6 is better when compare to ss-316 cost.

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