INTERNATIONAL JOURNAL OF ADVANCE RESEARCH, IDEAS AND INNOVATIONS IN TECHNOLOGY

IJARIIT

ISSN: 2454-132X

Impact Factor: 6.078

(Volume 7, Issue 3 - V7I3-1397)

Available online at: https://www.ijariit.com

Design and Analysis of Tidal Compressed Air Electricity Generator

Siddhesh Sandeep Thakur
sidst150899@gmail.com
Bharati Vidyapeeth College of Engineering, Navi Mumbai, Maharashtra

Rohit Shetty
rohitshetty1123@gmail.com
Bharati Vidyapeeth College of Engineering, Navi Mumbai, Maharashtra

Kartik Shah
k4kartik0409@gmail.com
Bharati Vidyapeeth College of Engineering, Navi Mumbai, Maharashtra

Prathamesh Swami
ppswami30@gmail.com
Bharati Vidyapeeth College of Engineering, Navi Mumbai, Maharashtra

Vinayak Patil
vinayak.patil@bvcoenm.edu.in
Bharati Vidyapeeth College of Engineering, Navi Mumbai, Maharashtra

ABSTRACT

This project aims to extract as much energy as possible from ocean waves/ tides to shift the dependency of power generation from conventional sources. With the world now veering to electric vehicles, the electricity demand will increase rapidly. A Mechanical system is designed to utilize tidal or wave energy to compress air. The system includes a reciprocating compressor (piston contained in a chamber including an air intake port). This unit is connected to a storage tank with a non-return valve. The piston is driven by a lever arm which on the other end is attached to a movable power transfer shaft. A float is present on the lower end of the rod and is set in the ocean. As the float is displaced upwardly by waves, so are the rod and the lever arm compelling the piston at another end to compress air. The compressed air is stored at a high pressure in a storage tank. Multiple compressor units will aid in filling the tank faster and reducing the load on the compressor. The compressed air is then transferred from the storage tank to a turbine, where electricity is generated. The calculations are carried out for the complete setup while taking standard turbine data. The project mainly focuses on the design and analysis of Storage Tank (structural), buoy (structural and Hydrodynamic simulation) and motion study on the entire setup. The aim is to produce 3 MW power in one cycle (approx. 12 hours).

Keywords— *Buoy, Design, Finite element analysis, Renewable energy, Storage Tank, Wave energy*

1. INTRODUCTION

Nowadays, electricity is becoming a crucial aspect of life. Since everything in the world is getting digitalized and the auto industry veering towards electric vehicles, there is an increase in electricity demand. In India, the share of fossil energy is 63.76% [1], whereas renewable energy is only 33.4%. Out of 33.4%, a significant percentage of energy comes from Wind power, solar power and Hydropower dams. Even now, one crucial renewable energy source is still underdeveloped, which is wave energy. The utilization of Wave Energy can give a boost in the share of renewable energy. As the ocean covers nearly 71% of the earth's surface, it acts as a natural collector of this energy.

Ocean energy majorly comprises Thermal and Mechanical Energy. The project focuses on exploiting mechanical energy. The majority of wind power is transferred to the ocean surface, which generates wave [2]. The oscillatory motion of the waves can be used to compress air that in turn can be used to generate electricity. The basic idea of the project is to avail the up and down movement of the waves or tides to drive a piston that will compress the air. The compressed air is then stored and expanded in a turbine-generator and produces valuable energy, i.e. electricity.

The compressed air is to be stored in a tank. For this, compressed air energy storage (CAES) systems are mainly used. These systems store the compressed air mainly in an underground cavern or an abandoned mine [3]. This storage of air is required because renewable energy cannot be extracted continuously. We can use steel tanks where caverns do not exist, but the installation charges are pretty high.

The calculations are carried out on the setup and design. The analysis is done using CAD and CAE software, essentially Solidworks and Ansys, with the majority of focus only on storage tank and buoy. Solidworks was used for 3D modelling, and structural analysis and Ansys workbench was used for hydrodynamic analysis and wave simulation to check the floatation.

2. DATA COLLECTION

2.1 Waves

It is a challenging task to convert the vast energies in the ocean waves into electric energy. Hence, the study of waves and their parameters is a crucial aspect. To exploit the oscillatory motion of waves, the wave height and time period of the wave are necessary parameters to be known.

The required parameters were taken from a survey [2, 4] around Indian Coast. The average wave height and the time period considered for the project are:
Wave height: 1.5 m
Time period: 6.7 sec

2.2 Mechanism

Various mechanisms were referred [5-9], and the mechanism mentioned [9] was selected for the design. This mechanism is used to exploit the mechanical energy of the wave, especially the oscillatory motion. The system includes a reciprocating compressor (piston contained in a chamber including an air intake port). This unit is connected to a storage tank with a non-return valve. The piston is driven by a lever arm which on the other end is attached to a movable power transfer rod. A float is present on the lower end of the rod and is set in the ocean. As the float is displaced upwardly by waves, so are the rod and the lever arm compelling the piston at another end to compress air. The compressed air is stored at high pressure in a storage tank. Multiple compressor units will aid in filling the tank faster and reducing the load on the compressor. The compressed air is transferred from the storage tank to a turbine, where electricity is generated.

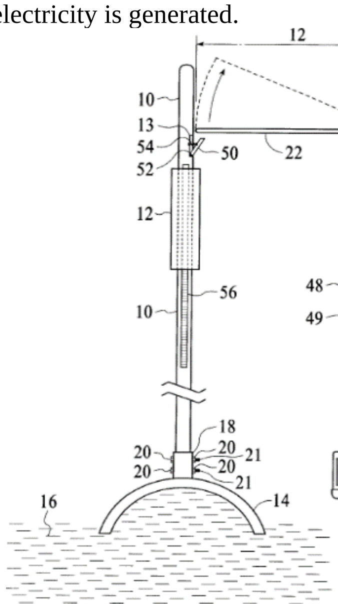

Fig -1: Compressed Air Electricity Generator [9]

2.3 Turbine

The turbine considered for the electricity generation is the Compressed Air Turbine-Generator (CAT-G) [10]. Data from the turbine was used for further calculations. Chart 1 shows the graph of flow speed versus shaft power generated for various inlet cross-sections, whereas Chart 2 shows the air pressure versus shaft output for the cross-sections. A power output of 3 MW in one cycle (approx. 12 hours) was decided and a cross-section of 1.02 m^2, so the flow speed of 1.05 m/s and air pressure of 9 atm were required inputs for calculations.

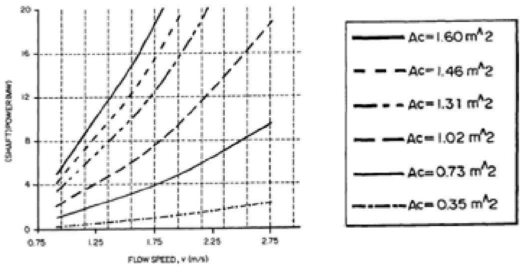

Chart -1: Shaft Power vs Flow Speed [10]

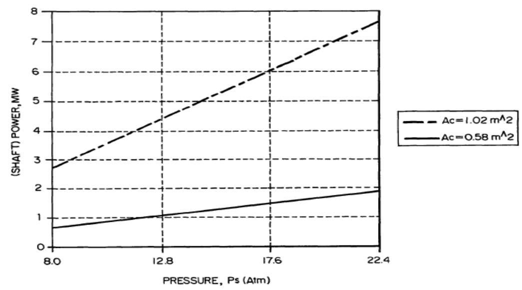

Chart -2: Shaft Power vs Pressure [10]

3. CALCULATIONS

3.1 Storage Tank

The compressed air from the compressor units is stored in the storage tank. Hence, the tank must be capable of sustaining the 9 atm pressure. The volume of compressed air required to generate the 3 MW in 12 hours approx of power from the turbine is

Volume stored, [10]

$$V = \frac{\Delta Q}{P_s \ \ln\left(\frac{P_s}{P_o}\right)} \qquad (1)$$

Where,
P_s - Storage tank pressure (9 atm)
P_o – atmospheric pressure
ΔQ – Energy to be generated (3 MW)

Thus, the required volume is around 5369.78 m^3 of compressed air. Storage tank capacity is rounded to 5500 m^3. The design is carried out so that it takes 10 hours to fill the required volume (5369.78 m^3). To run the turbine for the required output, the discharge is 1.071 m^3/s which takes 1.4 hours to empty the tank. During the discharging process, the charging of the storage tank can be carried out simultaneously.

Cylindrical containers are best suited, which are capped at the end of which common shapes of pressure vessel heads are typically hemispherical, ellipsoidal, and torispherical. In these shapes, an ellipsoidal shape is most appropriate [11]. Dimensions taken for storage tank are calculated for cylindrical with ellipsoidal head [12]. The internal length to diameter is taken as 3:1.

Total internal length (L_i),

$$L_i = h + R_i/2 \qquad (2)$$

We know that $L_i = 6R_i$
So, $h = 5.5 R_i$

The internal volume of cylinder (V_i)
V_i = volume of cylinder + 0.5*volume of ellipsoid

$$V_i = \Pi R_i 2h + 0.5 \frac{4}{3} \Pi R_i^2 \times \frac{R_i}{2} \qquad (3)$$

$V_i = 5500 \ m^3$ so, the value of R_i (internal radius) of cylinder is 6.695 m and cylinder height (h) is 36.823 m. Further, the internal length is calculated as 40.2014 m.

The outer radius (R_o) of the cylinder,

$$R_i = R_0 \sqrt{1 - \frac{1.73(Pi-P0)VMr\times S}{\sigma_y}} \quad (4)$$

Considering,
VM_r = Ratio of von misses stresses of head to cylinder = 1.5
S= Factor of safety = 25 (theoretical)
P_i= Internal pressure = 9 atm = 130.534 psi
P_0= outer pressure = 1 atm = 14.6959 psi
σ_y= Yield strength = 50991.06 psi

Hence, the outer radius of the cylinder is 7.2515 m.
Thickness of cylinder,

$$t = R_o - R_i = 0.5563 \text{ m} \quad (5)$$

Dimension of ellipsoidal head,

$$r_1 = 0.9\ D_i = 12.05145 \text{ m} \quad (6)$$

$$r_2 = 0.17\ D_i = 2.2763 \text{ m} \quad (7)$$

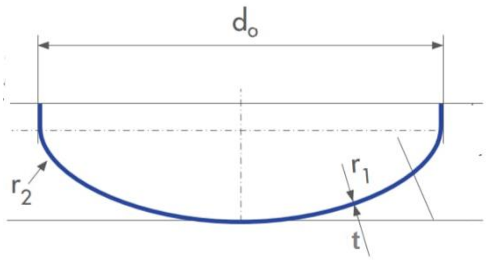

Fig -2: Ellipsoid Dimensions

3.2 Compressor

The fulcrum will drive the compressor through the up and down motion of the oscillating column. The compressor sucks the air from the atmosphere and will compress the air to 9 atm. Considering 40 compressor units, Total discharge (Q) from all the compressors of 536.9 m^3/hr, and the average time for one oscillation = 6.7 s (time period for waves, t),

The output volume from each unit in one oscillation is:
(Q * t)/no. of units (8)
536.9*6.7/ (40*3600) = 0.025m^3

Considering single-stage compressor and polytrophic process with the value of n = 1.3, [13]

$$PV^n = C \quad (9)$$

P_1: the pressure of air to be compressed = 1 atm
V_1: Volume of air to be compressed
P_2: Pressure of compressed air = 9 atm
V_2: Volume of compressed air = 0.025 m^3
We get, V_1 = 0.136 m^3

The lever arm ratio is taken as 3:1, and the average displacement from the wave is 1.5 m which gives a piston stroke of 0.5 m. So the compressor dimensions are a stroke (l) of 0.5m and a diameter (d) of 0.6m. Using the formula for volume of cylinder ($\Pi d^2 l$)/4.

3.3 Floating unit

The float is the unit that will be displaced by wave and drive the piston.

Force required to move the compressor piston,

$$F = P_{max} \times Area \quad (10)$$
$$= 911.925 \times \frac{\pi}{4} 0.6^2$$
$$= 257.8 \text{ KN}$$

The Force required on the float will be one-third of the Force on the piston (due to lever arm) i.e. = 257.8/3= 85.93 KN

After much iteration, the weight of the buoy came out to be 28 KN. After this iteration the change in diameter of buoy was negligible. Adding the weight to the force we get total force as 113.93 KN. Calculating the volume of water to be displaced for the same amount of Force,
Buoyant Force, [14]

$$F_b = \rho g V_{disp} \quad (11)$$
$$113.93*10^3 = 997*9.8*V$$
$$V = 11.66 \text{ m}^3$$

Taking hemispherical shell shape for buoy, the outer radius comes around 1.76 m.

4. DESIGN AND ANALYSIS

4.1 Setup

The mechanism is precisely discussed earlier in section (mechanism), with some minor changes, such as the buoy design. The buoy was designed heavier than the compressor piston so that the piston will move upward without the need for a spring mechanism.

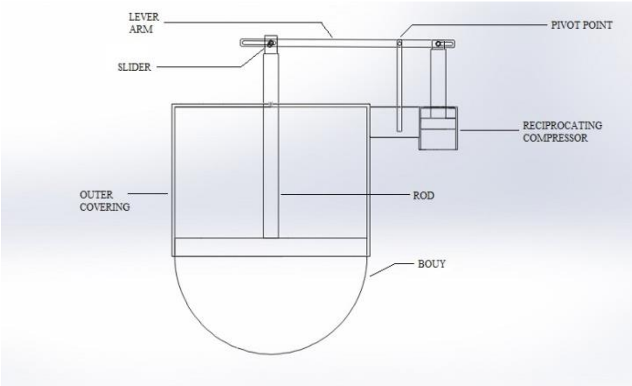

Fig -3: Designed Setup

4.2 Storage tank

After calculations, 3D models of the storage tank, the setup and float were made using Solidworks, and the analysis was carried out. Usually, a cylindrical tank with an ellipsoidal head is used for storing compressed air [15]. The storage tank was designed for 5500 m^3 with a cylindrical shape with an ellipsoidal head. The structural analysis was then carried out with carbon steel AISI 1020 as material in Solidworks, with 9 atm internal pressure as load conditions and the constraints given at all the sides since the tank was considered underground. For structural analysis for tank tetrahedral fine meshing was used (Figure 4) as tetrahedral mesh covers curvature of the shape properly. The mesh size is 711.065 mm, and the aspect ratio is 3.98.

Fig -4: Meshed tank for structural analysis

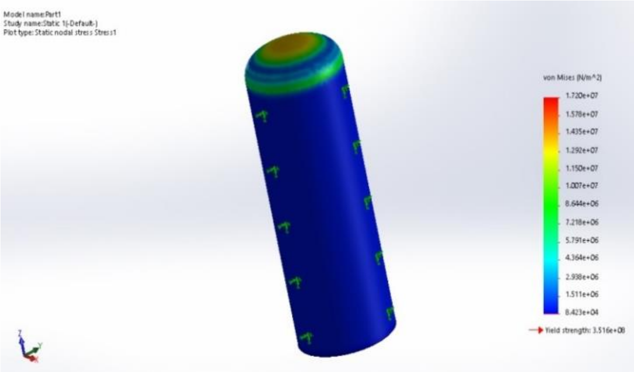

Fig -5: Stresses on Storage Tank

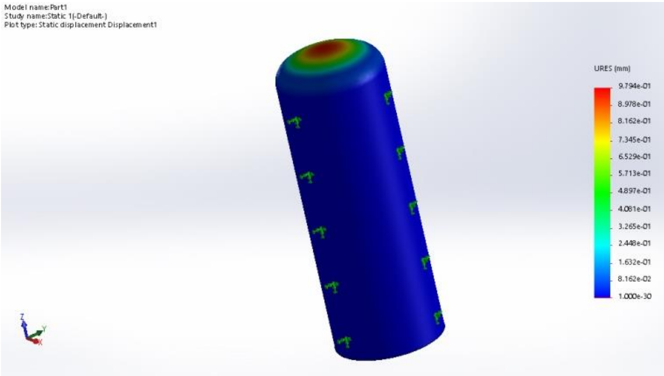

Fig -6: Deformation in the storage tank

The storage tank showed the maximum deformation of 0.97mm, and the maximum stress developed was 1.72 x 10^7 N/m^2. The stress generated is less than the yield strength of the material, and the designed tank has a Factor of Safety of 20.4. Hence, the design is safe.

4.3 Float/buoy

The float was also designed using Solidworks using a basic hemispherical shell. The float was also checked for hydrodynamic analysis in Ansys [16] to check its floatation. During hydrodynamic analysis, the object's mass was taken as the additions of both buoy mass (2800kg) and the Force (8593 kgf). The velocity of the wave was assumed to be 3 m/s, and the frequency was 0.1488 Hz. The hydrodynamic force which is obtained in the result is 80881N. We can also see the buoy floating in the motion study. Hence the calculation carried out for the flotation of the buoys by using the buoyant principle was came out to be correct.

For meshing, the triangles in tetrahedral elements will absorb most of the forces and will not give exact deformation. So, to avoid this in Hydrodynamic analysis, hexahedral elements were used. The element size range used is minimum element size of 0.001m to maximum element size of 0.05m.

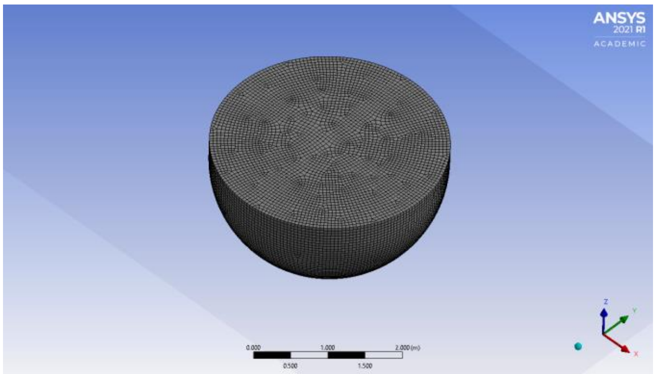

Fig -7: Meshed buoy for Hydrodynamic analysis

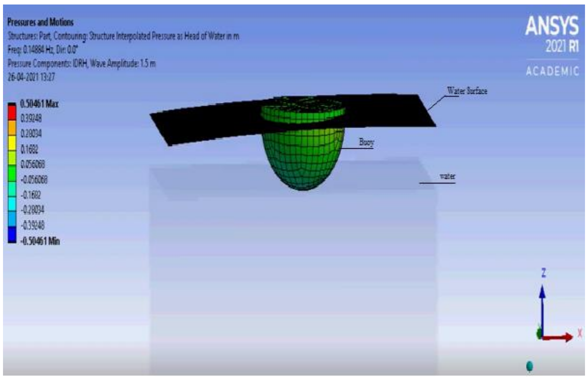

Fig -8: Hydrodynamic Analysis

Static-structural analysis: This analysis was carried on the float with different plastic materials such as polystyrene, polyurethane and polyethylene in SolidWorks. The load transmitted through the rod is considered in the buoy's structural analysis as the hydrodynamic Force is less. The mesh used for structural analysis is a mixed mesh with the majority of tetrahedral mesh as tetrahedral mesh covers the curvature of the shape adequately. The element size ranges from 1 mm to 50 mm, which gives about 200k elements.

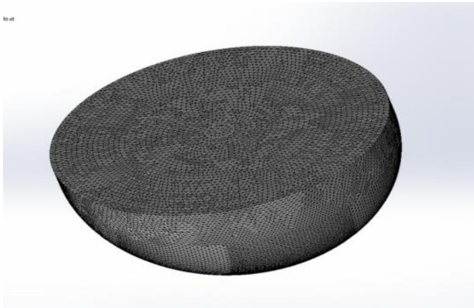

Fig -9: Mesh for Structural Analysis

CASE I

In the first case, the load of 87000N was applied at the hemispherical dome of buoy and constraints were applied on the flat surface of buoy but only at the region where the rod is attached to the buoy, i.e. 250 mm. Table 1 shows the results of the analysis.

Table -1: Structural Analysis Case 1

Material	Maximum stress (N/m^2)	Maximum Deformation (mm)
Polystyrene (Fig.10)	1.69 x 10^6	1.587
Polyethylene (Fig.11)	2.03 x 10^6	1.723
Polyurethane (Fig.12)	2.03 x 10^6	1.327

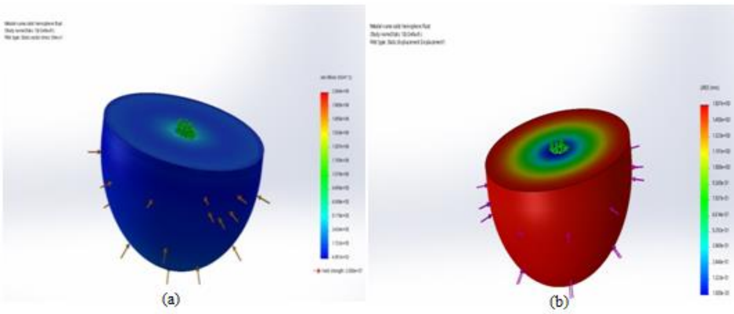

Fig -10: Polystyrene Structural analysis Case1 (a) Stress (b) Displacement

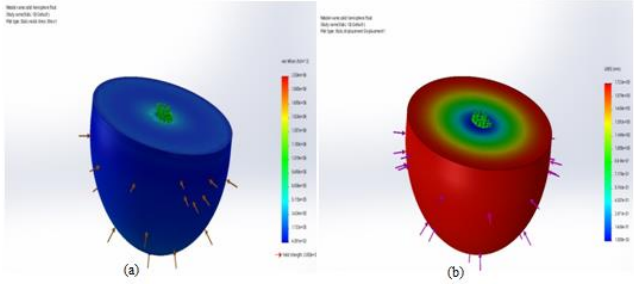

Fig -11: Polyethylene Structural analysis Case1 (a) Stress (b) Displacement

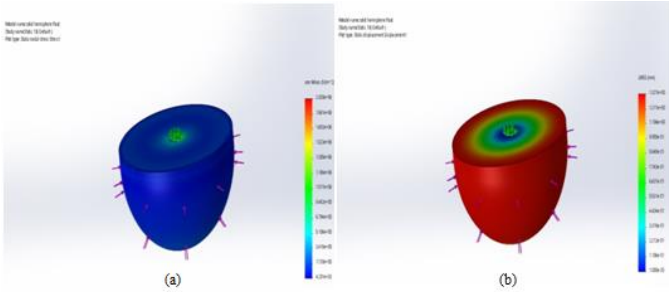

Fig -12: Polyurethane Structural analysis Case1 (a) Stress (b) Displacement

CASE II

In the second case, the load of 87000N was applied on the flat surface of the buoy but only at the region where rod is attached to the buoy, i.e. 250 mm and constrains was applied at the hemispherical dome of the buoy. Table 2 shows the results of the analysis.

Table -2: Structural Analysis Case 2

Material	Maximum stress (N/m^2)	Maximum Deformation (mm)
Polystyrene (Fig.13)	1.84 x 10^6	1.174
Polyethylene (Fig.14)	1.33 x 10^6	1.293
Polyurethane (Fig.15)	1.34 x 10^6	0.995

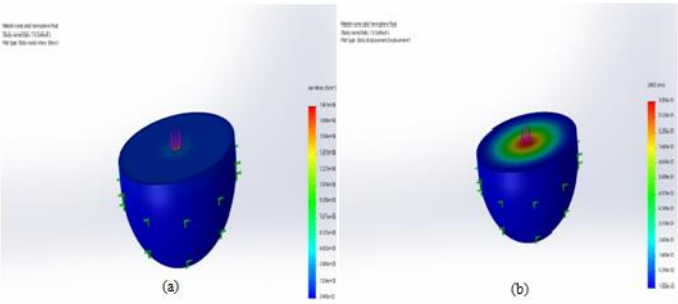

Fig -13: Polystyrene Structural analysis Case2 (a) Stress (b) Displacement

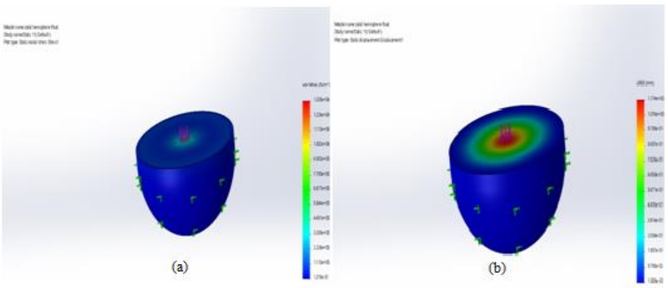

Fig -14: Polyethylene Structural analysis Case2 (a) Stress (b) Displacement

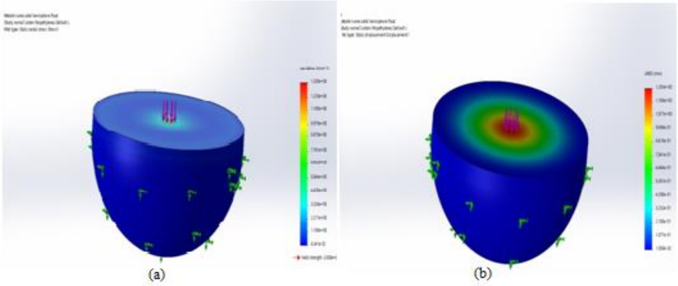

Fig -15: Polyurethane Structural analysis Case2 (a) Stress (b) Displacement

For the float, the deformations and stress in all the material are almost in the same range so; polyethylene material was considered as it has less weight and properties like durability and impact resistance. The float has a shell-like structure since the solid shape will have excess weight and will be a waste of material, so the buoy was optimized.

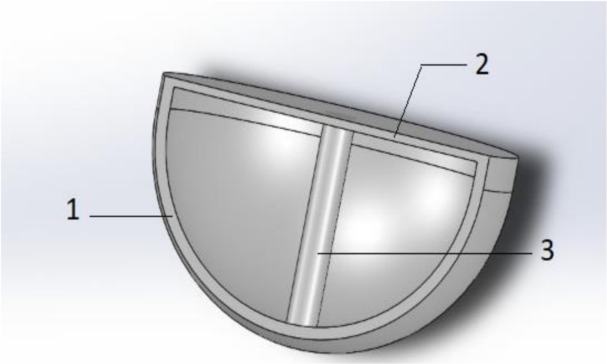

Fig -16: Sectional view of the designed buoy

Table -3: Dimensions of buoy

Number	Parameter	Dimension (mm)
1	Hemispherical Dome thickness	100
2	Base thickness	75
3	Inner Cylinder Diameter	250

5. RESULT

The different factors and parameters were considered to determine the design and carry out the calculations. The results obtained and the parameters considered are given in Table 4.

Table -4: Results

Sr. no	**Parameter**	**Values**
1	Average Wave height	1.5 m
2	Average Time Period for wave	6.7 s
3	Turbine inlet Area	1.02 m^2
4	Turbine inlet flow speed	1.05 m/s
5	The pressure of compressed air	9 atm
6	Discharge from the tank	1.071 m^3/s
7	Storage tank:	
	Capacity	5500 m^3
	Shape	Cylindrical
	Material	AISI 1020
	Internal Radius	6.695 m
	Thickness	0.556 m
	Total Internal Length	40.20 m
8	lever-arm ratio	3:1
9	Compressor:	
	Volume	0.05 m^3/unit

	Stroke	0.5 m
	Diameter	0.6 m
10	Buoyant Force	85.93 KN
11	Target Energy Generated per cycle (approx. 12 hours)	3 MW
12	Buoy Material	Polyethylene
13	Buoy Mass	2800 Kg

6. CONCLUSION

In this project, various mechanisms for generating electricity from ocean energy were studied, and a suitable mechanism and turbine is selected. The selected mechanism was further designed and simulated. The storage tank was checked for AISI 1020 material with a calculated dimension. Since the FOS for the storage tank was 20.44 and the deformation is less, i.e. 0.97mm, it is considered safe. As for the float, polyethylene material gave the better result as it has less weight and properties like exceptionally durable, and impact resistance. At 100 per cent efficiency, the setup must generate 3MW of power; for actual efficiency, the practical model can be made, which can serve as the future scope of the project.

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