Design Analysis of Power Extracting Unit of an Onshore OWC Based Wave Energy Power Plant using Numerical Simulation

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ABSTRACT

This research paper describes design and analysis of power extracting unit of an onshore OWC (Oscillating Water Column) based wave energy power plant of capacity about 100 kilowatts. The OWC is modeled as solid piston of a reciprocating pump. The power extracting unit is designed analytically by using the theory of reciprocating pumps and principles of fluid mechanics. Pro-E and ANSYS workbench softwares are used to verify the analytical design. The analytical results of the flow velocity in the turbine duct are compared with the simulation results. The results are found to be in good agreement with each other. The results achieved by this research would finally assist in the overall design of the power plant which is the ultimate goal of this research work.

Key Words: **OWC, Power Plant, Wave Energy, Ocean Energy.**

1. INTRODUCTION

Energy is the basic need of life. From ancient times it can be seen that energy has been used in three forms; low temperature heat for comfort of human beings, force required for motion and high-temperature heat in order to work on materials and lightening purposes. These forms of energy are still in extensive use. After industrial revolution, there was need of more energy and hence extensive use of fossil fuels started to meet the growing energy demands [1]. Being inexpensive and easily available, the fossil fuels lead towards the usage of mechanical engines and other machinery. However, fossil resources are limited and are rapidly depleting. Therefore, there is a need to exploit renewable energy resources. The renewable energy covers all forms of energy in which the source is continuously replenished [2]. The various types of renewable energy resources are shown in Fig. 1.

Among these renewable energy resources, ocean wave energy is an abundant, persistent and clean source of power and is available round the clock. Wave energy technology is an emerging technology [3-5]. Comparison among various renewable energy resources is given in Table 1.

According to World Energy Council, 2 TW of energy can be captured from world's oceans which are equivalent of twice the world's electricity production [7]. Pakistan is

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gifted with a long coastline and great source of ocean energy is available. This energy can be exploited to cope up with current crisis of energy shortage in Pakistan. This paper describes the design and simulation of power extracting unit of an onshore OWC based ocean wave energy power plant.

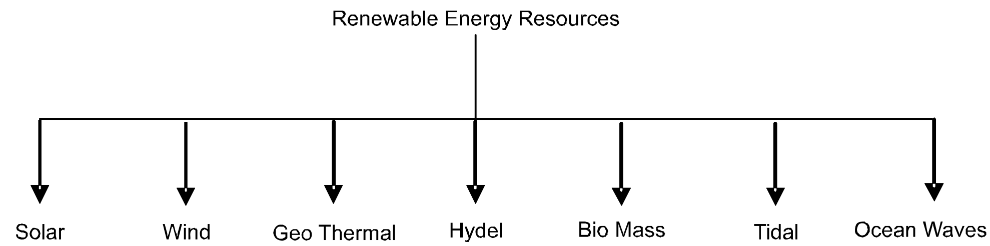

FIG. 1. DIFFERENT TYPES OF ENERGY RESOURCES

TABLE 1. ADVANTAGES AND DISADVANTAGES OF RENEWABLE ENERGY RESOURCES

Energy Type	Advantages	Disadvantages
Solar	Clean power source	Not available round the clock
	Inexhaustible power source	Solar panels are visually obstructive
	Free power source	Expensive to build
Wind	Clean power source	Not available round the clock
	Inexhaustible power source	Wind mills are visually obstructive
	Free power source	Expensive transmission of electricity
Geo Thermal	Clean power source	Not available in many locations
	Theoretically inexhaustible power source	Not much power per vent
	Free power source	Occasional escape of harmful gases & minerals
	Do not require structures like solar panels and wind mills	
Hydel	Clean power source	Requires high initial investment
	Water is free power source	Nearby areas are flooded
	Cost of hydro-electricity is very low	Availability of water depends upon rains
Bio Mass	Cheap source of energy	Not clean power source
	Theoretically inexhaustible power source	Requires ample space to grow bio mass crops
	Available throughout the world	Conversion into alcohol is expensive
	Easy to convert into high energy portable fuel such as alcohol or gas	
Tidal	Clean power source	Not available round the clock
	Inexhaustible power source	Only produce electricity during tidal surges
	Free power source	
	Tides are predictable	Construction of dams to capture tidal energy is expensive
	Generation of electricity is reliable	
Ocean Wave	Clean power source	Output from wave power plant is fluctuating but can be accommodated by using dump loads
	More consistent	
	Available round the clock	
	No visual obstruction	
	Higher power production owing to high density of water	
	Costs per net kilowatt are in the range of wind and below solar [6]	

2. LITERATURE REVIEW

Wave energy extracting devices may be classified in several ways. One way is to classify according to location in the sea. On the location basis they are onshore, nearshore and offshore devices [8-9]. Onshore devices are low cost, relatively easy to maintain and install [10-11]. They do not require deep-water moorings and long underwater electrical cables. This lessens the cost of installation of the plant and so improves the overall economy of the project. Although less wave energy is available onshore in comparison to nearshore and offshore locations but this is partly compensated by the concentration of wave energy that occurs naturally at some locations by refraction.

Three major classes of onshore devices are the OWC, the convergent channel (TAPCHAN) and the pendulor. The TAPCHAN requires low tidal range and a suitable onshore location. These requirements limit the wide acceptance of TAPCHAN. The pendulor devices installed worldwide are very small [9,12]. Where as OWC is more studied, tested and is found more promising, reliable and mature technology. Many full scale prototypes and projects built all over the world are based on this principle [13]. The world's first commercial wave energy power plant LIMPET connected to national grid of UK is an onshore OWC based wave energy power plant. During design and construction of an onshore OWC based wave energy power plant the design of power extracting unit , selection and design of turbine (power take off unit) and generator (power generation unit) require special attention [14-15]. The power extracting unit translates wave energy into pneumatic energy. Then, this pneumatic energy is converted into mechanical energy by turbine. Literature reveals that different kinds of turbines have been used for conversion of pneumatic energy into mechanical energy. Basic requirement of the turbine is that it should rotate in one direction in bidirectional air flow [16], such turbine is known as self-rectifying turbine. The Wells turbine was the first conception used in almost all early OWC plants. But this turbine has some inherent disadvantages [11].These disadvantages are narrow range of flow rate for high efficiency, mechanical solicitation due to reciprocating axial thrust, aerodynamic stalling and high rotational speed contributing towards high noise, etc. The disadvantages associated with the Wells turbine were mitigated by new concept i.e. self-rectifying impulse turbine. Focus of attention has been shifted towards impulse turbine during the last decade [16-17]. Impulse turbines can be axial flow type or radial flow type [18]. This mechanical energy produced by turbine is converted into electrical energy by power generation unit. Power generation unit incorporates selection and design of a suitable matching electrical generator, conventional electrical and control equipment. A variable speed electrical generator enables the turbine to respond more efficiently to a wide range of sea states. It also permits a temporary storage of excess available energy, by flywheel effect, with a short term smoothing effect on the electrical power supplied to grid. This is important for small grids in particular [15].

3. DESIGN OF POWER EXTRACTING UNIT OF ONSHORE OWC BASED WAVE ENERGY POWER PLANT

The main motivation behind the proposed research is to design a power extracting unit of an onshore OWC based wave energy power plant. Fig. 2 shows the schematic of onshore OWC wave energy power plant.

The OWC based wave energy power plant consists of a concrete or steel structure which is partially submerged in the sea water. This structure has an opening towards the sea below the water line, therefore enclosing air above the column of water as shown in Fig. 2. When waves of sea water travel and reach to the structure, they cause the water column inside the chamber of the structure to rise and fall. This rise and fall i.e., oscillation of water column causes the air to exhale and inhale. The exhaling and inhaling air is allowed to pass to and from the atmosphere through a self-rectifying turbine which drives an electric generator [19-21].

It is observed that the working of an OWC is analogous to the operation of a reciprocating pump. Therefore, OWC can be modeled as solid piston [5]. A set of equations can be derived for the design of OWC by modeling it as a solid piston. It is required to design power extracting unit of an onshore OWC based wave energy power plant of about 100 kW capacity. The available average wave power for Pakistan is around 10 kW/m wave crest [9]. The design equations are derived as follows:

The velocity of the piston is given by Equation (1) [22]:

$$V = \omega r \sin\theta \quad (1)$$

where ω is angular speed of rotating crank and r is radius of rotating crank. Velocity of piston is maximum at middle of the stroke when $\theta = 90^o$, so by substituting this value in Equation (1) we have maximum velocity, V_{max} as shown in Equation (2).

$$V_{max} = \omega r \quad (2)$$

The angular speed, ω is shown in Equation (3).

$$\omega = 2\pi N/60 \quad (3)$$

where N is denoted for revolutions per minute of rotating crank. By substituting Equation (3) into Equation (2) we have:

$$V_{max} = (2\pi N/60)r \quad (4)$$

Equation (4) can be rearranged as Equation (5):

$$V_{max} = \pi(N/60)(2r) \quad (5)$$

As f=N/60 and L=2r, where f is frequency and L is stroke length. By substituting these in Equation (5) we have new form of the equation as shown in Equation (6):

$$V_{max} = \pi.f.L \quad (6)$$

Stroke length L can be replaced by significant wave height (H_s), in Equation (6) resulting in Equation (7).

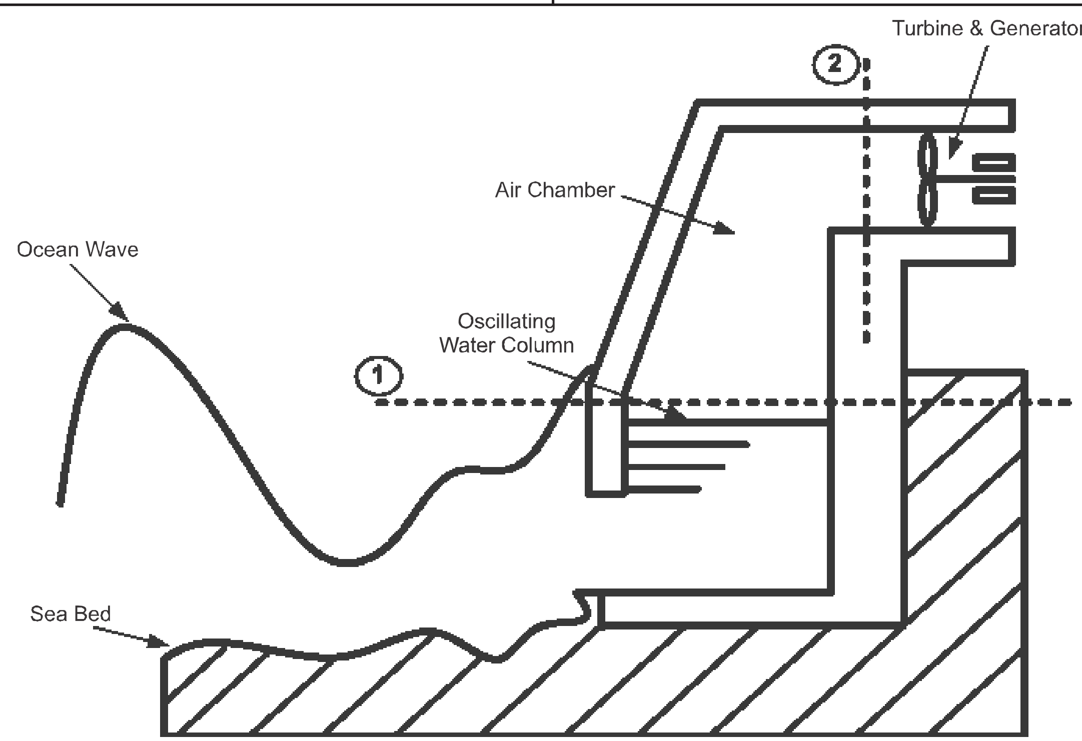

FIG. 2. SCHEMATIC OF ONSHORE OWC BASED WAVE ENERGY POWER PLANT

$$V_{max} = \pi.f.H_s \tag{7}$$

The significant wave height, H_s can be used to find out the wave power, P (measured in kW/m) by Equation (8) [10].

$$P = 0.49H^2_s\,T_e \tag{8}$$

where T_e is zero up-crossing period. Setting T_e=5 sec and P=10 kW/m (average wave power received by Pakistan 10 kW/m wave crest) in Equation (8), the significant wave height is calculated as:

$H_s = 2m$

Now by substituting the values of Hs and f (i.e., 1/ Te) in Equation (7), the maximum velocity, at the middle of the stroke in OWC is found as:

$V_{max} = 1.25m/s$

Minimum velocity, V_{min} is zero at the ends of the stroke, so an average velocity, V_{av} with which water oscillates in OWC is calculated by taking an average of V_{max} and V_{min} and that comes out to be as:

$V_{av} = 0.63m/s$

The dimensions of air chamber (Section 1 and Section 2 in Fig. 2) are shown in Fig. 3.

The air chamber is connected to the turbine by a duct. The maximum power can be achieved by using duct diameter of 1m. Now the flow rate of air through the air chamber and the turbine duct is created by the incident waves. Here it should be clarified that air is a compressible fluid but for subsonic flow especially at Mach number less than 0.3 it may be treated as incompressible fluid [23]. The flow rate of air can be obtained by using equation of continuity as in Equation (9).

$$A_1V_1 = A_2V_2 \tag{9}$$

where A_1 and A_2 are cross sectional areas, and V_1 and V_2 are velocities at Sections 1 and 2 respectively (Fig. 2). The areas A_1 and A_2 are calculated to be 100 and 0.786m^2 respectively. Velocity V_1 taken equal to average velocity of water in the OWC is 0.63 m/s as calculated earlier. The velocity of air in the turbine duct V_2 can be computed by putting these values in Equation (9) which comes out to be 80.153 m/s.

Now estimated power of air in the turbine duct can be computed by substituting V_2 and A_2 in Equation (10).

$$P_{air} = \frac{\rho.A_2V_2^3}{2} \tag{10}$$

where ρ is the density of air taken as 1.18 kg/m^3. P_{air} is calculated as 238.8 kW. The power output of turbine can be calculated by using Equation (11).

$$P_{tb} = \eta_{tb}.P_{air} \tag{11}$$

Taking efficiency of the turbine, η_{tb}, as 50%, the resultant power output of the turbine is found to be 119.4 kW.

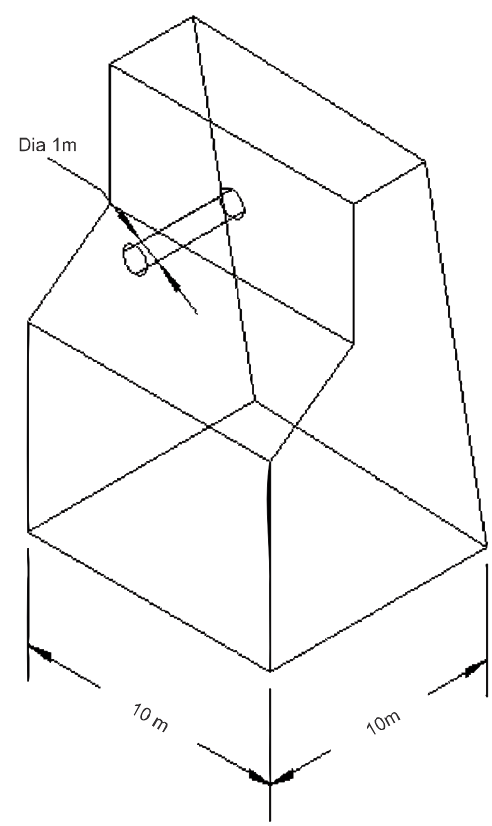

FIG. 3. AIR CHAMBER OF OWC

4. SIMULATION RESULTS

The proposed design of air chamber of power extracting unit is modeled using the Pro-E software. The flow analysis of the proposed model is carried out using ANSYS work bench. The air chamber model in Pro-E and ANSYS is shown in Fig. 4.

The next step in analysis is to have wire frame mode for the model of the air chamber. After having the wire frame mode of the model the boundaries of the model are created, and domain is made. Domain provides the field surrounded by the object where the analysis is carried out. Fig. 5 shows the wire frame mode of the model and model with boundaries respectively.

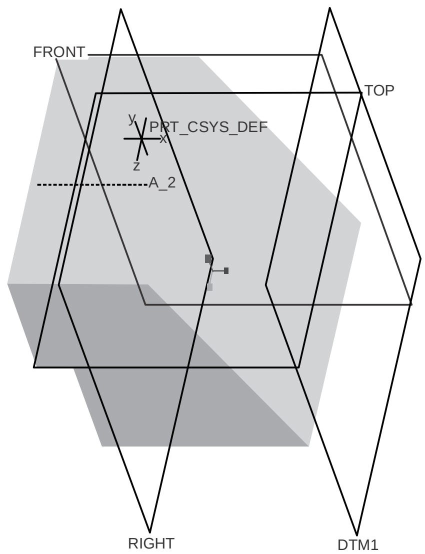

FIG. 4(A). MODEL OF AIR CHAMBER IN PRO-E

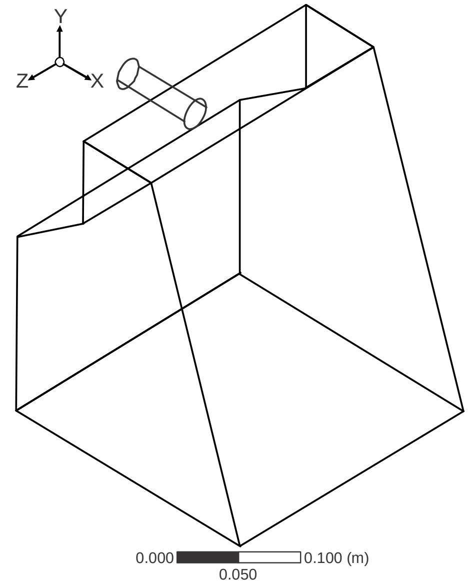

FIG. 4 (B) AIR CHAMBER IN ANSYS AFTER IMPORTING FROM PRO-E

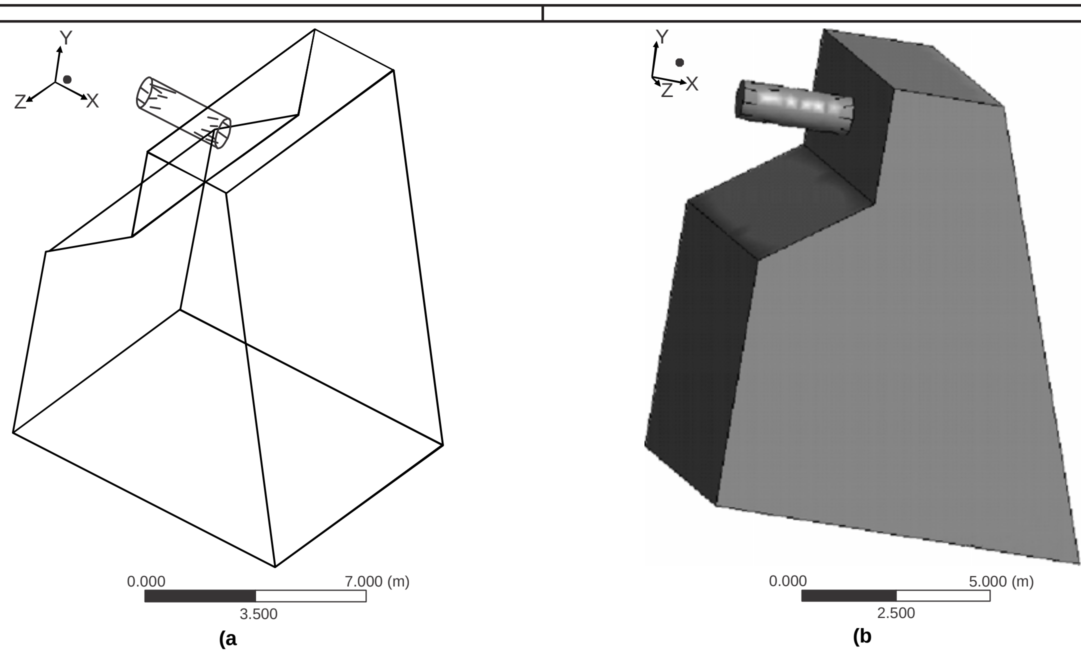

FIG. 5(A). WIRE FRAME MODE (B) MODEL WITH BOUNDARIES

Now it is required to mesh the model. The meshed model is exported to CFX solver version of ANSYS for flow analysis. There are the following three major steps to perform the flow analysis:

(i) Plotting of velocity vectors

(ii) Plotting velocity contours

(iii) Overall velocity distribution

The resultant meshed model of the air chamber and the turbine duct is shown in Fig. 6(a). Plotting of the velocity vectors is shown in Fig. 6(b). The velocity vectors for the turbine duct can be seen in this figure are of orange color. In the velocity bar, the orange color lying in the range of 78-85 m/s describes the velocity of air in the turbine duct. The velocity contours are plotted in Fig. 6(c).The velocity contours show the velocity of air in the turbine duct equal to 80 m/s.

The velocity distribution over the whole model is shown in Fig. 6(d). The color scheme at the turbine outlet duct when compared with the bar graph indicates the same range of air velocity as mentioned earlier. This resultant velocity from simulation matches with the analytically computed velocity, which gives validation of our results.

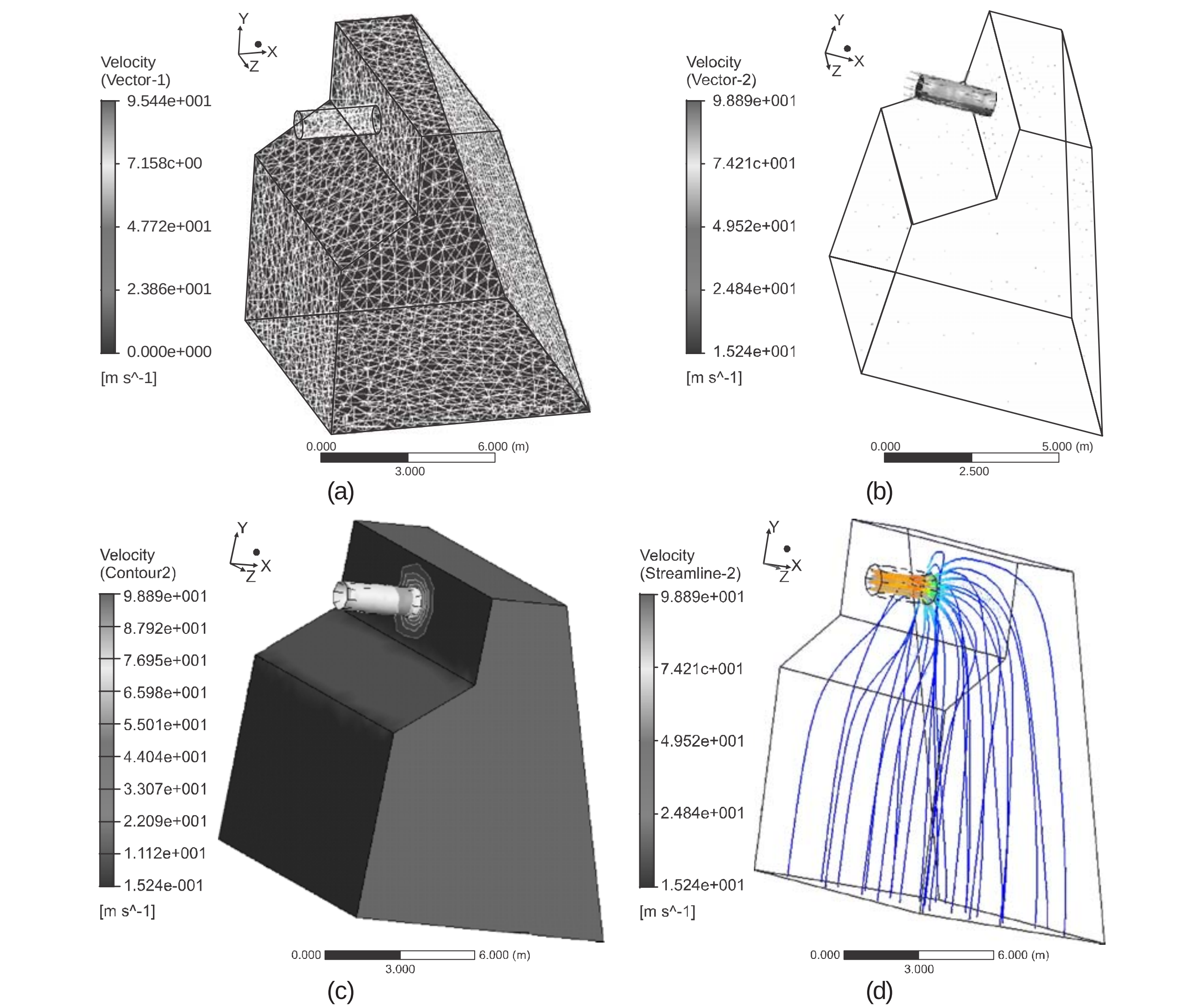

FIG. 6(a). MESHED MODEL (b) VELOCITY VECTOR FOR TURBINE DUCT (c) TURBINE DUCT VELOCITY CONTOURS (d) VELOCITY DISTRIBUTION OVER THE WHOLE MODEL

5. CONCLUSION

Power extracting unit of an onshore OWC based wave energy power plant of capacity about 100 kilowatts has been designed. The cross sectional areas of air chamber and the turbine duct are taken as 100 and $0.786m^2$ respectively. By taking incident wave power 10 kW/m with zero up-crossing period as 5 seconds, the average velocity of air in the air chamber is 0.63m/s. Velocity obtained in the turbine duct is 80.153m/s. Simulation results are in conformity with analytical results. Power of air in the turbine duct is calculated as 238.8 kW. By taking efficiency of the turbine as 50% the power output of the turbine comes out to be 119.4 kW.

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