Numerical Prospect of Ocean Wave Energy Harvesting Using Wells Turbine in Saint Martin Island, Bangladesh

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF REQUIREMENT FOR THE DEGREE OF BACHELOR OF SCIENCE IN MECHANICAL AND PRODUCTION ENGINEERING

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CERTIFICATION OF RESEARCH

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I HEREBY DECLARE THAT THE WORK PRESENTED IN THIS THESIS IS CARRIED OUT BY THE AUTHOR THEMSEVES UNDER THE WATCHFULL SUPERVISION OF DR.NURL ABSAR CHOWDHURY.EACH OF THE AUTHORS CONTRIBUTED EQUALLY IN FULFILLMENT OF THE THESIS PROJECT.

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ABSTRACT

Oscillating water column (OWC) powerplant harvests ocean wave energy by utilizing the rise and fall of ocean water level. In our project we designed a water column for the water level to rise and fall. And a pressure chamber to create substantial pressure drop in order to help the turbine to rotate. And turbine used for power generation is a Wells turbine, so that it can generate continuous power. The wave data i.e wavelength, time period, amplitude etc. were taken for the location of Saint Martins Island, Bangladesh. And Modelling of the power generation was done similar to the powerplat of Mutriku, Spain. For the blade design of the turbine, we used NACA 0015 model to maintain bade symmetry. The result obtained was very satisfactory and it showed a number of 16 generation units can easily meet the demand of power for Saint Martins Island, Bangladesh using (OWC) powerplant.

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Chapter 1: Introduction

1.1 Background:

Day by day the scarcity of energy around the globe is more and more evident. We currently harness energy in a number of ways that includes fossil fuel, nuclear, wind, solar, ocean wave and other renewable forms of energy. Among all of these ocean wave energy harvesting is the one of the cheapest and cleanest form of energy. Fossil fuel energy is the most common form of energy all around the world. And the most important factor for the modern world is a supply of sustainable energy[1]. Since fossil fuel is an exhaustible source of energy it can never be sustainable. Other forms of energy like nuclear energy have high initial set-up cost. Which is not suitable for use in small locations like Saint Martin's Island. There is also a concern of waste management in case of nuclear power. Research and Development of ocean wave energy utilization particularly in Europe is going on for a long time now and they came up with some bright technologies to deal with this problem of harnessing energy [2]. Carija et. al. dealt with involvement of Wells Turbine for power generation from ocean waves and it was seen that this model of turbine is very handy in continuous power generation [3]. Sunil Kumar Mishra along with other authors proposed a MPPT based algorithm for maximizing power output from OWC powerplant [4]. Alberdi et. al. used and optimized control system for controlling the stalling behavior of the turbine blades in order to generate power and showed that power output incase of controlled generation is much higher than uncontrolled generation [5]. Marjani et. al. did numerical modelling of OWC power plant by simulating the flow characteristics using FLUENT [6]. Fares et. al. simulated an OWC powerplant in the environmental factors of Mutriku, Spain and used DFIG model for power conversion and achieved significant results for efficiency enhancement and meeting the power demand [7] . Antonio et. al. designed and simulated a 400 KW OWC powerplant in Picco, Portugal and the paper presents the life of that powerplant for 20 years and some possible modifications [8] . Gato and Warfield did an experimental investigation of High -Solidarity Wells turbine in OWC power plant with 0.6m rotor diameter [9]. Sheng et. al. did a comparison between biradial and Wells turbine for the OWC powerplant in Mutriku, Spain [10].

1.2 Aim of our project work:

Although there are many existing OWC powerplant all around the globe but this technology has not yet been used in perspective of Bangladesh. Even though OWC powerplant has a huge potential for Bangladesh. The main aims of our work are:

- To check the feasibility of OWC powerplant in Bangladesh
- Getting an estimated idea about initial installation cost
- To find how many units are required to successfully meet the demand of Saint Martin's Island, Bangladesh

1.3 Project Work:

We simulated a OWC powerplant in Sain Martins Island, Bangladesh using data from BORI (Bangladesh Oceanographic Research Institute) and Modelling was done based of OWC powerplant in Mutriku, Spain.

1.4 Outcome of Project Work:

After the works fulfillment we can say that all of our objectives have been achieved and satisfactory results were obtained. And our calculations showed that 16 OWC units are required to meet the demand completely.

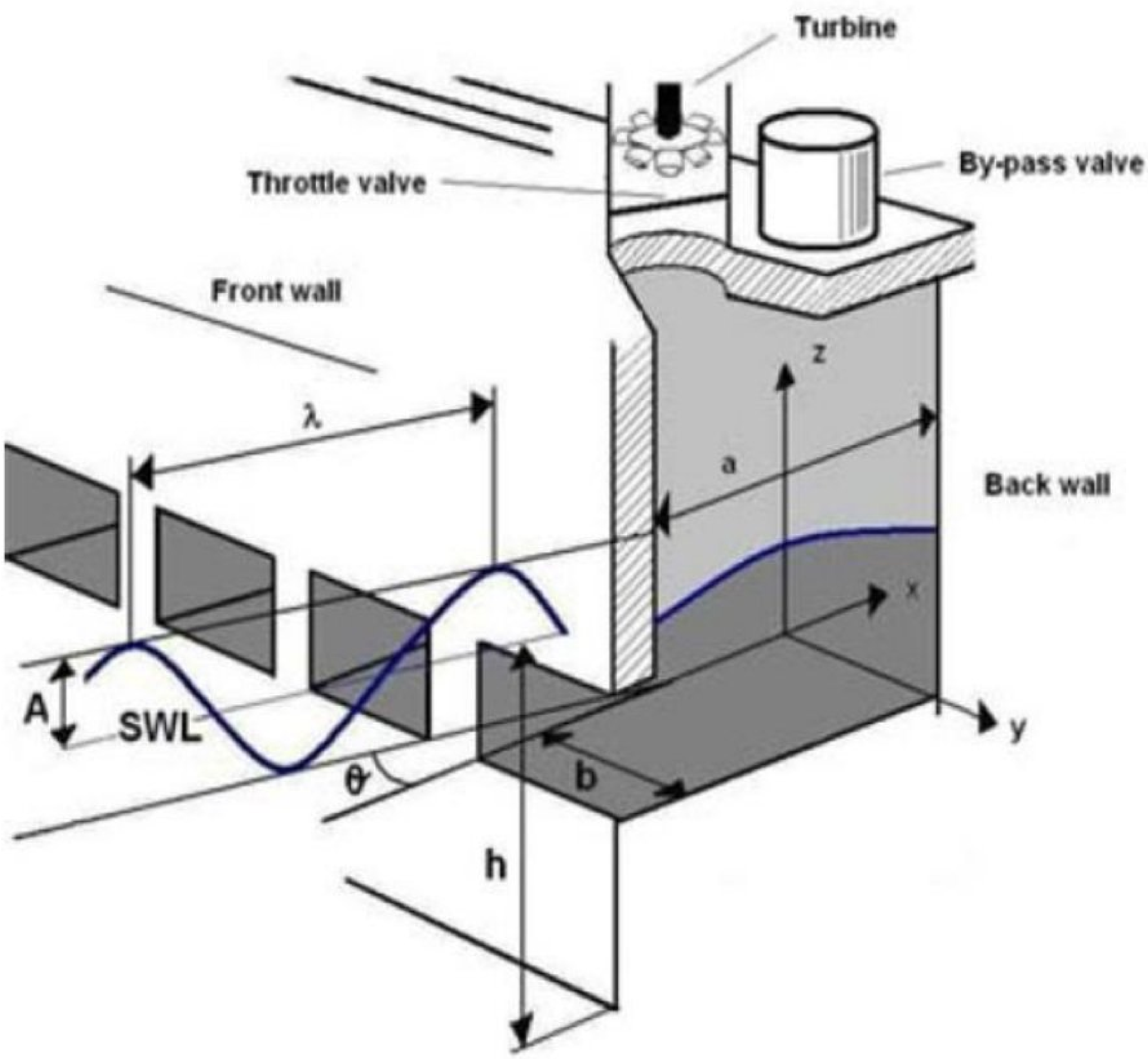

Figure 1: Oscillating Water Column Unit [5]

Chapter 2: Literature Review

In recent years there has been many advancement and improvements in the field of ocean wave energy harvesting technologies and many research works are still going on. Some of the significant works have been analyzed and validated in our project work

Alberdi and his co-authors have tried to improve the efficiency of an OWC powerplant using two different type of control systems. Their strategy was to introduce two control system one for air-flow another for rotational speed of the Wells turbine used for power generation. The air-flow control system was used to help the power generation unit to cope up with changing pressure-drop inside the chamber. While the rotational speed control system was to achieve smooth turbine operations. Their work showed that using this two control system significantly improves instantaneous power output and also helps increasing the overall efficiency of the OWC plant[5].

El Marjani et. al. dealt with a numerical model to predict the flow characteristics of different components of an OWC powerplant. They modeled the flow behavior with FLUENT. Turbulence of the air-flow was assumed to be k-ϵ model. They focused on particular energy loss which could affect the aerodynamic efficiency of the turbine. Their work considered the flow to be 3-D, viscous and turbulent [6].

Fares et. al. modeled an OWC powerplant situated in Mutriku, Spain. They used Model-in-Loop (MIL) and Software-in-Loop (SIL) as frameworks. For energy conversions along with Wells turbine they used Doubly-Fed-Inductive-Generator (DFIG) model. They chose a model of Wells turbine from 1970s for power generation. Their Simulink simulation showed that their validation was practical and model created by them actually simulated the power plant [7].

Antonio et. al. described and analyzed an OWC powerplant situated in Pico, Portugal. This is a shoreline OWC powerplant with 400 KW capacity, which uses a horizontal axis Wells turbine. Their paper describes life of the powerplant, its modifications and upgradations [8].

Carija et. al. did a numerical analysis of Wells turbine used for energy conversion. They simulated the flow characteristics of the turbine is software package FLUENT. Later they also simulated the operation of the turbine in Adriatic Sea conditions. And found that the output result was very satisfactory [3].

Sunil Kumar Mishra along with other authors of the paper took an optimization-based approach with maximum power point tracking (MPPT) algorithm for selection of appropriate external rotor resistance. They found out that one of the major problems with Wells turbine is that it has huge loss of power due its stalling behavior. This stalling can be control using rotor resistance. Their work tried to solve this problem in two ways (i) manually selecting the rotor resistance values. (ii) using particle swarm optimization method to select the rotor resistance values. In order to simultaneously increase average power output. Their simulations were done for turbine efficiency, power output and power loss in external rotor resistance [4].

Sheng et. al. did a comparative analysis between biradial and wells turbine for OWC powerplant in Mutriku, Spain. Each wells turbine is connected to a generator of 18.5 KW. In order to tackle the limitation of Wells turbine because of its stalling behavior and reduction of output power a new biradial turbine was simulated. This turbine had radial-guide flow vanes. They compared these two types of turbine based on time-domain model. A new hydrodynamic frequency model was designed for the powerplant using WAMIT software package [10].

Justino and Falcao dealt with the control of an OWC powerplant using variable speed electric generator. The control is regulated by changing the electric torque. Moreover, the speed of the turbine was made to match the sea energy level for maximum possible energy output. They proposed three different control strategies, two of them were numerically feasible [11].

Justino et. al. dealt with numerical simulation of OWC powerplant equipped with by-pass air valve. The main function of that valve was to keep the air-flow to the turbine below stalling conditions. Their work mainly analyzed number of valves, signal noise level in air-pressure chamber, valve response time and valve control algorithm [12].

Nader and Ehsan worked with chamber geometry of the OWC model. They did a number of experiments with different chamber geometry and tried to find which one is the most suitable for increasing the efficiency of the plant. They initially worked with chamber dimensions 10x50x53 cm. They observed that increasing the wave length could increase the outflow of air by 11%. And also the relative positions of back and front plate of the chamber changes the efficiency of the plant. And according to their experiment number 13 the efficiency of the plant can be up to 32% [13].

Paolo Boccoti compared a conventional OWC with a U-OWC. The only difference between these two is that a U-OWC chamber design has a vertical open duct on the wave beaten side of the chamber. Due to this vertical duct the eigen period of a U-OWC is greater than that of a conventional OWC. Secondly, the amplitude of the pressure fluctuations due the vertical duct is much higher than without duct. And after his work he found that for the higher eigen period the U_OWC could had better performance during high wind waves. And due to the second reason it was equally better during light wind waves [14].

Farrokh and Abdusselam worked with two sets of modeling each involving a numerical and a physical model to find the optimum chamber geometry for maximum power output. They found the optimum dimensional values from interpretation. They used Nash-Sutcliffe coefficient of efficiency as a criterion for evaluating the performance. Their experiment and numerical results were almost similar and hence satisfactory [15].

Howe and Nader investigated the hydrodynamic performance of two types of bent-duct OWC device with different inlet geometry. One of them is a rectangular duct other is a circular duct. They used a FEM based model. It was seen that difference was only around natural resonance of frequencies. And they significantly increased the capture width of water inside the chamber [16].

Chapter 3: Methodology

3.1 Ocean Wave Modelling:

It is difficult to mathematically model and analyze a periodic progressive wave. Researchers have suggested ranges of application for different wave theories, as shown in Fig. 1. Hence, various regular wave theories have been developed by the scientists to explain the kinematics of water particle based on the waves of varying degrees of complexity. The theories include Stokes second-order and other higher order theories, linear or Airy wave theory, stream-function and cnoidal wave theories. Among all of the theories, the earliest and the simplest explanation, attributed to Airy theory in 1845, is sufficiently accurate for many engineering purposes. Airy wave theory which is also known as Linear wave theory explains ocean waves as simple sinusoidal waves. However, surfaces waves can be ramified according to the ratio of the wavelength (L) to the water depth (h) as shown below [17], [7]

- Deep Water: $h/L > 0.25$.
- Transitional Water: $0.25 \geq h/L > 0.05$.
- Shallow Water: $0.05 \geq h/L$.

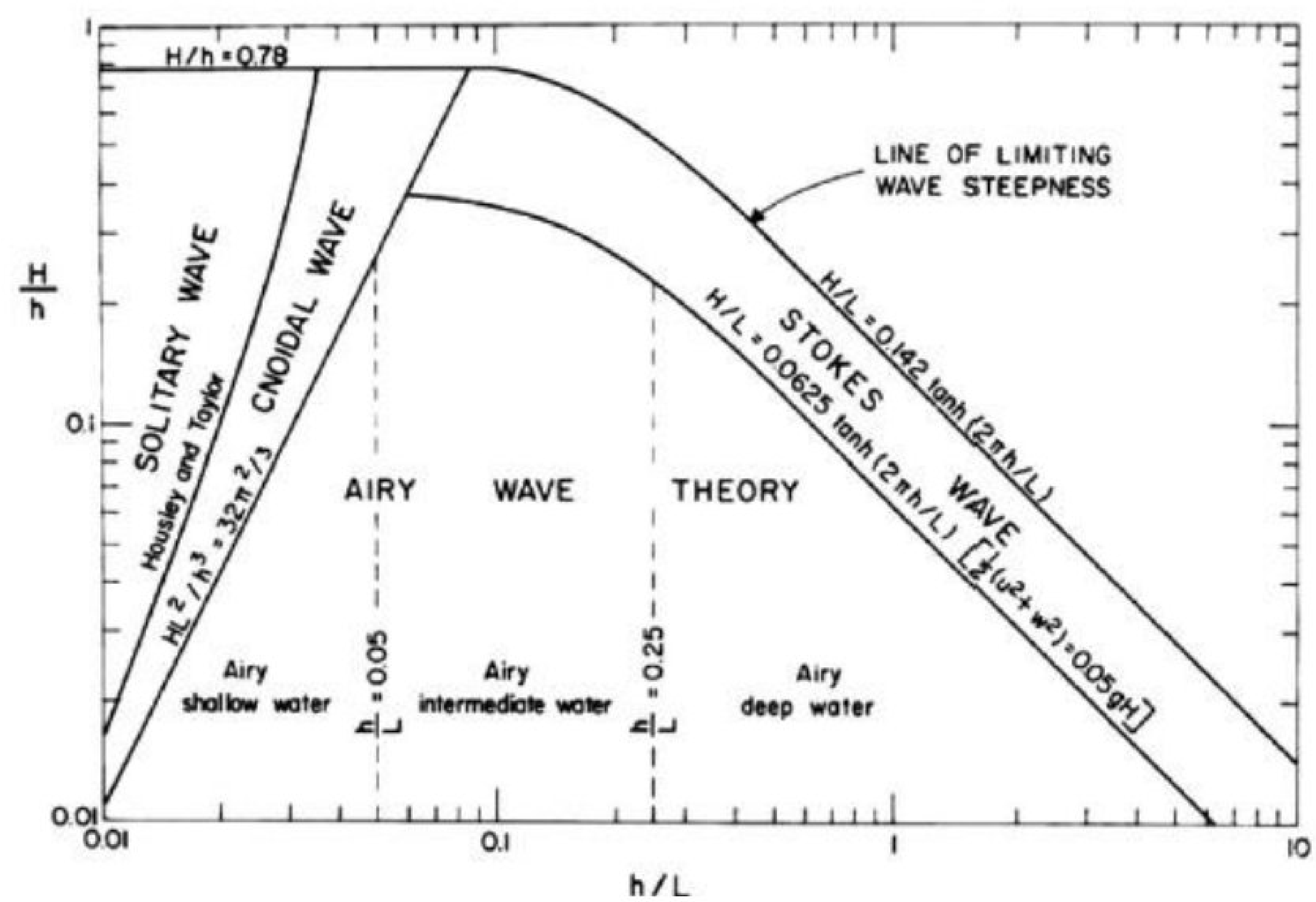

Figure 2: Ranges of Application for Different Wave Theories [17].

Our study is based on the wave data of Saint Martin Island [18], as shown in Table-1. According to Table-2, our study falls into the category of Transitional Water and linear wave theory has been used for this category.

Table 1: Wave data of Saint Martin Island

No. of Obs.	Wave Height (m)	Wave Period (m)
01	1.5	5
02	1.5	5
03	1.6	5
04	1.6	5
05	1.6	6
06	1.6	6
07	1.6	6
08	1.7	6
09	1.8	6
10	1.9	6
11	1.9	6
12	2.0	6
13	2.0	7
14	2.0	7
15	2.0	7
16	2.0	7

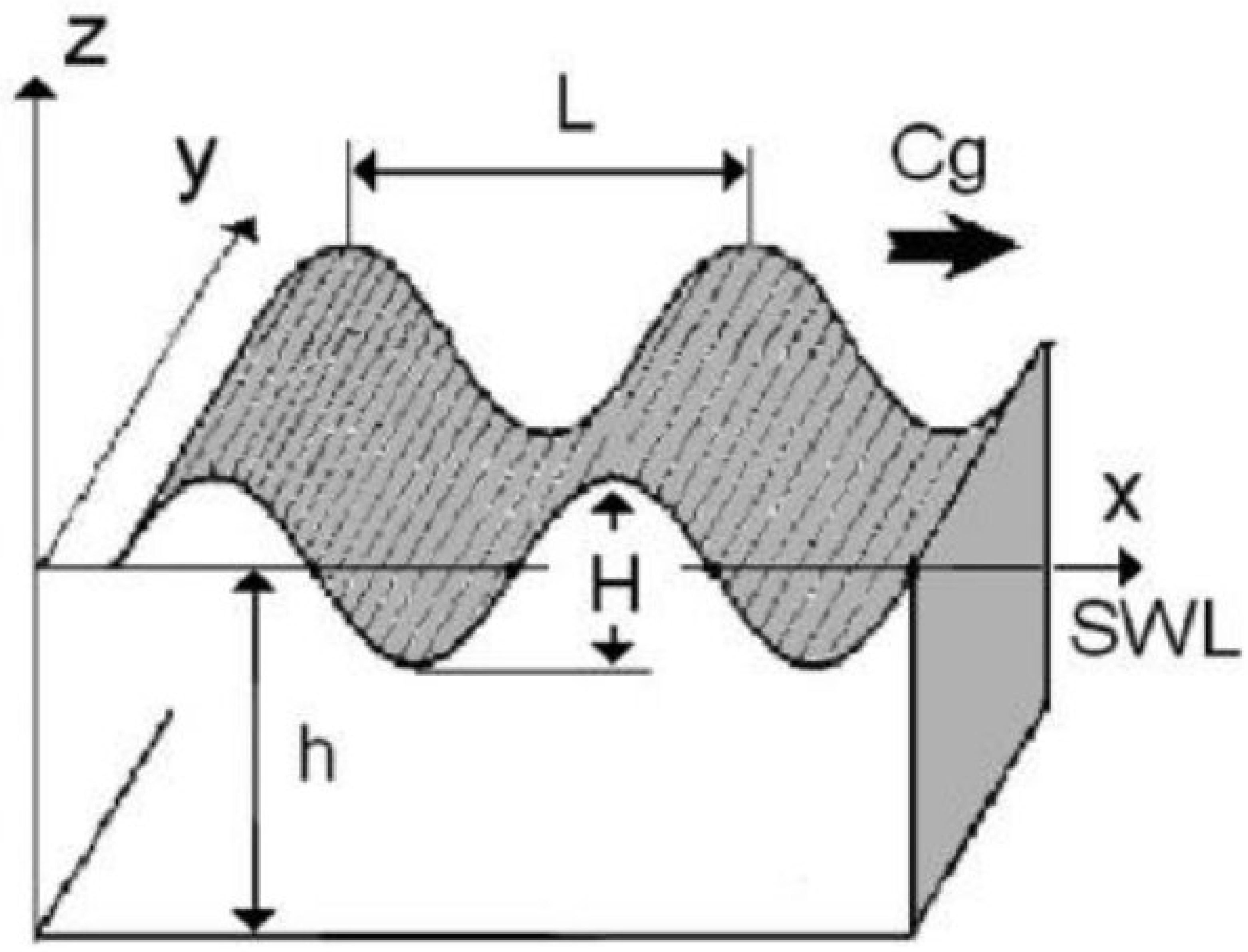

Figure 3: Ocean Wave Parameters [17]

Different parameters related to ocean wave are shown in Fog. 2. The average height (H) and period (T) of waves from Table-1 are 1.8 m and 6 s respectively. The interval from seabed to Still Water Level (SWL) is known as depth (h). Considering the location of our study, we have set the value of h at 8 m. The horizontal distance between two successive crests or trough is known as the wavelength (L) and it is defined by

$$L = \frac{g.T^2}{2\pi} \tanh\left(\frac{2\pi h}{L}\right). \quad (1)$$

The celerity or propagation speed of a regular wave is defined by

$$C = \frac{L}{T} = \frac{g.T}{2\pi} \tanh\left(\frac{2\pi h}{L}\right). \quad (2)$$

The total energy available in a wave energy harvesting system is the sum of potential energy and kinetic energy. The kinetic energy is due to water particle velocities combined with wave propagation. Whereas, potential energy is produced from a part of the fluid mass being above the trough of the wave crest. Linear wave theory says, if the potential energy is calculated with respect to SWL and waves are propagated in the same direction, the potential and kinetic energy portions will be equal. Thus, the total wave energy available in one wavelength per unit crest width is defined by

$$E = \frac{L.H^2.g.\rho_w}{8}. \quad (3)$$

Hence, the total average wave energy per unit surface area which is also known as energy density is given by

$$E_{density} = \frac{E}{L} = \frac{\rho_w . g . H^2}{8} . \qquad (4)$$

Energy density in (4) is defined as the average energy flux penetrating a vertical plane parallel to wave crest. The wave power density is known as the energy available per wave period and it is given by

$$P_{density} = \frac{E_{density}}{T} = \frac{\rho_w . g . H^2}{8T} . \qquad (5)$$

Here, energy density is in joules per square meter and power density is in watts per square meter. The group velocity depends on the rate at which wave energy propagates and is given by

$$C.g = n.C \qquad (6)$$

where n is the group velocity factor and it is determined by

$$n = \frac{1}{2}\left[\frac{1 + \frac{4\pi h}{L}}{\sinh\left(\frac{4\pi h}{L}\right)}\right] . \qquad (7)$$

The rate at which wave energy is dispatched in the direction of propagation across a vertical plane is known as wave energy flux. As shown in [19], a wave resource is conventionally expressed in terms of power per meter of wavefront which can be determined by multiplying the energy density by the celerity.

$$P_{wavefront} = n.C.E_{density} = C.g.E_{density} . \qquad (8)$$

$$P_{wavefront} = \frac{\rho_w . g . H^2 . L}{16T}\left[1 + \frac{\frac{4\pi h}{L}}{\sinh\left(\frac{4\pi h}{L}\right)}\right] . \qquad (9)$$

The equations used for modelling ocean waves are from [17]. Energy density and power per meter of wavefront in terms of height are shown in Fig. 3 and Fig. 4 respectively.

Table 2: Ocean wave parameters

Ocean Wave Parameter	Magnitude
Depth (h)	8m
Period (T)	6s
Height (H)	1.8m
Wavelength (L)	45.2105m
Wavenumber (k)	0.1390
Phase speed or Celerity (C)	7.5351m/s
Group Velocity (Cg = nC)	5.6016m/s
Group velocity factor (n)	0.7434
h/L	0.18

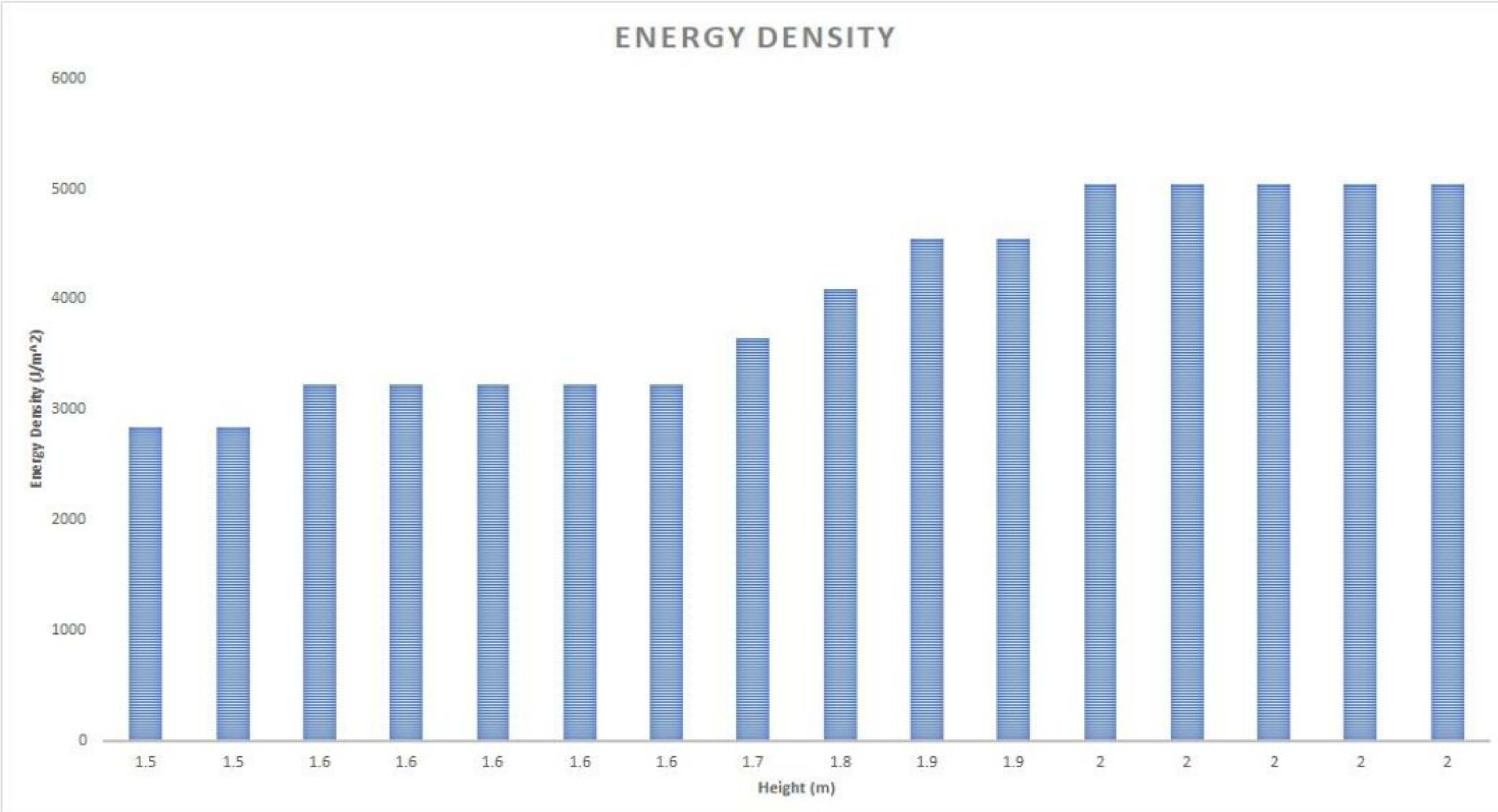

Figure 4: Energy Density vs Height.

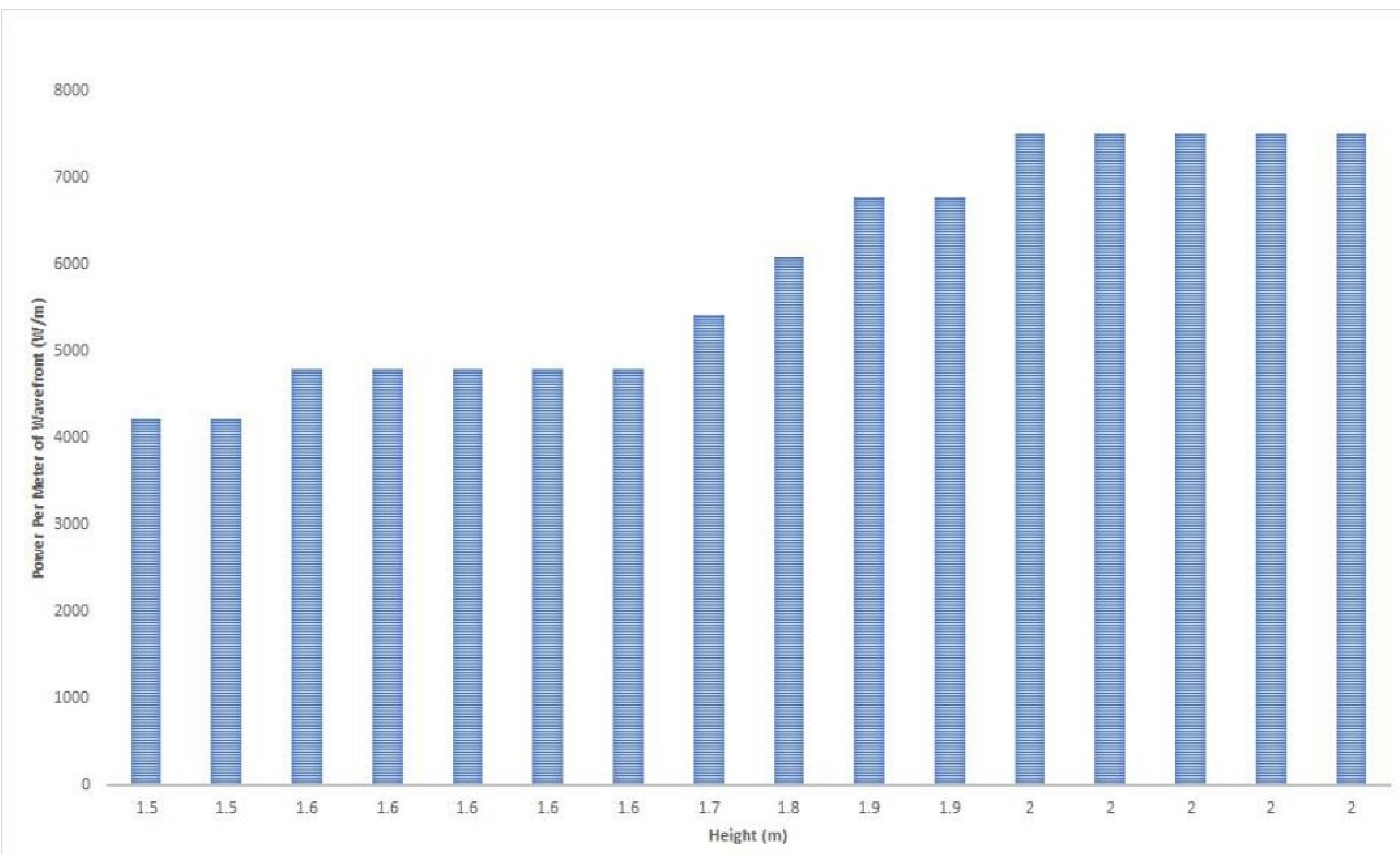

Figure 5: Power per meter of Wavefront vs Height.

3.2 Modelling of Oscillating Water Column (OWC):

Oscillating Water Column (OWC) is basically an air chamber with an opening to the ocean below the Still Water Level (SWL) as shown in Fig. 5. This air chamber is connected to the Wells Turbine. As waves approach, water is forced to compress the air inside the chamber. The compressed air will then rotate the turbine blades which eventually will turn the generator. When the water retreats, air inside the chamber gets expanded and driven in the opposite direction [20], [21]. Width and length of the air chamber are 4.5 m and 4.3 m respectively [22].

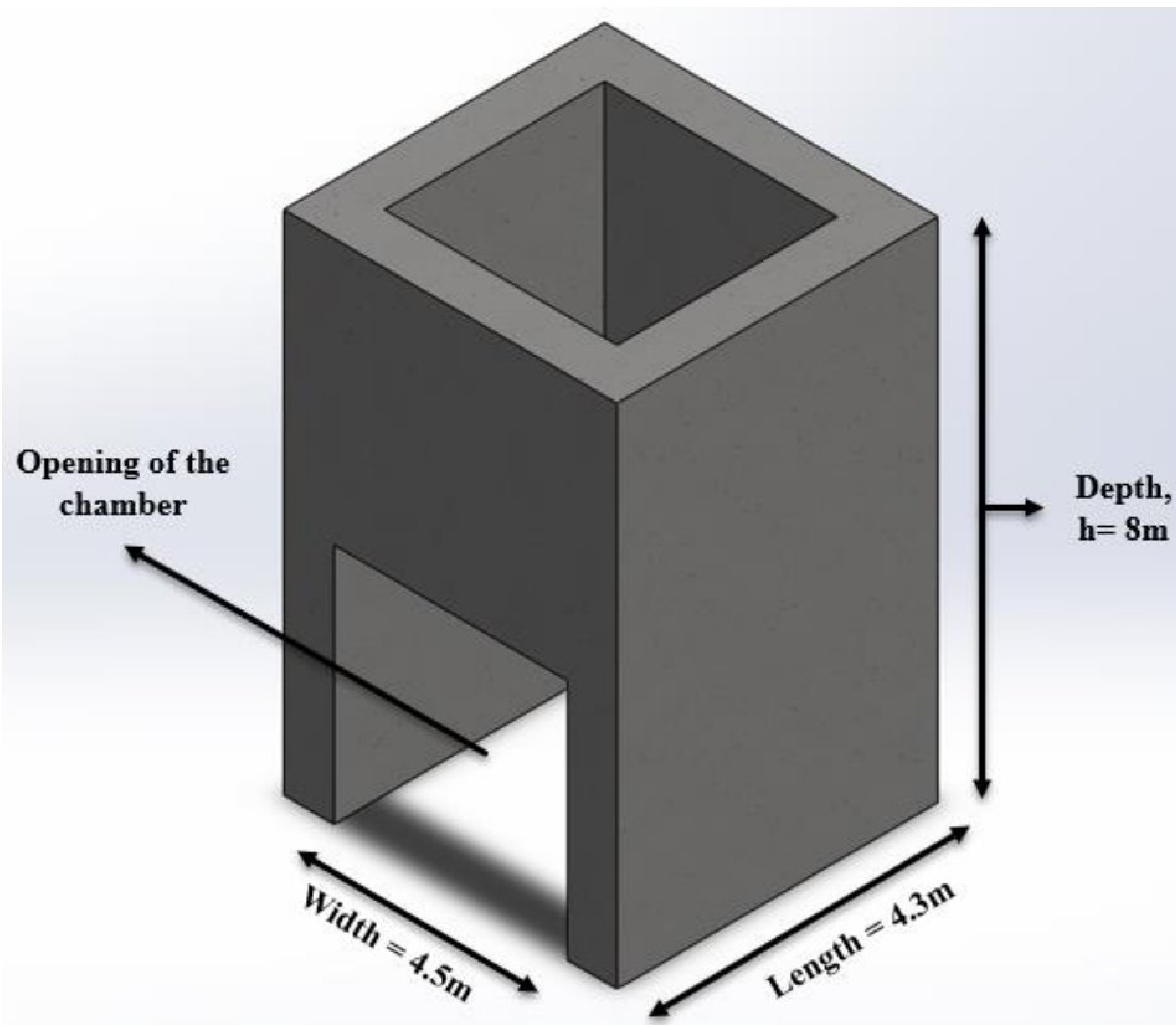

Figure 6: Oscillating Water Column (OWC) Chamber.

Chapter 4: Turbine Modeling

4.1 Wells Turbine:

Wells turbine is a specially designed turbine for energy conversion. Due to their symmetric blade design, they are allowed to rotate in one direction although the air-flow is bi-directional. Wells turbines. The blade exergy for a Wells turbine increases from hub to tip [23]. For this particular project work a Wells turbine was designed in SOLIDWORKS software package.

4.2 CAD Model of Wells Turbine:

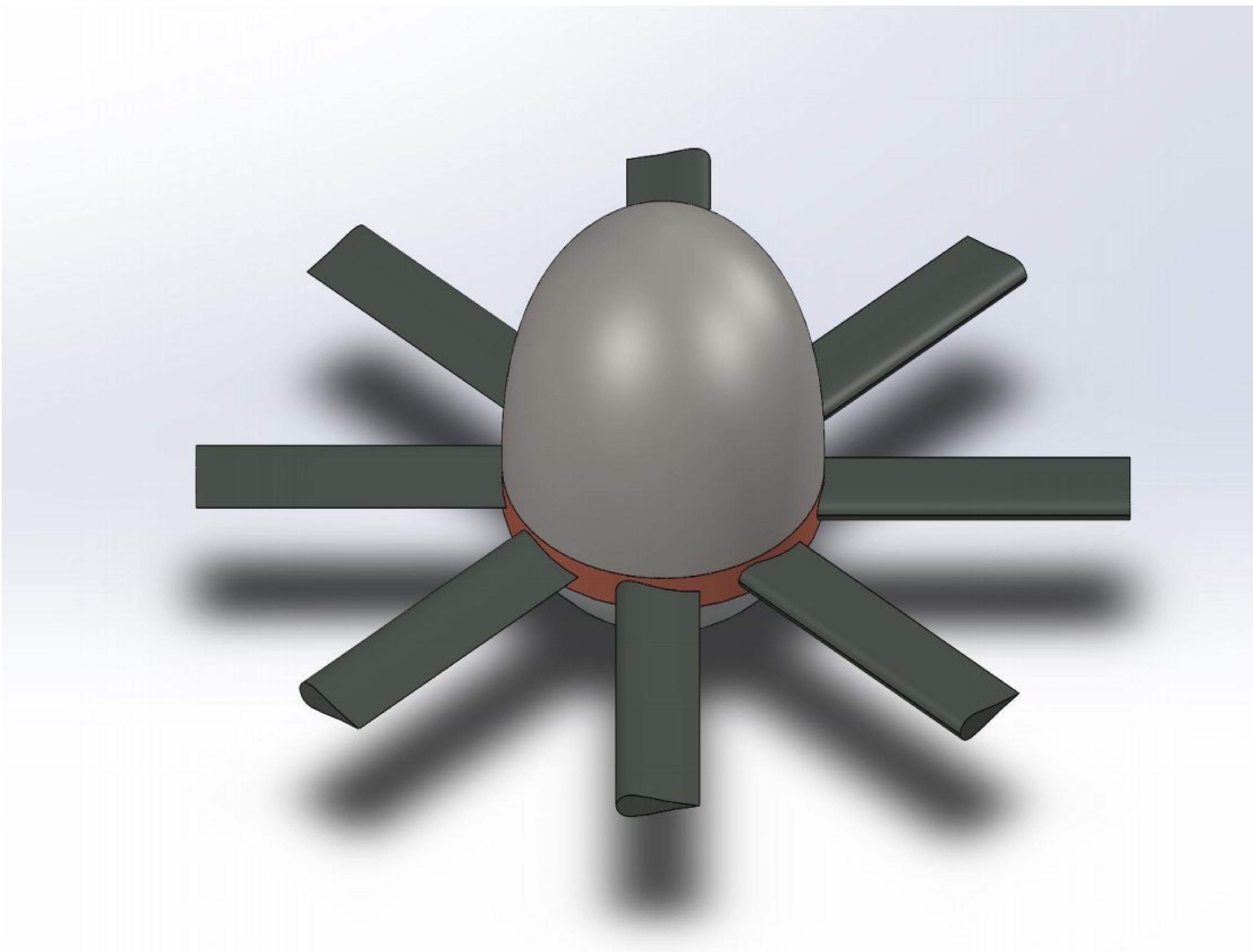

Figure 7: Front View of Wells Turbine

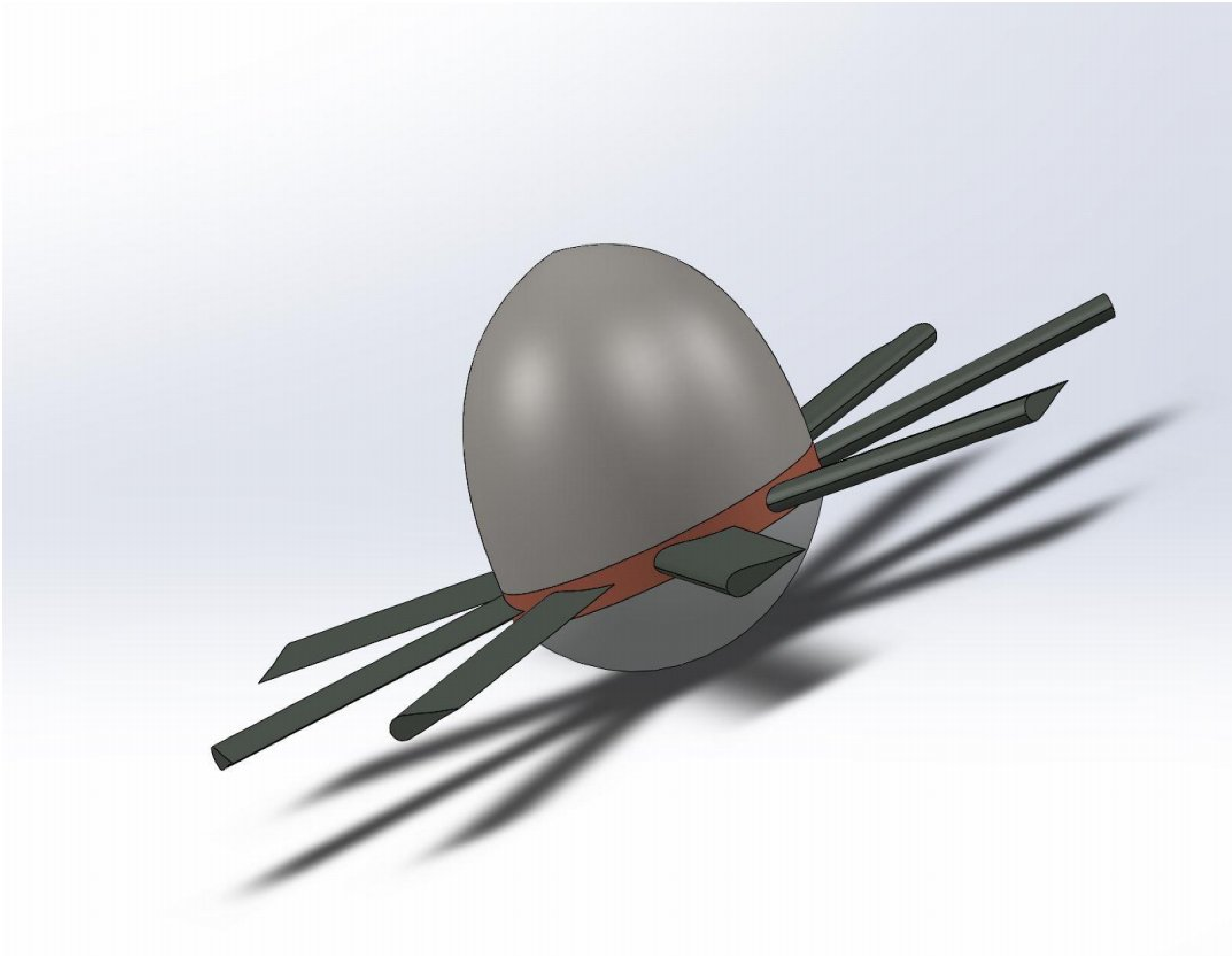

Figure 8: Isometric View of Wells Turbine

The Wells turbine for this project work can be seen in the above figure. It comprises of 8 blades of similar blade design. The hub is kept as small as possible to reduce as much pressure drop as possible.

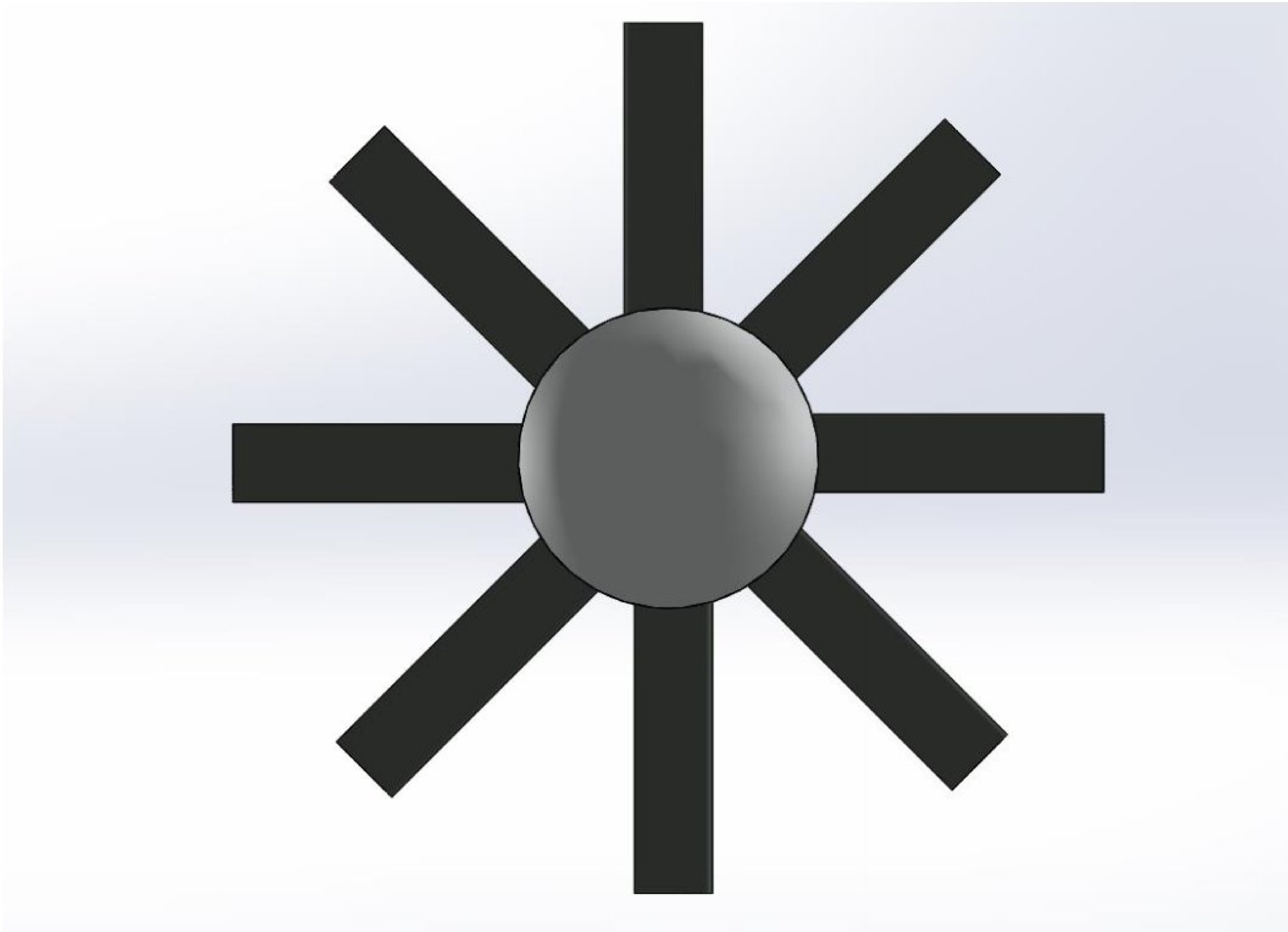

Figure 9: Rear View of Wells Turbine

The Wells turbine is a horizontal axis turbine. This will operate by the help pressure drop inside the pressure chamber of the OWC powerplant. The exit and intake of air inside the chamber will cause the turbine to rotate. The efficiency and performance of Wells turbine heavily depends upon the blade profile of it [24].

4.3 Blade Profile Design:

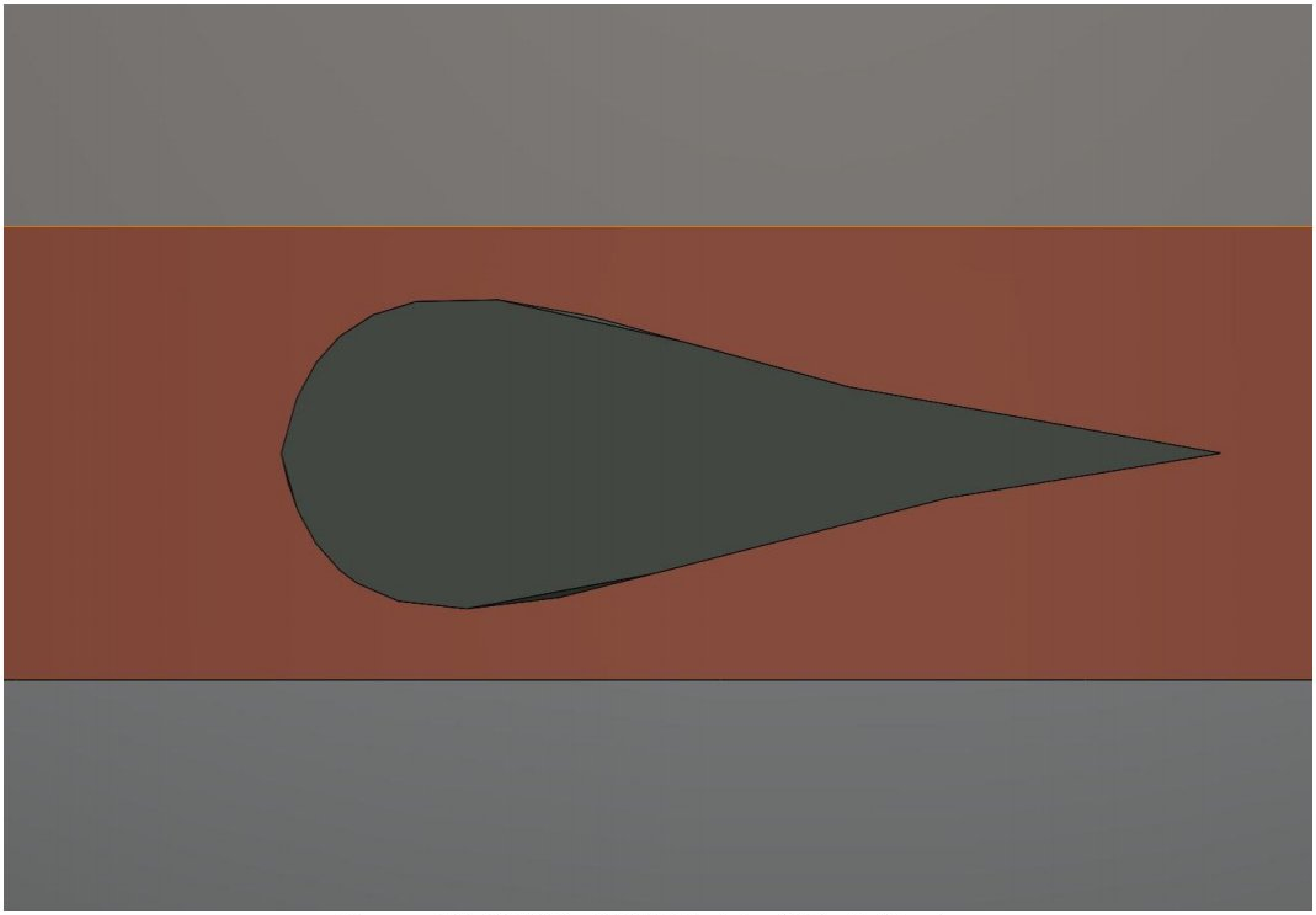

Figure 10: NACA 0015 Model of Blade Design

Table 3: Blade profile parameters

Parameter	Value
Number of Blades	8
Blade Length	01.165m
Blade Chord Length	0.03m
Mean Radius of Turbine	0.53m
Turbine Constant	0.7

The main reason behind choosing this NACA 0015 blade profile is that it is symmetrical chordwise. The benefit of this symmetry is in the rotational direction of the turbine. Due to this symmetry instead of having bi-directional air-flow the turbine rotation will be uni-directional.

The power available in the Oscillating Water Column is produced by air flow inside the chamber and is defined by [25]

$$P_{in} = \left(dp + \rho_a . \frac{V_x^2}{2}\right) . V_x . a . \qquad (10)$$

Where dp is the pressure drop across turbine rotor in (Pa), ρ_a is the density of air in (kg/m^3), V_x is the airflow velocity in (m/s) and a is the duct area of turbine in (m^2). Equation (10) explains the power available from airflow in the OWC chamber. Here, the airflow kinetic energy term (V_x^3.a.ρ_a/2) is common to wind turbine analysis but the air pressure term (dp.V_x.a) is unique for Wells turbine analysis. The airflow velocity is defined by [22].

$$V_x = \frac{8Awc}{\pi D^2} . \sin\left(\frac{\pi l}{cT}\right) . \cos\left(\frac{2\pi}{T} t\right) . \qquad (11)$$

Where A is the amplitude of wave in (m), w is the width of chamber in (m), D is the duct diameter and c is the ratio of the frequency (f) to the wavenumber (k).

4.4 Stalling Behavior of Wells Turbine:

Stalling is the loss of torque in turbine blades. This happens due to the loss of air flow or the fluctuation of air pressure inside the chamber. Since each wave cycle generates two power cycles, a short-term variation in any power cycle eventually causes fluctuation in the medium and long-term wave environment that produces the corresponding change in the output [17]. Characteristic curves represent the variation of power coefficient (C_a) and torque coefficient (C_t) in terms of flow coefficient (ϕ) are shown in Fig. 6 and Fig. 7. As shown in Fig. 7, after reaching an optimum value (C_t = 0.3399), the torque coefficient drops drastically because of the stalling behavior [26]. Since this work does not include airflow control, the turbine has been modelled in such a manner so that it maintains an optimum flow coefficient (0.3).

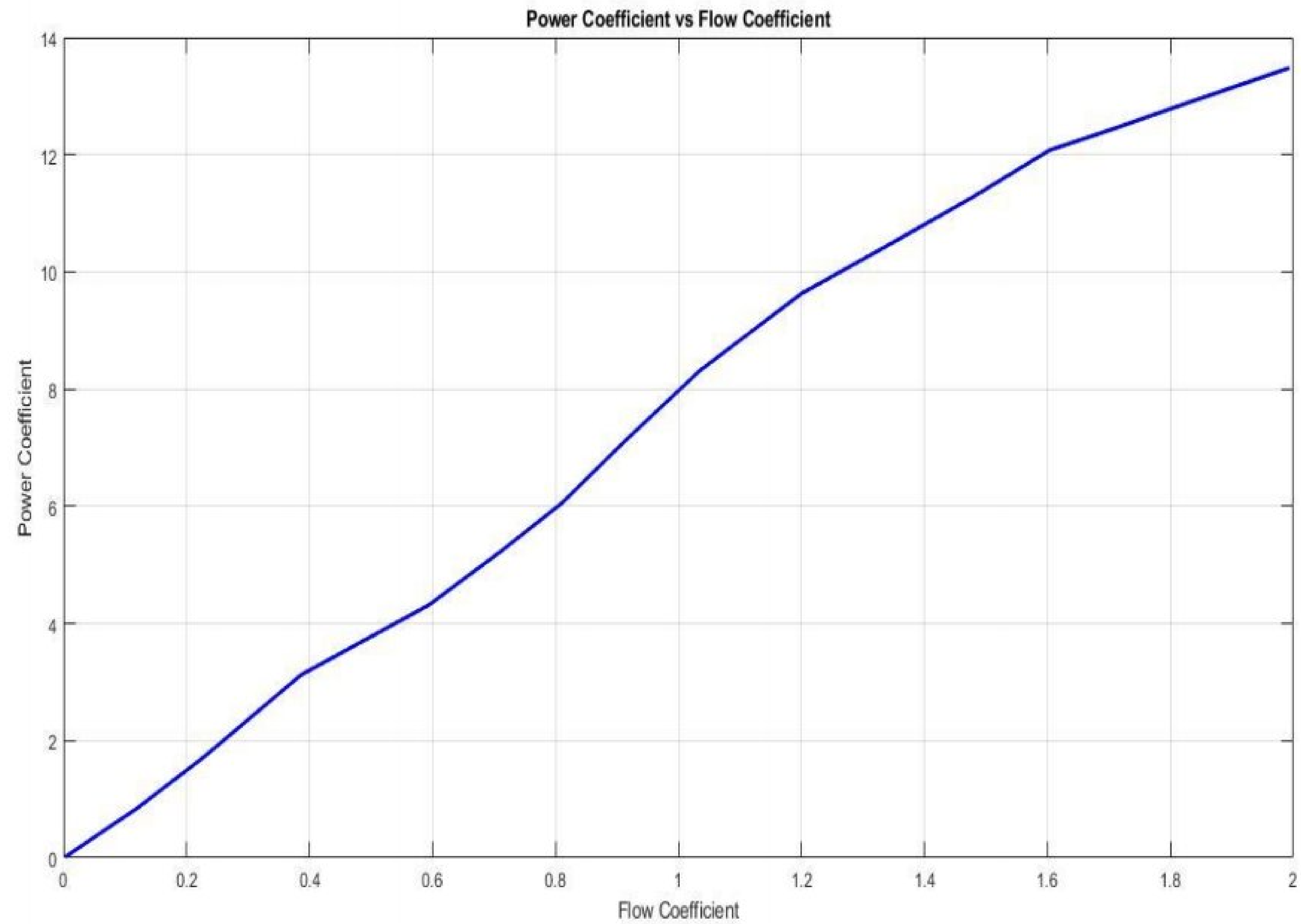

Figure 11: Variation of Power Coefficient.

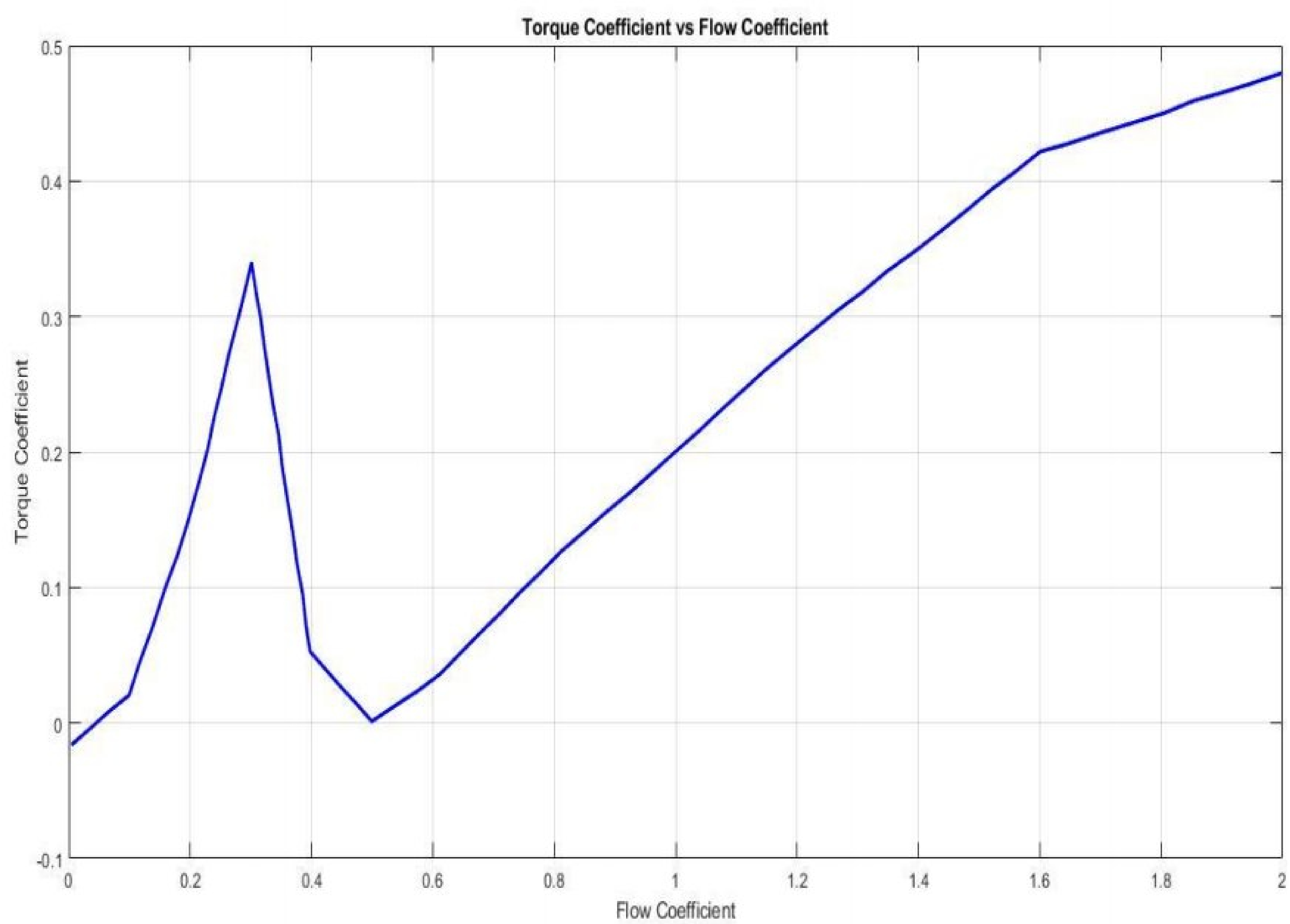

Figure 12: Variation of Torque Coefficient.

4.5 Mathematical Modelling of Wells Turbine:

The following equations are used to model Wells air turbine as shown in [27].

$$dp = \frac{C_a . K}{a} . [V_x^2 + (r.\omega)^2] . \quad (12)$$

$$T_t = C_t . K . r . [V_x^2 + (r.\omega)^2] . \quad (13)$$

$$T_t = \frac{dp . C_t . r . a}{C_a} . \quad (14)$$

$$\phi = \frac{V_x}{r.\omega} \quad (15)$$

$$Q = V_x . a \quad (16)$$

$$P_{in} = dp . Q \quad (17)$$

$$P_t = T_t . \omega \quad (18)$$

$$\eta_t = \frac{P_t}{P_{in}} = \frac{T_t . \omega}{dp . Q} = \frac{C_t}{C_a . \phi} \quad (19)$$

Fig. 8 shows the input pressure drop has been set numerically as [6180sin(0.5t) Pa] [28], [26]. Here, r is the mean radius of turbine in (m), ω is the angular speed of turbine blades in (rad/s), K is the turbine coefficient, Q is the flowrate in (m^3/s), T_t is the turbine torque, P_t is the turbine power output and η_t is the turbine efficiency. Angular speed (ω) and mean radius of turbine (r) have been adjusted in such a way so that an optimum flow coefficient (0.3) is maintained.

Table 4: Wells turbine parameters for modelling

Turbine Parameter	Magnitude
Duct Area (a)	1.1763 m^2
Turbine Constant (K)	0.7
Mean Radius (r)	0.53 m
Angular Speed (ω)	125.6637 rad/s

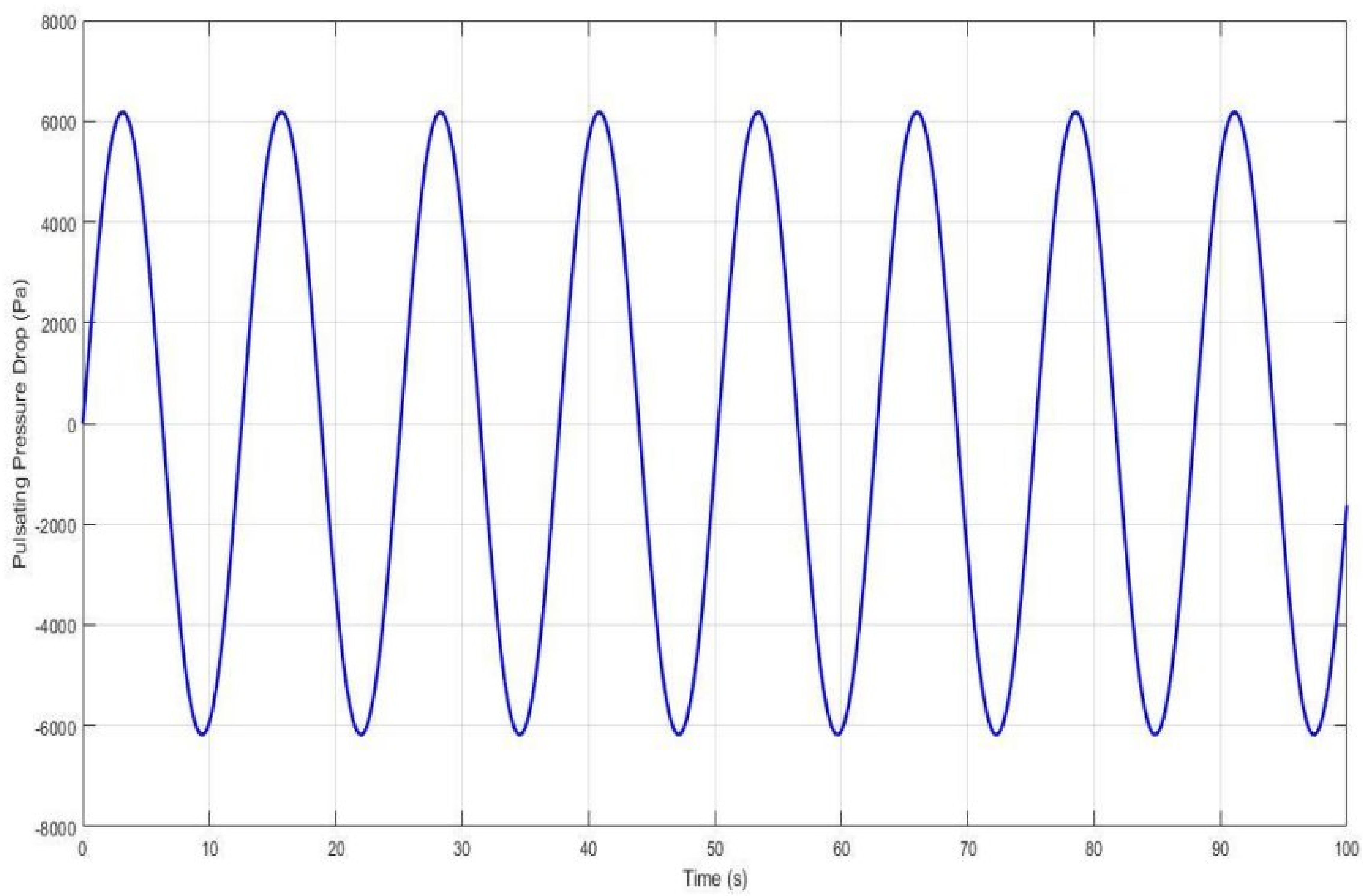

Figure 13: dp = 6180sin(0.5t) Pa

Chapter 5: Results and Discussions

5.1 Results from Numerical Analysis:

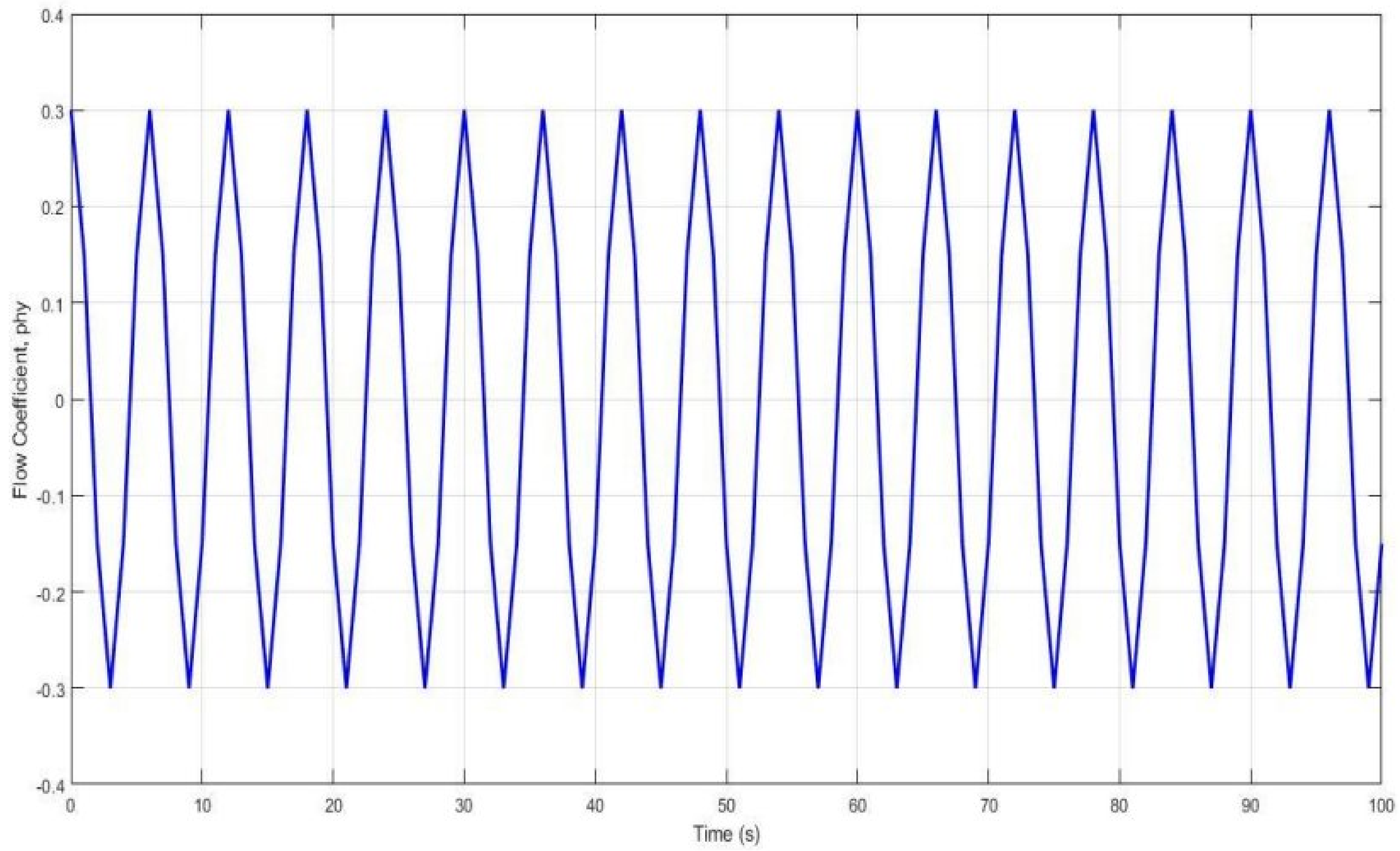

Figure 14: Airflow Velocity vs Time.

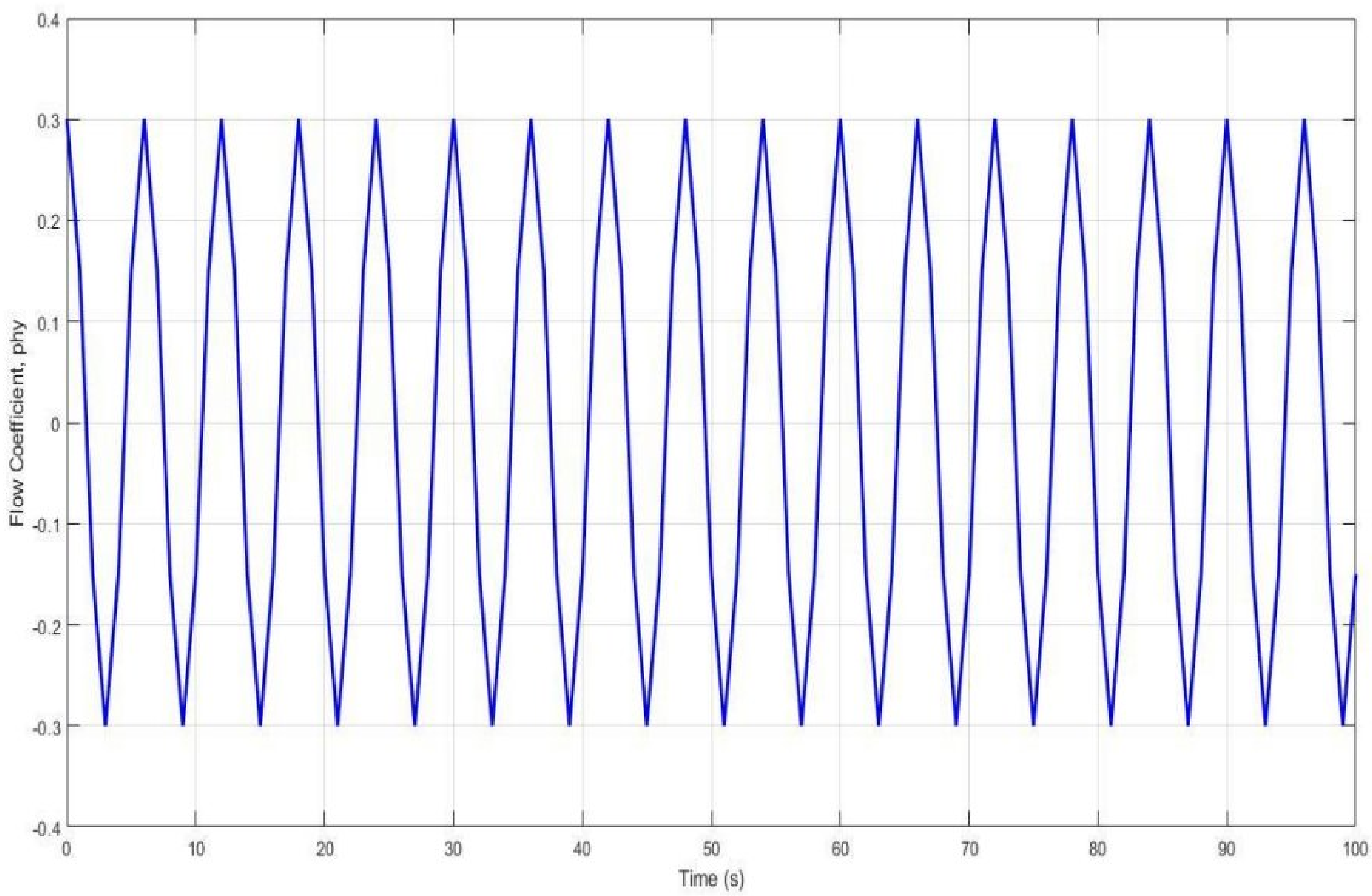

Figure 15: Flow Coefficient is Maintained at 0.3.

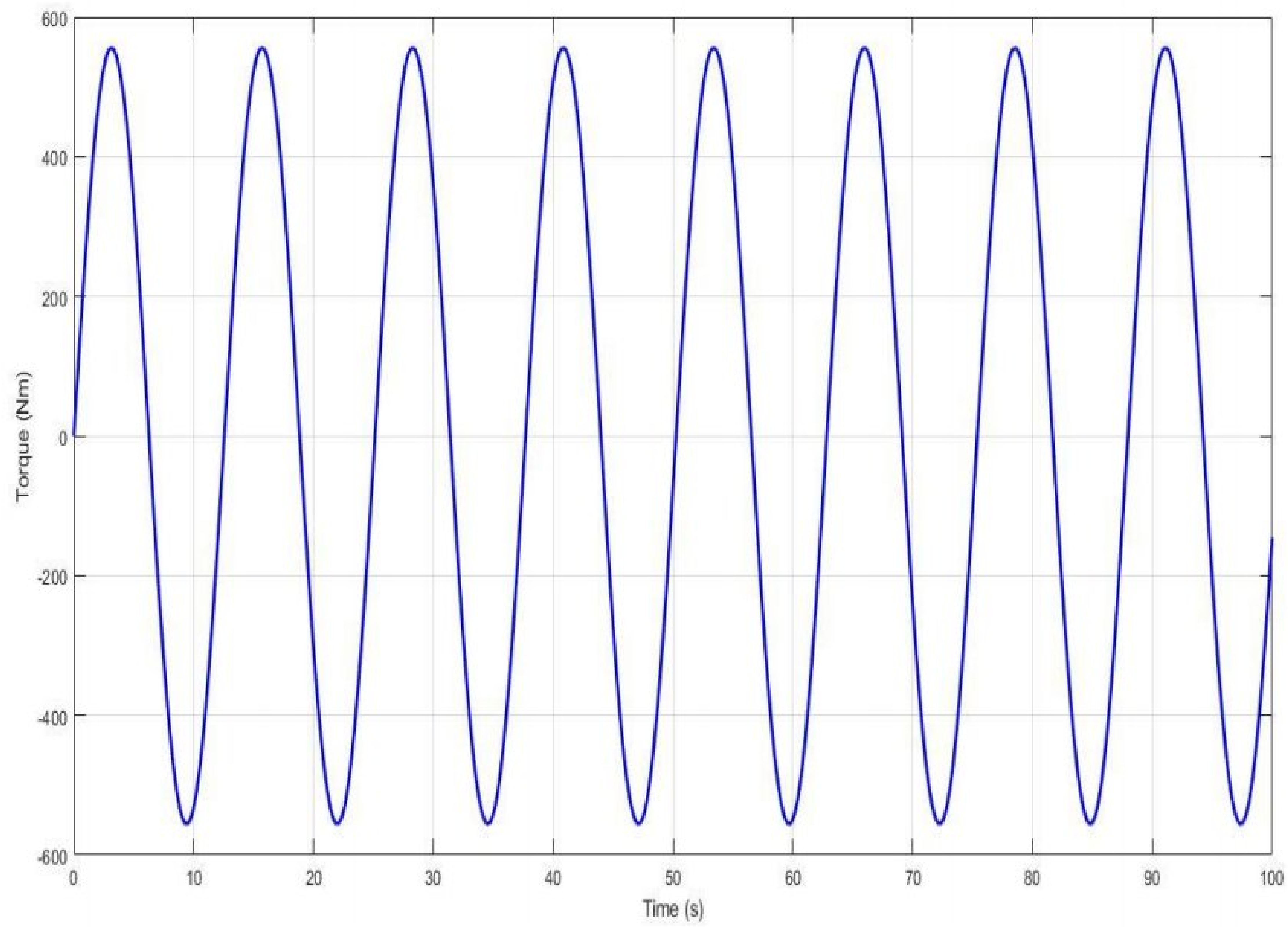

Figure 16: Turbine Torque vs Time

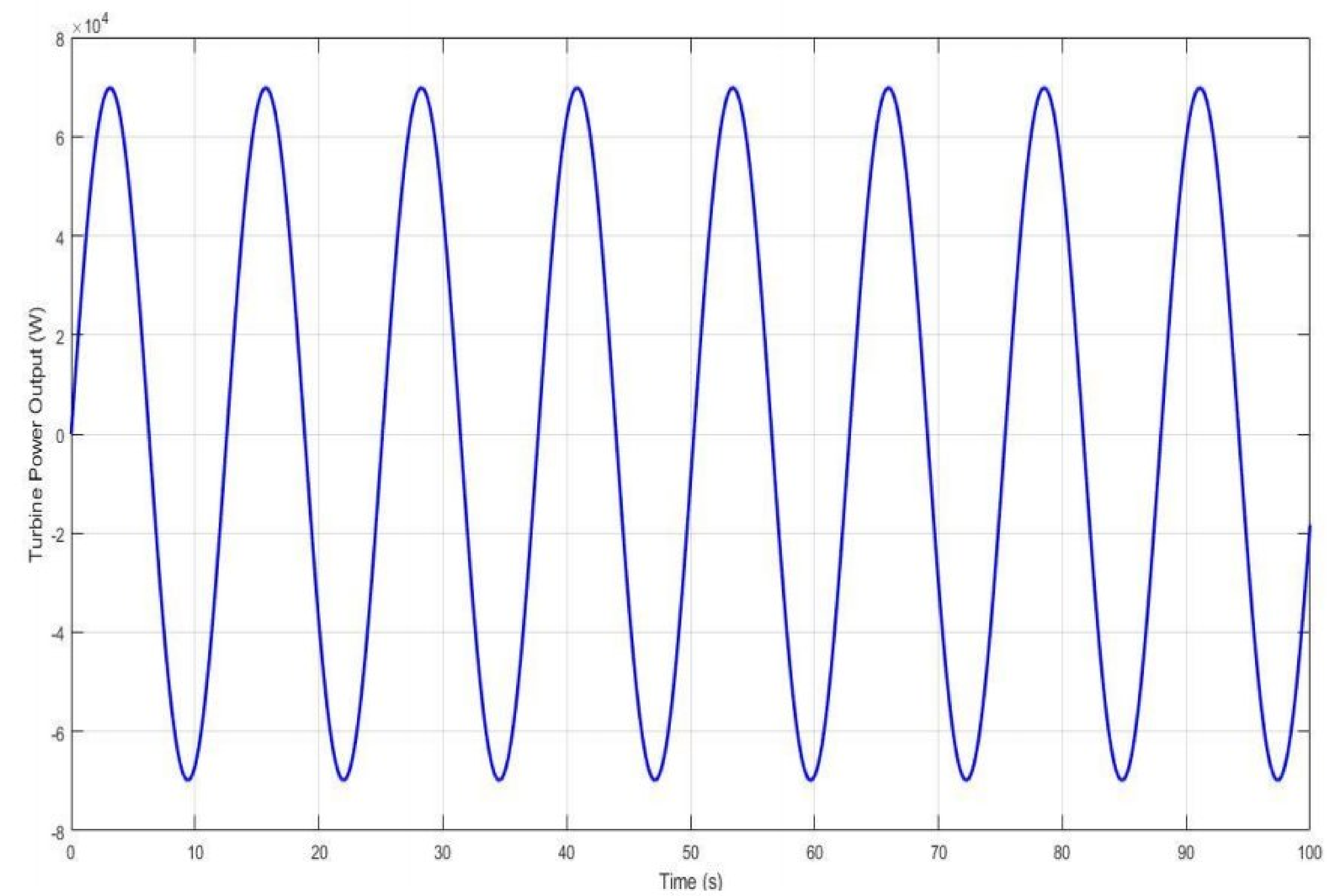

Figure 17: Turbine Power Output vs Time

Table 5: Input and output parameters of overall system.

Parameter	Magnitude
Pressure Drop (dp)	6180 Pa
Airflow Velocity (V_x)	20 m/s
Input Power (P_{in})	165.51 KW
Flowrate (Q)	23.5331 m^3/s
Flow Coefficient (ϕ)	0.3
Power Coefficient (C_a)	2.35688
Torque Coefficient (C_t)	0.3399
Turbine Torque (T_t)	555.6 Nm
Turbine Power Output (P_t)	69.82 KW
Turbine Efficiency (η)	42.1856 %

5.2 Discussion on Results:

An optimum flow coefficient has been maintained to avoid the stalling behavior as shown in Fig. 10. For an optimum value of flow coefficient, corresponding value of power coefficient is shown in Table-4. The airflow velocity inside the chamber is shown in Fig. 9. The turbine power output and the turbine torque for a pulsating pressure drop of [6180sin(0.5t) Pa] look satisfactory when compared with the result of [27] for uncontrolled case. Thus, the calculated turbine efficiency is 42.1856 % as shown in Table-4. Enhancement of the overall performance can be obtained by controlling the airflow inside the OWC chamber. Regular control system includes a rotor side control and a grid side control [17]. A fuzzy logic based advanced control system is shown in [26].

5.3 Conclusion:

One of the probable locations for setting up our OWC powerplant can be in Chera Dwip area of South Saint Martin. Since this area is open to vast ocean, there will be rigid soil which is suitable for the powerplant. Chera Dwip is far away from densely populated area which is a big advantage. Average turbine power output from our study is 69.82 KW. A series of 16 OWC chambers will produce approximately 1120 KW and installation of which will take approximately 800 m of shoreline. In terms of cost and land usage, it is one of the most clean and feasible renewable energy harvesting systems.

Figure 18: Probable Location of the Project [https://www.google.com/maps/place/Chera+Dwip/@20.6047021,92.3087723,13z/data=!4m5!3m4!1s0x30ae248e59f2808d:0x6a0fc317f655c623!8m2!3d20.5788356!4d92.3381879]. [source: google maps]

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