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A New Method for Extracting Ocean Wave Energy Utilizing the Wave Shoaling Phenomenon

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Abstract—Fossil fuels are the major source to meet the world energy requirements but its rapidly diminishing rate and adverse effects on our ecological system are of major concern. Renewable energy utilization is the need of time to meet the future challenges. Ocean energy is the one of these promising energy resources. Three-fourths of the earth's surface is covered by the oceans. This enormous energy resource is contained in the oceans' waters, the air above the oceans, and the land beneath them. The renewable energy source of ocean mainly is contained in waves, ocean current and offshore solar energy. Very fewer efforts have been made to harness this reliable and predictable resource. Harnessing of ocean energy needs detail knowledge of underlying mathematical governing equation and their analysis. With the advent of extra ordinary computational resources it is now possible to predict the wave climatology in lab simulation. Several techniques have been developed mostly stem from numerical analysis of Navier Stokes equations. This paper presents a brief over view of such mathematical model and tools to understand and analyze the wave climatology. Models of 1st, 2nd and 3rd generations have been developed to estimate the wave characteristics to assess the power potential. A brief overview of available wave energy technologies is also given. A novel concept of on-shore wave energy extraction method is also presented at the end. The concept is based upon total energy conservation, where energy of wave is transferred to the flexible converter to increase its kinetic energy. Squeezing action by the external pressure on the converter body results in increase velocities at discharge section. High velocity head then can be used for energy storage or for direct utility of power generation. This converter utilizes the both potential and kinetic energy of the waves and designed for on-shore or near-shore application. Increased wave height at the shore due to shoaling effects increases the potential energy of the waves which is converted to renewable energy. This approach will result in economic wave energy converter due to near shore installation and more dense waves due to shoaling. Method will be more efficient because of tapping both potential and kinetic energy of the waves.

Keywords— Energy Utilizing, Wave Shoaling Phenomenon

I. INTRODUCTION

INCREASED energy demand worldwide and diminishing fossil fuel resources has urged the scientists and lawmakers to developed many new technologies and projects to harness renewable energy from a different of sources. Environmental concerns related to fossil fuel consumption are also increasing social pressures to become less reliant on this source. International quest of energy has focused its major efforts in exploiting renewable energy sources of solar and wind resources. Resultantly, technology for wind and solar energy are well now established and commercially being used for long time. Ocean energy technology is the next inline option. The potential for development of wave, ocean current and tidal energy is the subject of growing international investigation. Ocean contains abundance of untapped energy whose small fraction can meet the requirement of whole world. Ocean energy mainly covers energy from waves, tide and thermal. Although since the 1970's, the wave energy is under consideration as a potential source of renewable energy [1], but this field is still in its infancy. However, if significant resources and efforts are focused for the research and development of ocean energy, it is conceivable that techno-economic solutions to the problems of harnessing ocean wave and other energy sources will emerge. Waves are produced due to the blowing of wind on the ocean surface. This wind originates from the major influx of solar energy to this planet. The energy contained within waves is huge. A rough estimate tells us that in some places values of more than 50MW/km of wave front are expected.

Many attempts to design wave energy converter (WEC) devices have been made in the past, and many have failed due to the hostile environment the devices have to endure. Despite long research the technology has not yet settled down to one or two basic forms as has happened with most major inventions [2]. This technology faces multidimensional challenges and involves a broad range of engineering disciplines, including civil, electrical, Mechanical, Marine, Naval Architecture and control engineering. Main challenge and a critical issue is regarding structure design, which must be extremely robust, keeping in view the safety and cost constraints.

II. UNDERSTANDING THE WAVE CLIMATOLOGY

Tapping the ocean energy requires correct understanding and prediction of the ocean wave and tide climatology. Rise and fall of tides is influenced by the moon movement and hence behavior of tide is well established. Ocean waves are generated by the wind blowing at ocean surface. Sea waves are complex in nature and do not possess any particular mode. The energy (wave energy) carried by these waves is also irregular and oscillating at low-frequency. However designing a device to harness this energy requires sufficient knowledge of dominant wave frequency modes and amplitudes etc.

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A time history of ocean waves exhibits varying behavior as shown in Fig. **2**. Besides having different wavelengths and different amplitudes, the waves travel in different directions When added together, there tends to be a predominant direction corresponding to the direction of greater amplitude and longer period components. On top of this there is some directional 'noise' caused by smaller-amplitude and high frequency (shorter-period) components traveling in other directions [24]. Considering the wave spectra as shown in Fig. **2**, a statistical analysis is required to establish the dominant wave parameters. Therefore a term significant height (H_s) is normally used which is four times the RMS value ($4\sqrt{\varsigma^2}$) of wave height [28], where $\sqrt{\varsigma^2}$ is the standard deviation.

$$H_s = 4\sqrt{\varsigma^2}$$

Similarly a term zero up-crossing periods (T_z) is used, which is the average time between successive crossings of the mean water level in an upward direction.

Energy of the waves is often measured in the form of energy flux [kW/m], which refers to the energy carried by each meter of wave front per second. The power associated with a wave of wavelength λ and height H and a front b is therefore given by [27]:

$$P = \frac{1}{2}\gamma g H^2 T \lambda b \text{ Watts} \quad (1)$$

where γ is the water specific weight and g is the gravity acceleration. The power across each meter of wave front associated to a uniform wave with height H (m) and wavelength λ (m) is then:

$$P_u = \frac{P}{b} = \frac{1}{2}\gamma g H^2 T \lambda \quad \text{W/m} \quad (2)$$

A more generic mathematical form is commonly used for power estimation over a unit width of wave front [17].

$$P_u = \frac{\rho g^2 T H^2}{32\pi} \quad \text{W/m} \quad (3)$$

A more compact formulation to calculate the wave power in KW/m by using significant wave height (H_s) and Peak time period T_p is given by following [18]:

$$P_u = 0.42 T_p H_s^{\,2} \text{ KW/m} \quad (4)$$

Multiplier 0.42 gives most of the time an exact estimation; however its value may vary between 0.3 to 0.5.

Above mathematical expressions clearly indicate that wave climatology is mainly governed by the two parameters; Significant wave Height (H_s)and Time Period (T_p). Experimental observations can only be made at few locations for measurement of these two parameters, but to have an overall statistical data of a region (Wave Climatology) requires numerical modeling and simulations.

III. Numerical Simulation

Extensive research in numerical modeling and simulation of fluid dynamics has resulted in state of the art models and methods. With the advent of state of the art computational facilities accurate prediction of many practical applications has now become possible. Numerical simulation of ocean wave has also become a growing field of Computational Fluid Dynamics (CFD).

Application of CFD techniques to sea waves is not straight forward due to difficulties in ascertaining the proper boundary and initial conditions. In near shore it is even more difficult due to bottom resistance and suspended solid particles. Few models and codes have been developed to deal specifically with the wave behavior, an introductory review will be given here and detailed can be seen in references cited therein.

History of wave modeling is approximately 6 decade old and stems from the theoretical work of Phillips [29] and Miles [30]. Spectral models are mostly based upon their work. Initial work in 1940s by Sverdrup and Munk gave generalized arguments for wave generation and development.

After the initial work of Sverdrup, Munk and Philips the various model were developed in 1960s. Mostly proposed models were based upon the Energy balance equation and known as 1st Generation Models (1G):

$$\frac{\partial E}{\partial t} + C_g \cdot \nabla E = \sum S_i$$

where E is the two-dimensional wave spectrum. The value of E depends on the spatial coordinates x and y, the temporal variable t, the frequency domain *f*, and the direction domain θ. The parameter Cg is the group velocity and is governed by *x,y,f*, and *θ*. The parameter S_i defines source/sink terms, such as the atmospheric input S_{in} , the nonlinear wave-wave interaction S_{nl},, and the high frequency dissipation S_d.

Further improvement in these models presented 2nd and 3rd generation models [31]. Major cited work on wave modeling is contributed by WIS (Wave Information Studies). Role WIS is to generate wave climatologies for U.S. coastlines to provide wave information for coastal engineering studies. WIS uses the numerical wave generation model WISWAVE (Resio 1981, Hubertz 1992) together with input wind fields and bathymetry to simulate wave generation and propagation. It is considered as a 2nd Generation (2G) Model.

Wave generation due to wind and its transformation to different scales forms different regimes. Whole mechanism can be studied in three separate processes; generation, transformation, and local. Wave generation occurs in deep water and across the continental shelf. Atmospheric input as a wind dominates the processes for wave generation. This process is further influenced by the nonlinear wave-wave interactions, and wave dissipation (whitecapping). Transformation process covers the intermediate to shallow water depths. In this scale, wave shoaling, refraction, and breaking are dominant. In shallow depths and near coastal structures, local-scale process of diffraction, reflection, and wave nonlinearities govern.

2G and 3G spectral models based upon the energy balance equation are being utilized by the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL). The most known models are WISWAVE, STWAVE and WAM model. Fig. **1** shows the numerically simulated significant wave height using WISWAVE model.

Other than the spectral models based upon the energy balance a action balance equations, Wave generation can be solved using basic flow equations; Continuity, Momentum and energy equations. Solution of these equations will best represent the wave climatology, however well posed boundary and initial conditions are the key barriers. Following are few such methods:

AMAZON-SC is a Navier Stokes solver, which is based on the artificial compressibility method [9, 10] in which the pressure, density and velocity fields are directly coupled to produce a hyperbolic system of equations. A numerical wave flume is simulated in this method to capture the free surface as described by Kelecy and Pletcher [11]. Amazon-Sc is considered a most used approach to study the wave behavior.
VOFbreak[2] is another code developed by UGent which is based upon volume of fluid approach [12]. It is derived from original SSOLA-VOF code and it has the capability to compute free surface flow when flow domain becomes multiply connected. It is also governed by Navier-Stoke Equations and uses finite difference discretisation method. At UGent [12] a new solver, based on a Large Eddy Simulation (LES) turbulence model, was developed for the simulation of overtopping of water waves over sloping and vertical structures. The new solver has been validated with two test cases for regular and irregular waves, respectively. These results demonstrate that UGent's new solver can describe most of the significant features of breaking wave-induced flows. In particular, the wave form is well captured even during a lengthy test. Detailed information is given by Ingram et. al. [13]Goda [14] has presented a random wave breaking model, which manipulates the probability density function (pdf) of wave height distribution with a triangular cut to represent its gradual shape change in the surf zone. The ratio of the wave height to the water depth at breaking, or the so-called breaker index, has been set by the formula based on compilation of various laboratory data on
different beach slopes [15].

More models that are specifically designed for coastal and estuarine processes include the Stanford Unstructured Nonhydrostatic Terrain-Following Adaptive Navier- Stokes Simulator (SUNTANS6), DELFT3D7, or the semi-implicit TRIM model , Following are also useful approaches [16] :

a) The WAVE code which solves the equations for Airy, third-order Stokes and the Laitone solitary gravity waves.
b) The shallow-water SWAN code which solves the long wave, shallow water, nonlinear equations of fluid flow.
c) The two-dimensional ZUNI code which solves the incompressible, viscous fluid flows with a free surface using the Navier-Stokes equations.
d) The three dimensional ZUNI code (SOLA) that solves the incompressible viscous fluid flows with a free surface, also using the full Navier-Stokes equations.
e) The Carrier linear gravity wave LGW code which uses analytical methods to solve the linear gravity model.
f) TIDE, a classic computer program used for calculating tides.

IV. Review Of Ocean Energy Devices And Concepts

Several [3, 4,6,7,8, 21, 22] reviews have been written on wave energy converters. Here we will summarize few recent developments for sake of completeness:

A. *Iwave*

This is a simple and easy to maintain device, where all critical parts are above the sea level. It comprises of a floating device tethered with chains to piles driven to ocean bottom. The wave action raises the heavy partially buoyant piston that drives the overhead crankshaft by half turn. The receding wave drops the piston completing the balance half turn. One revolution is obtained for every wave. Using gear box and generator the current is produced continuously [19]. .

B. *Manchester Bobber*

This is also a recent invention and developed at University of Manchester. The vertical motion of waves drives a generator and it is expected that a full-size unit should be able to produce a mean power output of around 5 megawatts. Bobber will respond to the waves from any direction. The vulnerable mechanical and electrical components are housed in a protected environment well above sea level, which makes for ease of accessibility.

C. *Anaconda*

The two-year project 'The Hydrodynamics of a Distensible Wave Energy Converter' which has received EPSRC funding of just over £430,000, has come up with a new device [26]. This device consists of a giant rubber tube. It is a very simple and innovative wave energy concept and name after a snake ‘Anaconda’ due to its shape. The snake like tube is closed at both ends. The fluid in the tube is squeezed due to wave movement. This squeezing motion causes a bulge wave to be formed inside the tube. The bulge wave then turns a turbine fitted at the far end of the device and the power produced is fed to shore via a cable.

D. *Pelamis*

It is a semi-submerged, articulated structure and comprised of sections linked by hinged joints (See Fig. **5**). The passing waves produce a motion in the joints which is resisted by hydraulic rams. This resisted motion by rams pump high-pressure oil through hydraulic motors. The motors are connected to generators to produce electricity. Several devices can be connected together and linked to shore through a single seabed cable This device is one of the best and successful wave energy converter. World’s first commercial wave farm ‘Aguçadoura Wave Park’, which is located in Portugal uses three Pelamis wave energy converters to produce electricity.

Each machine has rated capacity of 750 KW and net output of the form is nearly 2.25 MW. The farm was inaugurated on the 23 September 2008 by the Portuguese Government.

E. Nasa Hydrokinetic Energy Transfer System

Jones and Chao from NASA [24] have recently proposed a new concept to harness tidal energy. In the proposed hydrokinetic energy transfer system, the flow of water current causes turbine blades to rotate. The rotor's rotational speed is increased through a gearbox, which drives a high-pressure fluid pump. The high-pressure fluid would be transported though flexible tubes to a larger pipe and then to an efficient, onshore hydroelectric power plant. This design can provide a stable electric out put. A schematic is shown in Fig. **6**.

V. A NOVEL CONCEPT

Most of the previously proposed method involves heavy metal structure, which make it difficult to sustain the extreme sea conditions. Furthermore, installation of such converter also faces serious cost to power ratio barrier. Sea waves produced in the sea surface also do not follow a particular wave form. A time dependent data of waves as shown in Fig. **2** is of a complex nature, which prohibits a stable electric power output or a regular mechanical output. Ocean waves carry both the kinetic and potential energy. Wave height in fact is a measure of the potential energy and time period indirectly relates the velocity of the wave. Most of the converter mainly utilizes the potential energy as vertical movement of the converter harness the energy. Energy carried in the form of wave velocity is not much extracted.

As waves reach to shallow water, their height increases due to the shoaling effect. Bottom effects dissipate some energy, but ensure conservation of total wave energy, the loss in speed is compensated by increase in the wave height. This in turn reduces the wave length. Increased wave height due to shoaling essentially, carry more potential energy. Ardhuin [32] has also concluded that from momentum balance for the waves and the mean flow that the wave action flux generally remains conserved. Author also discussed that this conclusion leads to an approximate conservation of wave energy flux for waves shoaling near beach. Reduction in velocity (i.e. K.E) and wave length due to shoaling results in wave crowding. Due conservation of energy flux Potential energy of the wave will increase. The concept is shown graphically in Fig. **3**

Keeping in view the concentrated energy at near shore due to shoaling, a new concept is being proposed. This new concept uses the extracted energy of waves in the form of potential energy. Potential energy either in the form of pressure or mechanical head is used to produce useful power output. The design description is similar to a floating bed, which consist of a large rubber float. Float internally consists of a number of large diameter tubes placed parallel to each other. Ends of all these tubes are connected to a combine manifold (Pressure manifold). Float is placed in sea such that in coming manifold face the incoming waves.

The design is extremely simple and totally innovative in nature. The simple design will ensure low manufacturing and maintenance cost, hence cheap green energy.

This converter is a flexible float which consists of water fluid passages separated from each other and resembles to an array of flexible hoses placed parallel to each other. This converter is designed for near shore application and energy from the waves approaching the shore will be driving this converter. The Shoaling waves hitting the converter will pass through the converter, which will produce a zig zag motion in the float. This zig-zag motion will run through the whole converter and will perform a squeezing action in the passages. Since converter is floating, the external pressure applied by the waves on both sides of the converter, which will transfer the potential energy of waves to the converter. This transfer of energy will produce a squeezing action which will result in increased velocities of the fluid in the passages.

Length L of the float is designed such that it is at least more than three times the average wave length λ of the waves. This ratio (L / λ) of more than 3 will ensure a regular squeezing action to maintain continuity in energy transfer (Fig. 7 is relevant). Converter is designed to have its neutral buoyancy such that it is fully or ¾ submerged. Converter will be moored from atleast 6-8 points with sufficient flexibility to assist in producing a bulge wave in the passages. Pressure manifold (see Fig. **4**) is at farthest end where all passages will discharge giving a high pressure and flow rate (combine effect of all passages). This high pressure fluid will be transported to power generating unit through flexible hose. The proposed converter can be used as an open or close cycle. In a close cycle feed water or any other fluid can be used. Closed loop will have increased running cost but substantial low maintenance cost for machinery, whereas open loop will utilize the sea water as a working fluid. Open lloop is more recommended because it will utilize the high speed wave water. Water entering the converter will carry wave's kinetic energy part and external squeezing effect by wave will convert the potential energy of the wave. A schematic view of the converter is given in .

Analytical efficiency estimation has shown that wave frequency, significant height Hs and length of the converter are important parameter.

Fig. 7 shows the efficiency response to length ratio N. Where N is the ratio of converter physical length (L) and Wavelength of incident sea waves as shown in equation below:

$$N = \frac{L}{\lambda} \tag{5}$$

VI. CONCLUSION

This paper gave a review of mathematical and numerical back ground of wave energy and different devices has shown very promising results. Wave energy is becoming a viable source of green energy. More focus on its research will bring its cost further down to be compared with wind and solar energy. With advent of CFD techniques it is now realistic to undertake modelling and simulation before installing a prototype plants. A better comprehension of wave climate will result in a best utilization of most relevant device. New proposal is also promising, however more detailed analysis is required before this device can be made available for power generation. Numerical analysis and prototype testing of the concept remains our future work. A 1/100th scale at laboratory level will be tested soon.

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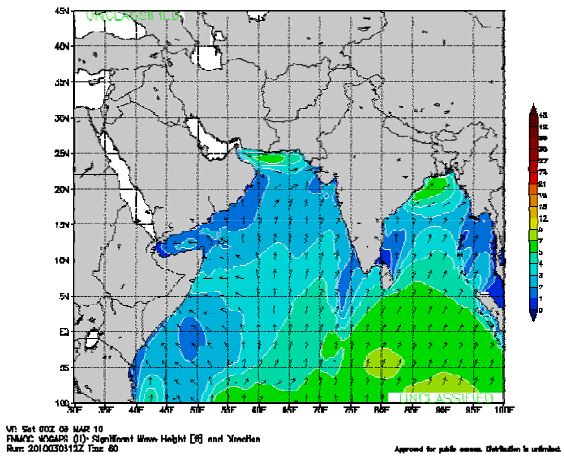


Fig. 1 Numerically calculated significant wave height.

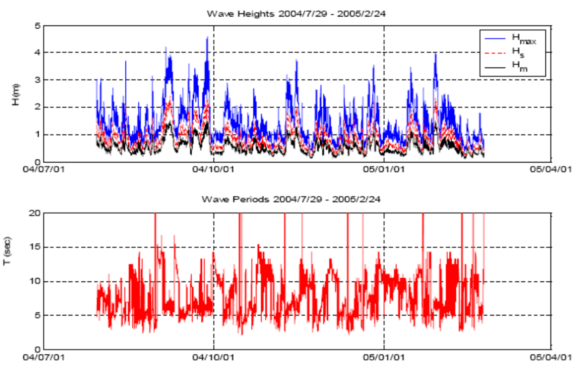


Fig. 2 Random behavior of wave amplitude and frequency [Taken from ref [5]]

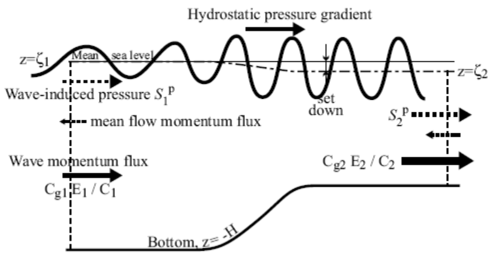


Fig. 3 Balance of forces for waves over a smooth step, in the case without dissipation or wave reflection. Fluxes of momentum across two vertical sections (dashed lines) are indicated by arrows. The force that corresponds the divergence of the wave pseudo-momentum flux *CgE*/*C* combines with the gradient of the wave-induced pressure *Sp*. This combination is generally balanced by the hydrostatic pressure gradient related to the mean sea level gradient. The acceleration of the mean flow (small dashed arrow), due to a divergence in the Stokes transport, is generally much weaker [32].

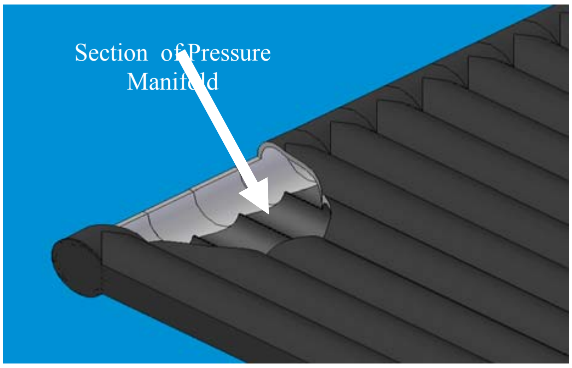


Fig. 4 A section view of pressure manifold.

Fig. 5 Pelamis machine facing the sea waves. (From Ocean Power Delivery)

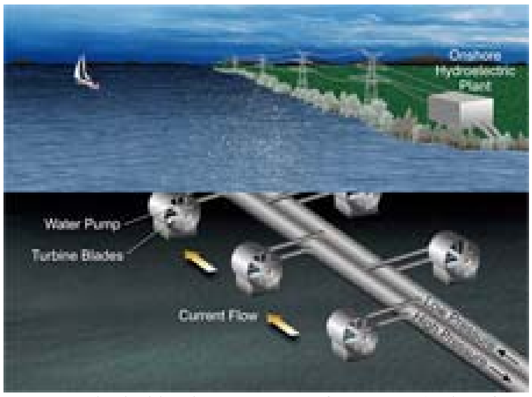


Fig. 6 NASA hydrokinetic energy transfer system (Taken from ref [25])

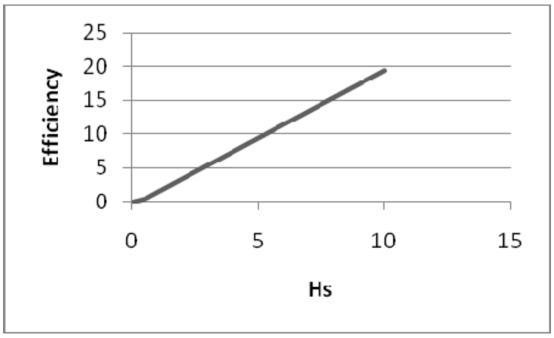


Fig. 7 Relationship between length ratios N to efficiency

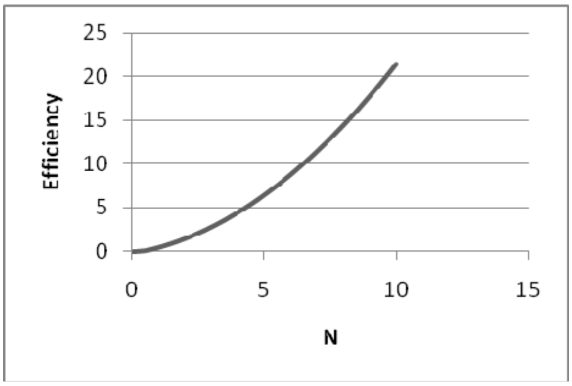
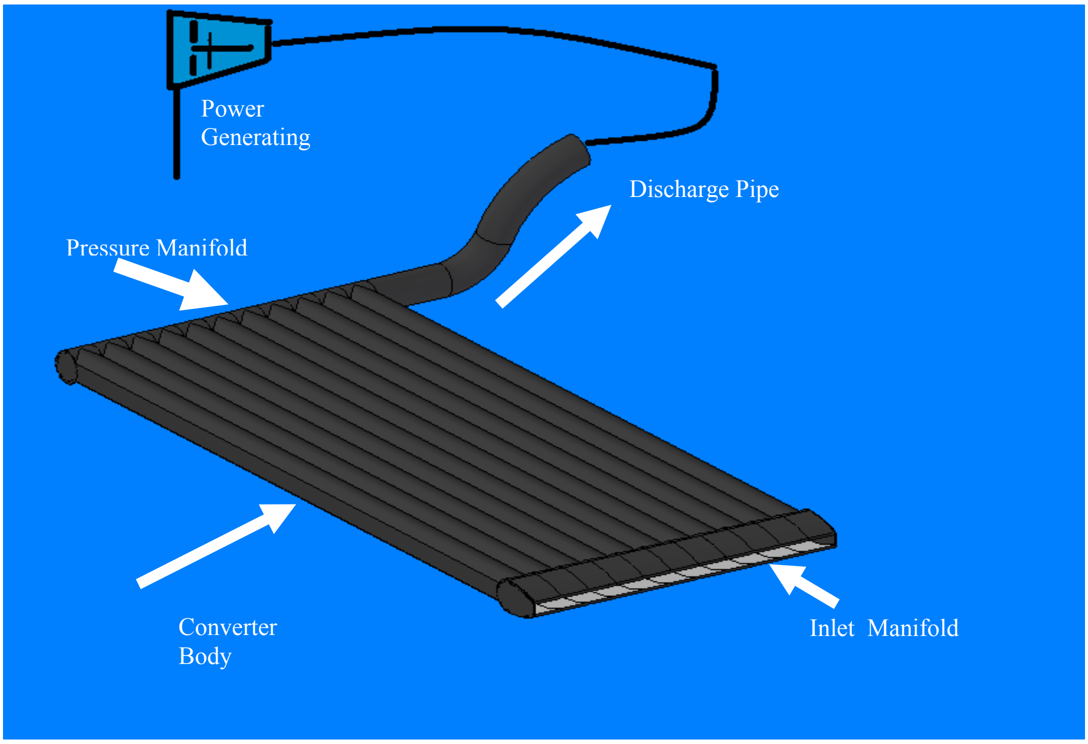


Fig. 8 Relation between significant wave heights to Efficiency


Power
Generating
Discharge Pipe
Pressure Manifold
Converter
Body
Inlet Manifold