# Pneumatic Power Measurement of an Oscillating Water Converter Model

Bavesh Kooverji
University of Stellenbosch

Centre for Renewable and Sustainable Energy Studies

## Abstract

An accurate pneumatic power measurement tool was developed for the performance of an Oscillating Water Column (OWC) model. The analysis of the pneumatic power is significant due to the energy efficiency from wave energy to pneumatic energy being the primary energy conversion within which the most energy losses can be predicted. The research study addresses the accurate measurement of unsteady and bidirectional air flow in OWC experiments. The two fundamental measurements required for the pneumatic power measurement were the pressure difference over an orifice on the OWC model and the volume flow rate of air through the outlet. The designed, constructed and assembled measurement tool comprised of a venturi flowmeter, containing a hot film anemometer, which could measure the pressure drop and the volume flow rate in one device. The assembled pneumatic power measurement tool was calibrated in a vertical wind tunnel at steady state. A Perspex physical model of a simple OWC device was designed and constructed for use as a test unit with the pneumatic power measurement tool in the wave tank at the University of Stellenbosch (US). The results from the experimental tests were validated with a simulated OWC air-flow model using Matlab Simulink.

*Keywords*: pneumatic power measurement, air-flow meter, OWC model, wave energy converters

## 1. Introduction

The majority of the Earth's energy production is extracted from non-renewable energy resources such as fossil fuels and nuclear energy. In particular, the use of fossil fuels has led to negative anthropogenic environmental impacts resulting in climate change. This change is a result of increasing pressure on the earth's atmosphere to absorb greenhouse gases (GHG). The excessive use of fossil fuels has also resulted in the rapid depletion of these finite resources, which in turn has resulted in them being an expensive commodity. In essence this situation has created a demand for new, clean renewable energy resources. The current renewable energy research of the world consists predominantly of the following energy resources: solar, wind, bio and ocean energy. The platform upon which this research study is based is ocean energy. Ocean energy research is comprised of five sectors: ocean waves, ocean currents, tides, thermal gradients and salinity gradients. Renewable energy systems that are employed by the action of the waves are known as Wave Energy Converters (WEC) and it forms part of the research area for this article. The specific type of WEC, the Oscillating Water Column (OWC) is the specific area pertinent to this research.

### 1.1. Overview of OWC's and WEC's

#### 1.1.1. Description of an OWC device

As an overview, Mendes (s.a) has concisely stated that an OWC device is basically a hydraulic machine whose power take-off (PTO) mechanism is of a pneumatic nature, where this mechanism is a pneumatic chamber that is connected to an air turbine to generate energy. In particular, it is the pneumatic power take-off which is being investigated in this research, since it is the product of the primary energy conversion in an OWC device. An OWC device can be classified as a WEC that is commonly a terminator device and is also a fixed structure relative to the movement of the waves. These devices are found to be either a near shore or shoreline structure and utilise the pneumatics from an air chamber for the power take-off system.

OWC devices integrate the conversion of wave energy to pneumatic energy through the oscillation of a trapped water column in a chamber. At the bottom of the structure, the energy from the waves is fed into the water column through a submerged opening, which results in the water column movement. Thereafter the air pocket, located above the water column, undergoes the induced oscillatory behaviour which is essentially utilised to drive an air turbine. The mechanical energy attained by the turbine can consequently be converted to electrical energy via an electrical generator. With regards to the turbine selection for an OWC device's pneumatic PTO, there has been a preference towards the use of the bidirectional Well's' turbine as opposed to the Impulse turbine due to the bidirectional air-flow property. Even though this turbine seems well suited to the oscillatory motion of the air chamber, there remain accounts of this turbine having a lower than predicted efficiency. A key advantage for the use of a unidirectional turbine is that it normally delivers high efficiencies as opposed to the Well's turbine (Ackerman, 2009).

Figure 1-1 illustrates a three-dimensional sectional layout of an OWC structure, where multiple chambers are placed alongside each other. The air pocket above the water column leads to the turbine-generator area through an inter-leading vent. The ballast chamber seen in Figure 1-1 is strategically located on the OWC device to create structural balance through operation in the harsh marine environment.

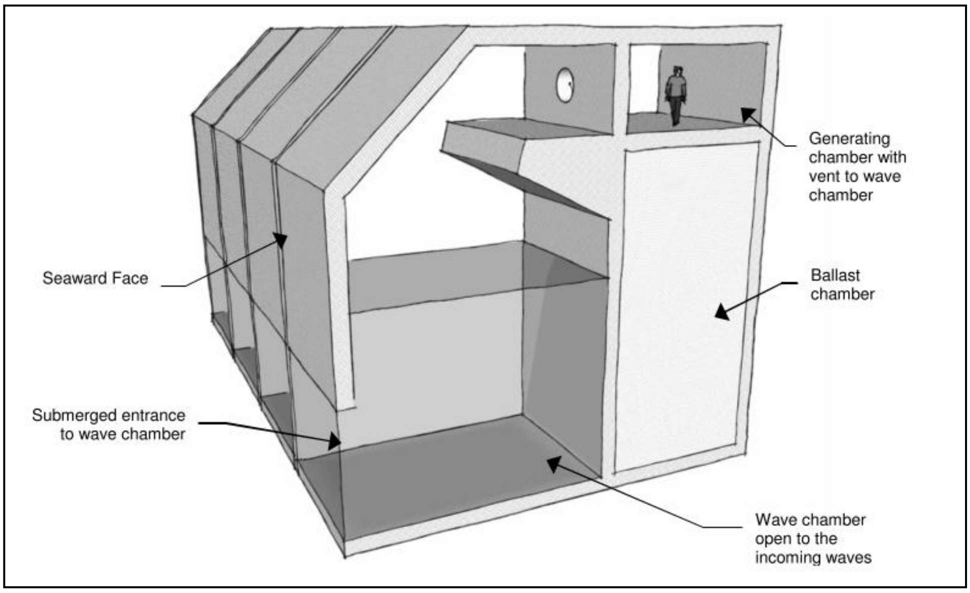


**Figure 1-1: Three-dimensional layout of an OWC device (Patterson et al, 2010)**

To date, there have been many accounts of experimental tests performed on OWC models. Some of these tests are based on OWC model design for efficiency analysis, investigation of the air flow characteristics in the air chamber and air turbine modelling. None of them have accurately researched the measurement of the pneumatic power generated from an OWC device.

### 1.1.2. Brief summary of commercial OWC's

The history of WEC's can be dated back to the 18th century where the first ever patent for a wave energy device was reported in 1799 by a father and son from Paris (Ross, 1979).

Not much is known on the success of this patent but it can be described as being of a pump-action nature that utilises the potential energy of the ocean's waves. In terms of the history of OWC devices, the first recorded conceptualisation of an OWC is the whistling buoy used for its ability to act as a navigation buoy (Heath, 2012). This design acted as a successor to the traditional bell buoys due to its audible nature and was patented by J. M. Courtney of New York.

Some of the infamous commercial OWC devices which have been in successful operation are the LIMPET, Pico power plant, Sakata, Ocean Energy buoy and the Oceanlinx Mk3 (Heath, 2012). The most recent development is the Mutriku wave power plant, which is a breakwater OWC plant located in Mutriku, Spain.

### 1.1.3. Wave climate – global and local

When it comes to renewable energy platforms, the reliability and variability of the energy resource must be taken into account. The origin of ocean waves is known to be from solar energy. This energy from the sun creates winds which blows over the ocean; thus converting wind energy into wave energy (Vining, 2006). Ram et al (2010) states that as long as there is a wind blowing over the ocean the water waves will always be present. This provides an infinite source of wave energy whose variability, from the winter to summer seasons, can be predicted in advance. The factors that would most commonly affect the wave conditions are as follows:

1. Wind velocity,
2. Distance over which the wind is in contact with the ocean ( known as the fetch),
3. And, duration over which these wind conditions is in contact with the ocean.

Figure 1-2 below, shows the approximate global distribution of wave power levels in kW/m and the direction vectors of these wave trains. From this figure it can be noted that the western coastlines hold a greater power distribution due to west-to-east winds; therefore it is a more attractive resource for wave energy conversion. Depending on the area conditions and wave conditions, a particular type of WEC can be implemented. The countries that have installed the highest power capacity WEC's thus far are the United Kingdom, Portugal, and Denmark, each with a capacity rating of 315kW, 400kW and 215kW respectively (OES-IA, 2009).

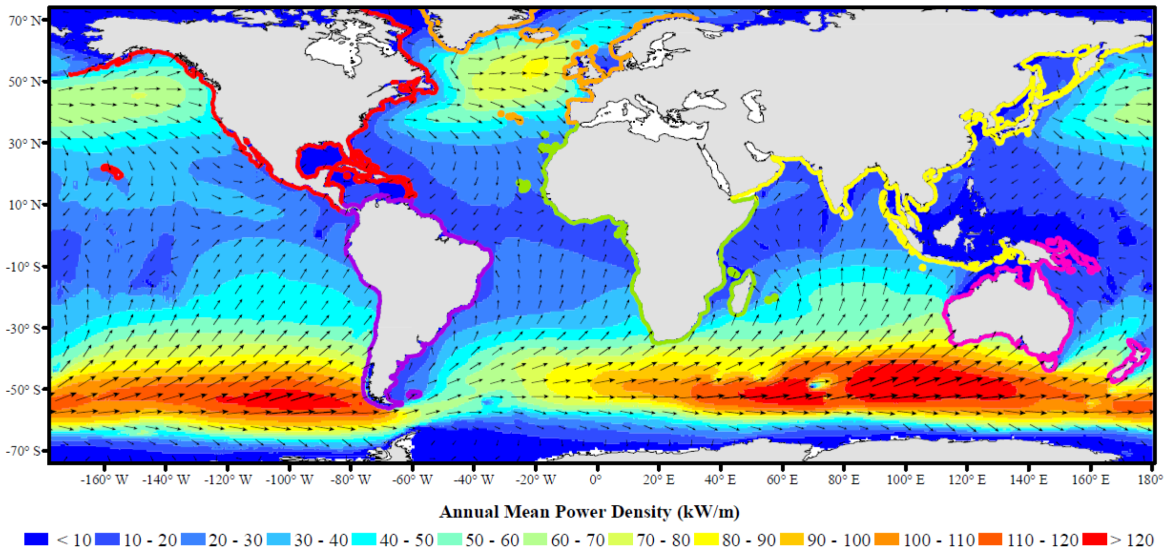


**Figure 1-2: Global map of the Annual Mean Power Density (Gunn and Stock-Williams, 2012)**

## 1.2. Previous work

The air flow in an OWC device's air chamber has been studied in detail over the years. This research ranges from numerical simulation of the air-flow to experimental testing of the chamber, the latter being relevant to this research study. This section deals with the experimental tests performed on OWC models, while looking closely at the air-flow measurement techniques.

The pneumatic power measurement in the closed-loop air flow system of the SWEC model, involved the use of a volumetric gas flow gauge and a differential pressure sensor (Retief, 1982). The gas flow gauge measured the volume flow rate of the air from the high to low pressure manifolds, while the pressure transducer measured the pressure drop over the flow gauge.

The efficiency analysis of a Multi-resonant OWC (MOWC) wave energy caisson in an array for a breakwater application was looked at by Thiruvenkatasamy (1997). Each caisson comprised of an OWC chamber, a dome in the air chamber to concentrate the flow and a duct for the turbine placement. The efficiency of the MOWC model in the wave tank was defined for the pneumatic efficiency which required the pneumatic power flowing through the air chamber. This was achieved using an inductive-type pressure transducer with and the velocity fluctuations of the oscillating water column, measured by a wave probe. The pressure transducers were positioned in inner portions of the top of the dome of the caisson. In this experimental analysis, the volume flow rate of air flowing through the air duct was calculated using the water column velocity.

During the physical OWC model testing performed by Mendes and Monteiro (s.a), they calculated the airflow rate across the exhaust orifice using the water column velocity, as seen in Thiruvenkatasamy (1997). However this was performed using a video camera to record successive movements of the water column through each oscillation. The single frames of the water column movement along with the pressure readings in the OWC chamber were shown in real time on a digital multimeter. The pressure readings were measured using a pressure transducer.

In earlier OWC experimental tests, Sarmento (1992) performed wave flume experiments on OWC models to compare the theoretical and experimental curves for the efficiency and the reflective and transmission coefficients. It was noted that the rate at which the water column is displaced cannot be used for the volume flow rate of air through the turbine due to the effects of air compressibility (Sarmento, 1992). Furthermore for scale model testing, Sarmento and Falcão (1985) explained that for a full sized WEC plant, the air compressibility effect plays a substantial factor in the performance analysis. Given this information, the volume flow rate of air through the air chamber for these tests was determined by measuring the instantaneous pressure in the air chamber as a result of calibrated filters. The pneumatic pressure of the air chamber was measured using a differential manometer, whose range could be selected from 1 % to 100 % of the full scale, at 5 different increments.

Other methods involving the measurement of the volume flow rate of air generated from the oscillating air chamber is the use of an air rotameter. Basically, this equipment is made up of a scaled and transparent tapered tube which contains a 'float' (Hayward, 1979). When there is no flow present, the 'float' rests at the base of the tube and as the flow increases the float ascends in the tube which results in a wider flow opening for the moving fluid. The flow rate of the fluid can be determined from the risen height of the float which can then be directly read off the appropriate scale on the tapered tube. Dizadji and Sajadhan (2011) utilised an air rotameter for flow rate measurement in their experimental analysis of the geometry of an OWC model. In all their experiments, the compression or either the expansion of the air chamber were only investigated therefore a rotameter was an appropriate selection given its ability to only measure the flow in one direction. They also measured the air pressure at the top of the air chamber using a Pitot tube prepared with a digital manometer.

During the model studies on an OWC caisson, Tseng et al (2000) calculated the pneumatic power of the WEC model by utilising pressure measurements along with the rotational velocity of a 48-blade air turbine at the top of the model. This turbine rotated in one direction, despite the bidirectional flow of air. A steel shaft and a 3 cm aluminium thread roller protruded above the turbine, from which a load of various weights were suspended via a pulley system. The operation of this velocity measurement system was that as the air turbine rotated, the attached load would rise a certain height in a measured time frame; therefore allowing the velocity of the air through the turbine to be calculated. The rate of displacement of the volume of the oscillating water column was also taken into consideration during energy efficiency analysis of the caisson model. The air pressure was measured in the air chamber and the front orifice of the air turbine using two differential pressure transducers.

Ram et al (2010) performed a peculiar experimental analysis on a fixed OWC model in a two-dimensional wave tank to analyse the air flow characteristics. The airflow patterns were analysed using Particle Image Velocimetry (PIV) of the air chamber, during which no turbine was present. The PIV system utilised in these experimental tests composed of a Diode-Pumped Solid State continuous light laser and a high-speed camera, which captured the effects of the air flow on the imposed particles. The laser light highlighted the influence of the air flow on the particles, which was subsequently captured on the high speed camera. In addition to the evaluation of the air flow characteristics, the pressure in the specially designed OWC model was measured using a digital micromanometer. The results showed that the airflow through the air chamber was much stronger during the compression stage of the air pocket compared to the airflow during the rarefaction stage.

### 1.3. Objectives

The energy efficiency which is of the utmost importance in OWC devices is the conversion from wave energy to pneumatic energy, since it is the primary energy conversion and the area within which the most energy losses can be predicted. The objective of this research study is to test a designed, constructed and assembled pneumatic power measurement tool that can accurately measure the power of the air-flow from an OWC model.

The designed air flow measurement tool will offer a platform for quantifying the power capacity of an OWC design at a scaled down level. This is considering that the resultant power of the air flow in an OWC system is a measure of the rate of acquired energy that can be utilised to generate electricity.

The sub objectives of this research study are as follows:

- Design a theoretical model of the air-flow in the OWC model's air chamber by examining the fluid mechanics of the pneumatic system. This entails the comprehension of the incoming wave energy source and the resultant air-flow in the system. Through this understanding, the establishment of the required measurement and measurement ranges can be defined to compute the pneumatic power in to and out of the OWC air chamber.
- Investigate different strategies of performing the pneumatic power measurement and determine what appropriate equipment is needed for these imperative accurate measurements.

- Design, construct and assemble the pneumatic power measurement system that will be implemented with the chosen model of the OWC device.
- Perform calibration testing of the measurement tool in order for accurate measurements to be recorded during model testing in the wave flume.
- Design and build OWC model that will be implemented with the pneumatic power measurement tool during the testing phase of the research study.
- Compare the results of the experimental testing from the pneumatic power measurement tool with the theoretical results from the air-flow model.

This investigation of the pneumatic power through model testing of an OWC device design allows the power capabilities of a full scale system to be calculated.

## 2. Theory: Ocean waves to Pneumatic power

The energy conversion boundaries for an OWC device are as follows:

1. Wave to pneumatic energy (water to air)
2. Pneumatic to mechanical energy (air to turbine)
3. Mechanical to electrical energy (turbine to electricity)

These energy transformations are performed over certain control boundaries where the energy is transmitted to the next medium. Even though this research study only deals with the pneumatic power flowing through an OWC model, the energy entering the OWC device must be investigated before looking at the energy movement through the air chamber. Firstly, the water waves will be studied and then the power of the water waves will be examined.

### 2.1. Wave theory

The waves of the ocean are made up of various combinations of wave types which contribute to its complex nature. Before the description of the wave types are given, the following nomenclature for wave theory is defined: $H_w$ is the wave height, $D$ is the water depth, $h_c$ is the crest length, $h_t$ is the trough length and $\lambda$ is the wavelength (Vining, 2006).

### 2.2. Ocean wave power

When considering the power available from the oceans waves, the energy transported in the wave motion should first be analysed. The energy density of waves ($E$) is the amount of energy that is transported in an area of wavefront, perpendicular to the wave direction which is given by equation 2-1. The energy density of waves is transported by waves propagating through the ocean at a specific transport velocity, known as the group velocity $c_g$, and is calculated from equation 2-2. This velocity differs from the wavefront velocity in that the group velocity takes into account a train of waves. Equation 2-3 defines the power flux (wave energy flux) of the waves *P* calculated from the product of the average energy density of waves along and the group velocity $c_g$. The wave energy flux provides the power per metre of wavefront (kW/m). If, for example, the incident wave power capacity $P_i$ on a width of an OWC device's opening is desired, the wave energy flux *P* should be multiplied with the opening width b to determine the power (kW). By utilising the incident wave power $P_i$ (Mendes, s.a), the total average incident wave power over a wave period $T$ can be solved for by using equation 2-4.

$$E = \frac{\rho g H^2}{16} \quad \textbf{(2-1)}$$

$$c_g = \frac{g \tanh kh}{2\omega}\left[1 + \frac{2kh}{\sinh 2kh}\right] \quad \textbf{(2-2)}$$

$$P = E\, c_g \quad \textbf{(2-3)}$$

$$P_{T,inc} = \frac{1}{T}\int_0^T P_i\, dt \quad \textbf{(2-4)}$$

### 2.3. Energy Balance

In the energy conversions from the waves to pneumatic power, there must be an energy balance of the system, so that the various energy components can be accounted for. In this section, the wave energy conversion to pneumatic energy is firstly described by the law of conservation and then the energy equation is utilised to investigate the energy in the air chamber.

The law of energy conservation is applied to the system so that it takes into account the energy entering and leaving the OWC due to the waves. Tseng et al (1999) encompasses the use of the law of energy conservation for the OWC application by equation 2-5.

$$E_I = E_W + E_R + E_L \qquad \textbf{(2-5)}$$

Where, $E_I$ is the incident-wave energy, $E_W$ is the energy transmitted to the pneumatic chamber, $E_R$ is the reflected wave energy and $E_L$ is the frictional energy loss due to viscosity and turbulent motion of the waves. Equation 2-5 states that the energy of the incident waves to an OWC device will be distributed into three divisions of energy forms: reflected wave energy ($E_R$) in the water, frictional energy ($E_L$) in the walls of the OWC and sea bed and the most important energy form for the air flow measurement: the pneumatic energy ($E_W$).

The process flow from incident waves to heave enables the energy transfer from the water column to the air chamber. The heave motion of the waves is the upward lift of the water column in an OWC device, which contributes to the compression of the air in the pneumatic chamber. This would then provide energy for the PTO process.

### 2.4. Pneumatic Power

For the accurate measurement of the power of the air flow, the necessary measurement components for pneumatic power need to be defined. Firstly, the instantaneous power $P_i(t)$ is defined by equation 2-6.

$$P_i(t) = p(t) \int v(t)\, dA \qquad \textbf{(2-6)}$$

Where, $p(t)$ is the air pressure in the air chamber relative to the atmosphere, $v(t)$ is the velocity of air through the turbine and $\int dA$ is the area through which the volume of air flows. The instantaneous air power $P_i$, given by equation 2-7, can be translated to a total average absorbed power $P_{T,abs}$ by measuring $P_i$ over a time interval T (Thiruvenkatasamy, 1997).

$$P_{T,abs} = \frac{1}{T}\int_0^T p(t)\, Q(t)\, dt \qquad \textbf{(2-7)}$$

From the above the derivation of the total average absorbed power $P_{T,abs}$ in an OWC device, it can be established that the pressure drop over the turbine and the volume flow rate $Q(t)$ through the turbine are the fundamental components in measuring the pneumatic power that is delivered to a turbine.

## 3. Development of the pneumatic power measurement tool

### 3.1. Design to assembly of pneumatic power measurement tool

The design of the pneumatic power measurement tool is based on the characteristics of the volume flow rate of air and air pressure in an OWC device, which was documented in the literature studies. This section describes the concept designs, final design, construction and assembly of the pneumatic power measurement tool from the concept to the final product stages.

### 3.1.1. Design concepts

As mentioned before, the measurements required for the calculation of the pneumatic power of an OWC device is the pressure drop over an orifice and the volume flow rate of air through the orifice. After the completion of the literature studies, it is evident that the measurement of the volume flow rate is the main concern and not the air pressure measurement which is more of a standard selection procedure. The volume flow rate of air in OWC devices are both unsteady and bidirectional which limits the types of flow meters one can apply to the model to ensure accuracy of the pneumatic power measurement.

#### 3.1.1.1. Volume flow rate measurement

The investigation of the various types of flow meters helped to identify the correct equipment for the volume flow rate measurement. Hayward (1977) and Figliola and Beasley (2006) were used to generate a complete list of flowmeters that could be utilised for the volume flow rate measurement of air. In addition to unsteady and bidirectional flow suitability, the air-flow meter would also have to be easily integrated with the OWC device.

The air-flow measurement instruments that were shortlisted for the concept designs as part of the pneumatic power measurement tool were pressure differential meters, pitot-static probes, thermal anemometers and vane anemometers. The idea behind these selections was due to their potential ability to measure turbulent and bidirectional air-flow.

From the selected concept designs for the volume flow rate meter, the advantages and disadvantages of the concept design instruments had to be weighed against each other for a final selection to be made. Obstruction meters, the sub-category of pressure differential meters, was the chosen flow meter classification due to its ability to be constructed (machined) according to a specific design that can be incorporated with the designed OWC model. These types of flow meters are also simple in design where there are no moving parts to facilitate malfunctions and there are a substantial amount of codes of practice to aid in the design of the flow meter (Hayward, 1977). The reasons for the other three concept designs not being chosen are highlighted in Table 3-1.

**Table 3-1: Reasons for exclusion of the other flow meter concepts**

| Flow meter | Reasons for not being selected |
|---|---|
| **Pitot-static tubes** | The tube design measurement causing a delay with the bidirectional measurement<br>Rangeability of these devices are also limited due to inaccuracies at low air velocities (Hayward, 1977) |
| **Thermal anemometers** | Recalibration of the probes necessary if accurate data is needed |
| **Vane anemometers** | Inertial losses are present during variation of fan rotation in bidirectional flow conditions |

The three obstruction meters that can be used for flow measurement are orifice plates, flow nozzles and venturi flow meters. The use of flow nozzles cannot be incorporated into bidirectional flow systems therefore was excluded from the selection process. The final selection of the specific flow meter type from the pressure differential meter category for the volume flow rate measurement for the pneumatic power measurement tool was the venturi flowmeter. This selection was primarily based on the venturi flow meter’s relatively low pressure head loss compared to that of a square-edged orifice plate.

#### 3.1.1.2. Pressure measurement

Pressure measurement for the pneumatic power is required for two scenarios. First is the measurement of the pressure drop over the venturi, where the volume flow rate of air is measured, and second is the pressure measurement in the venturi flow meter to calculate the volume flow rate of air. The pressure transducers to measure the pressure drop also measure the volume flow rate of air in the venturi. For this pressure measurement to be acquired, a suitable pressure transducer is required. A pressure transducer converts a mechanical measurement into an electrical signal through the deflection of an elastic element such as a diaphragm or Bourdon tube.

The possible pressure transducer measurement scales are absolute, gauge and differential pressures. In terms of the pressure measurement for the pressure drop over an OWC model, either one of the three types of pressure measurement scales can be used. The first thought of selecting a pressure transducer would be to use a differential pressure transducer to calculate the pressure difference between two points of the bidirectional flow. The problem arises in the tubes leading up to the differential transducer because there is a substantial dead volume in the length of the connecting tubes which will cause delays in the capturing of measurements, consequently causing inaccuracies in the measurements. This is especially pertinent since it is an unsteady system. Therefore for the pressure measurement in the venturi meter, an absolute pressure transducer or preferably a gauge pressure transducer is required so that the pressure measurement is as close to the air-flow as possible. The pressure transducers used in all the measurement scenarios will measure the static pressure.

### 3.1.2. Venturi flow meter

Since the standard venturi flow meter is normally used for unidirectional flow measurement, the design had to be altered according to the application with an OWC device. The typical design of the venturi shown by Figure 3-1 has a convergent section and a divergent section joined to a throat.

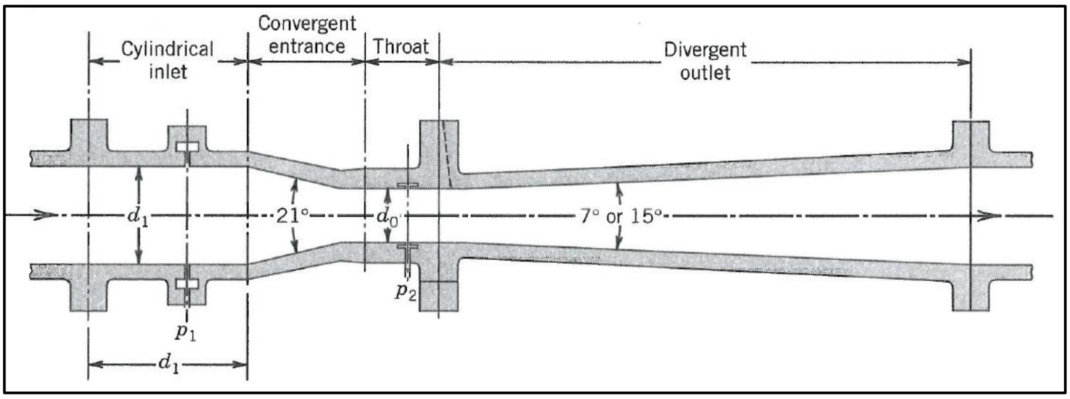


**Figure 3-1: Typical layout of a venturi flow meter (Figliola and Beasley, 2006)**

The design of the venturi flow meter as the volume flow rate meter in the pneumatic power measurement tool is based on manipulating the original design by making it symmetrical for the bidirectional measurement. The calculation behind this reasoning resulted in a subtended angle of 14° for the bidirectional venturi flow meter. The beta value $\beta$ determines the area ratio of the throat of the venturi flow meter to the air-duct. According to the venturi meter standards (ISO 5167-1:1991) the range of the beta value is 0.4 to 0.75 and it is used determine the throat diameter $d_t$ through equation 3-2. Figure 3-2 shows the dimensions of the designed bidirectional venturi meter with the air-ducts, which connects it to the roof of the OWC model.

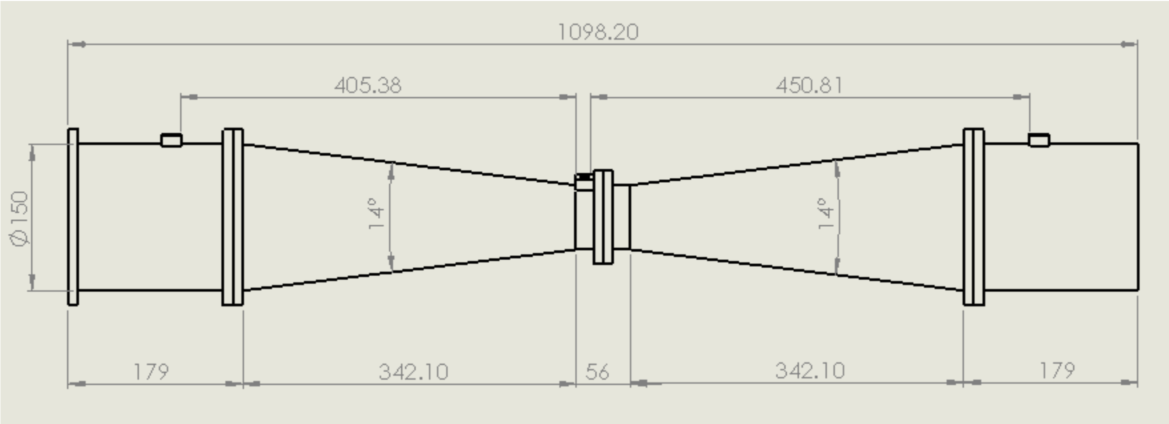


**Figure 3-2: Dimensions of the designed venturi flow meter with the connecting air ducts (mm)**

Equation 3-1 describes the non-linear relationship between the volume flow rate of air and the pressure drop in venturi flow meter. The coefficient of discharge $C_d$ is a correction factor for the measured flow rate which is determined during calibration. The square relationship shown by equation 3-2 results in inaccurate readings at low volume flow rates due to the pressure drop being measured as zero for a range of low flow rates. These inaccuracies had to be catered for by an additional flow meter to measure the volume flow rate accurately at low flow rates. The chosen flow meter would have to be placed at the throat of the venturi where the air-flow velocities are the highest.

$$\boldsymbol{Q = C_d A_d \sqrt{\frac{2\Delta p}{\rho\left(\left(\frac{A_d}{A_t}\right)^2 - 1\right)}}} \qquad \textbf{(3-1)}$$

Where, $A_d$ is the area of the air-duct, $A_t$ is the throat area of the venturi flow meter and $\Delta p$ is the pressure drop between the air-duct and the throat

$$\boldsymbol{Q^2 \propto \Delta p} \qquad \textbf{(3-2)}$$

It was decided that a hot-film anemometer would be incorporated with the venturi flow meter because it has a linear relationship between the output voltage and the air-flow velocity, a high frequency response to suit the oscillations of the air-flow in an OWC model and has a small probe which can be easily incorporated into the designed venturi flow meter.

The bidirectional venturi flow meter was machined in the mechanical workshop at Stellenbosch University. The material used to construct this flow meter is polyvinyl chloride (PVC) since it can be machined quite easily to a smooth finish for minimal friction losses during use. The design of the venturi flow meter as two symmetrical pieces facilitated the machining process and ensured that each piece was smoothly machined to an acceptable level.

## 3.2. Air-flow model

This section describes the theoretical model of the air chamber’s operation and the pneumatic power in an OWC model. The three models described in this chapter define an OWC model with a closed roof, a roof with an orifice and the main model which describes an OWC model with the designed venturi flow meter on its roof. The aim of the simulated models was to accurately predict the air chamber pressures from the OWC models operation and the performance of the designed pneumatic power measurement tool.

The simulation models use the ideal gas laws to do derive the state equations for the air flow in the air chamber. These laws are applicable for this system since the air chamber pressures are considerably under the critical pressure level and the operating temperatures are substantially higher than the critical temperature. The application of the first law of thermodynamics on the system assists in evaluating the energy balance for the air-flow model.

The third model for the validation of the pneumatic power tests is still under progress; therefore it is not used in this article.

## 4. Testing: Calibration and Experiments

### 4.1. Equipment for the pneumatic power measurement tool

The equipment that was used for the measurement of the pneumatic power of an OWC model comprised of the relevant transducers and the data acquisition (DAQ) unit, which is directly connected to a laptop via USB cable.  Three gauge-type pressure transducers were utilised which have a working range of -5kPa to 5kPa and an accuracy of 2.5% of the full-scale output. The pressure transducers were used for the pressure drop measurement in the venturi flow meter. The pressure transducers have an analog output of 4-20 mA. The selected hot-film flowmeter from the Schmidt catalogue has a working air velocity measuring range of 0-20 m/s and a pre-set frequency response of 0.01s. This flowmeter has an analog output of 0-10V. The DAQ unit chosen to handle the analog inputs from the transducers was an Eagle MicroDAQ unit which has 16 analog inputs and a frequency response of 250 kHz.

The wave probes used to measure the incoming wave heights and the water column oscillations in the OWC box were resistive type transducers that are available at the wave flume facility.

### 4.2. Calibration of the Venturi flow meter

The calibration of the venturi flow meter was performed in a vertical wind tunnel at the Mechanical and Mechatronics department of Stellenbosch University. The wind tunnel operated in such a manner that the fan created a pressure drop over its structure resulting in air-flow being drawn into it from the atmosphere. A pre-calibrated pressure differential meter in the wind tunnel measured the actual volume flow rate of air through the structure. The venturi flow meter was placed vertically in the tunnel and calibrated with its roof joined so as to resemble the experimental setup during the wave flume tests. The calibration was performed for incrementing values of the volume flow rate so that the operating flow rates during experimentation would be covered. The actual volume flow rate was compared to the measured volume flow rate and a coefficient of discharge was found for specific ranges of the flow rate. This coefficient is a correction factor for the measured flow rates. An average coefficient of discharge for the venturi was 0.9. The A block test was also performed on the venturi flow meter to check if there were any air-leaks in the system.

### 4.3. Wave flume experiments

The wave flume at the Civil Department of the University of Stellenbosch is where the model tests of OWC and the pneumatic power measurement tool were performed. This section describes the wave flume, the set-up of the equipment and the testing procedure of the OWC model.

#### 4.3.1. Overview of the wave flume

The wave flume used for the experimental testing of the pneumatic power measurement tool is a HR Wallingford flume wave generation system. This wave tank is considered a small wave tank which is uses a piston paddle, driven by a small electric AC servomotor, to generate waves. A signal-generation computer with the HR Wavemaker program, located next to the wave flume, controls the paddles to generate the wave types that are programmed into it. The specifications of the small wave flume allow it to generate waves at a maximum of 0.8m. The wavemaker has the ability to generate numerous wave heights at different frequencies as long as it obeys the theoretical performance curves for the applied water depth. The wave probes of the wave flume are controlled through a HR Wallingford DAQ system.

#### 4.3.2. Experimental set up

The OWC model used to test the pneumatic power measurement tool was constructed out of Perspex sheets and glued together using tensol adhesive. The dimensions of the Perspex box are shown in Figure 4-1. Two threaded rods were placed between the front wall and the back wall to stabilise the box during testing and to prevent the front and back wall from moving during operation in the wave flume. The diameter of the orifice of the OWC model is the same as the inner diameter of the air-duct on the venturi flow meter.

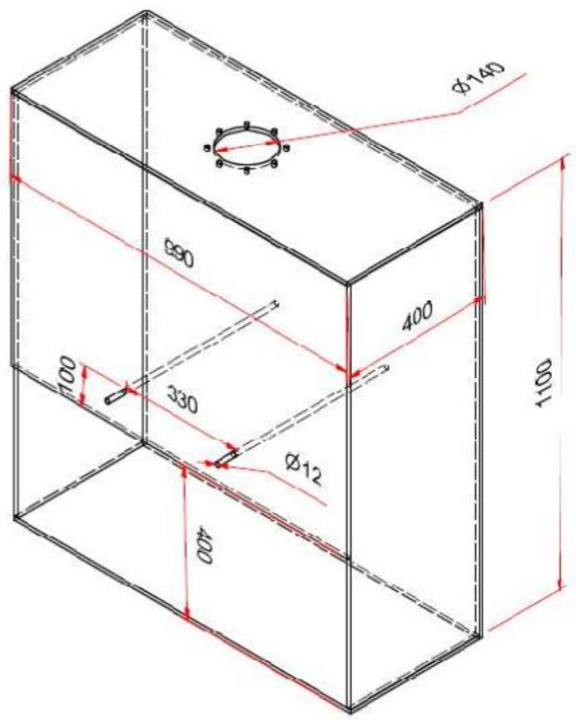


**Figure 4-1: Dimensions of the OWC model (mm)**

#### 4.3.3. Test schedule

The testing schedule for the pneumatic power measurement tool was performed for various wave conditions. The wave height and wave frequency was varied for three different water depths. The water depths that the OWC model was tested at were 0.5m, 0.6m and 0.7m, which were all within the theoretical performance specifications. The crest-to-trough wave heights that were tested were 0.05m and 0.1m and the wave frequencies ranged from 1Hz to 0.33Hz, depending if they obeyed the theoretical performance curve of the wavemaker. In total, there were 34 tests which were performed for the performance of the pneumatic power measurement tool. These exclude the separate tests of a closed-box OWC model and an OWC model with an orifice, which did not include the designed pneumatic power measurement tool.

## 5. Results and Discussion

The results shown below describe the pneumatic power output at the wave frequency which has the optimum average power at water depth 0.6m. This is the water depth at which most of the depths could be performed. Figure 5-1 shows the pneumatic power for wave height 0.05m and Figure 5-2 shows the pneumatic power for wave height 0.1m. The positive pneumatic power was calculated directly from the pressure and volume flow rate measurements.

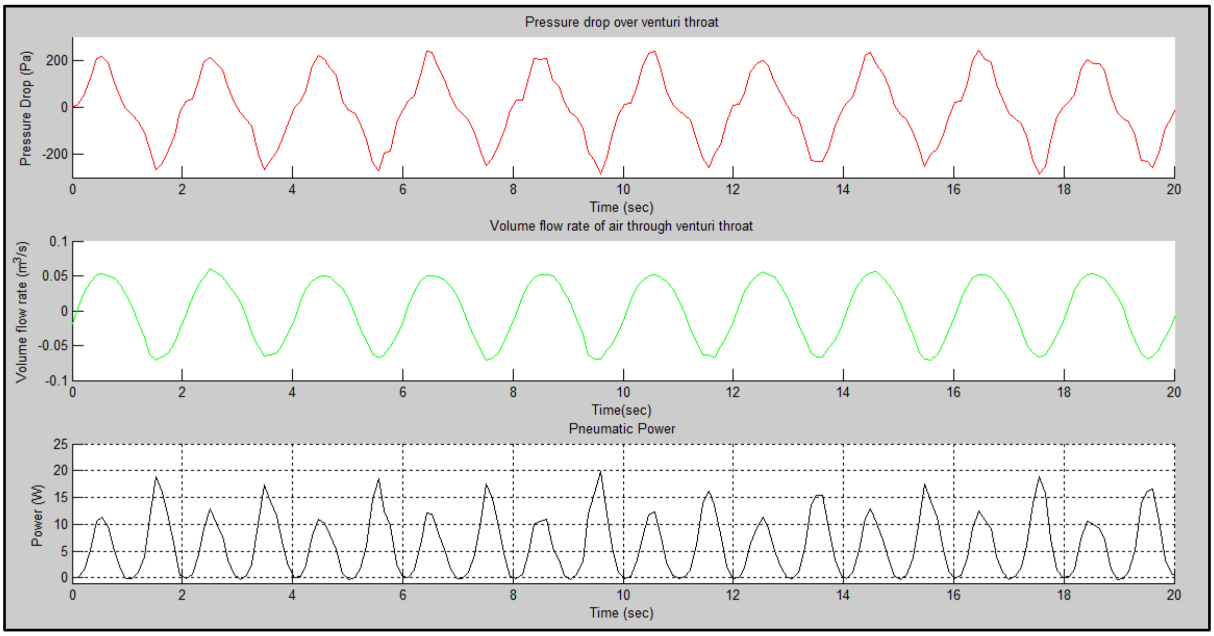


**Figure 5-1: Pneumatic power output for wave height of 0.05m at wave period of 2.0s**

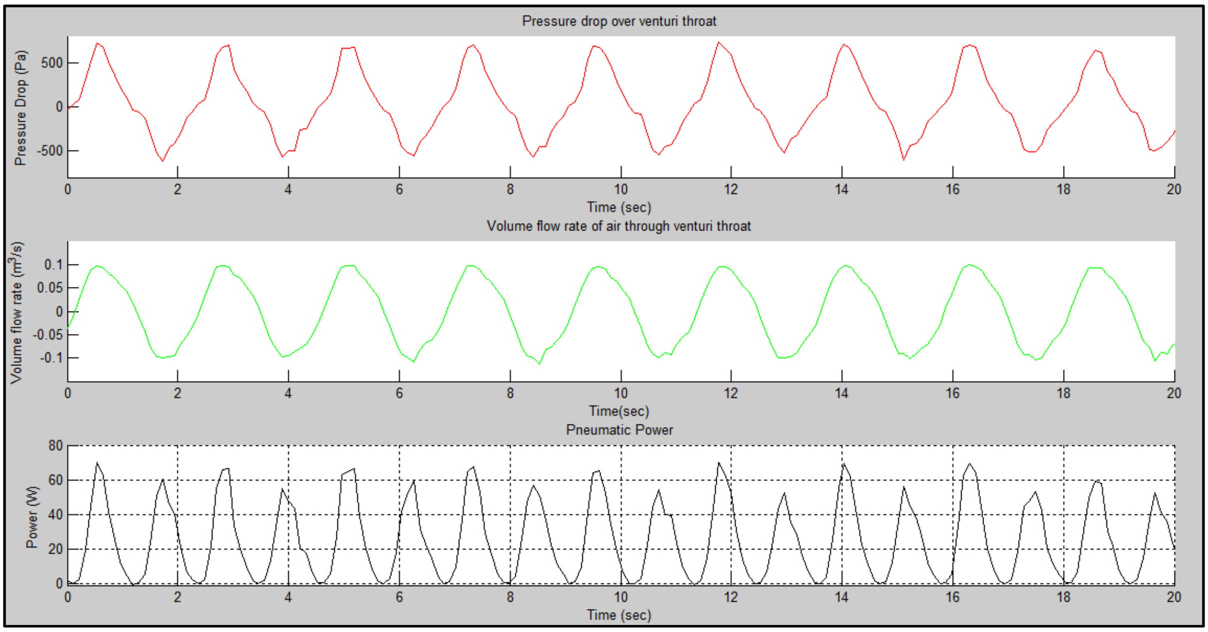


**Figure 5-2: Pneumatic power output for wave height of 0.1m at wave period of 2.25s**

From the above results it can be seen that the maximum instantaneous power increases by a considerable margin with the increase of the wave height at a constant water depth. From figure 5-1, it is evident that the oscillations of the air pressure, volume flow rate and the pneumatic power have a higher peak when air flows back into the OWC air chamber (expansion of the air column).

The average power output from the processed pneumatic power for all the tests was compared. The average power was calculated for ten oscillations at each test. Table 5-1 shows the results of the average power for the tests done at water depth D=0.6m and water depth D=0.7m for the wave periods T=1.5s to T=3.0s.

**Table 5-1: Comparison of average pneumatic power**

| | Average Pneumatic Power (W) | | | |
|---|---|---|---|---|
| **T(s)** | **Hw=0.05m D=0.6m** | **Hw=0.01m D=0.6m** | **Hw=0.05m D=0.7m** | **Hw=0.1m D=0.7m** |
| 1.5 | 5 | 19.02 | 2.61 | 9.45 |
| 1.75 | 4.4 | 15.26 | 3.74 | 13.58 |
| 2 | 6.08 | 20.9 | 3.81 | 14.18 |
| 2.25 | 4.66 | 25 | 8.03 | 28.51 |
| 2.5 | 4.15 | 16.85 | 2.39 | 11.74 |
| 3 | 7.01 | 30.8 | 6.77 | N/A |

The above results show that as the water depth is decreased, the average pneumatic power increases. This is due to the energy being the greatest at the surface of the water; therefore at the lower water depth of 0.6m, it is more accessible for the energy to enter the water column.

## 6. Conclusions and recommendations

An evaluation platform for OWC model testing, with regard to the acquired pneumatic power is required to quantify its operational performance. This is achieved in the research study through the design, construction and assembly of a pneumatic power measurement tool for an OWC model.

The design of the measurement tool was for the unsteady and bidirectional air-flow characteristics found in OWC systems. The use of a single device to measure the pressure drop and volume flow rate simplifies the testing set-up and makes it possible for the device to be implemented on different OWC platforms. The calibration of the pneumatic power measurement tool before testing with the OWC model was a fundamental step in ensuring that the recorded measurements were accurate. It enables the exact tuning of the measurement equipment before the wave flume testing stage. The simple design of the Perspex OWC model allowed easy construction of the model and also facilitated the development of a simulation program of the air-flow in the OWC model.

For further developments, the designed pneumatic power measurement tool can be used to calculate the efficiency of the OWC model and it could also be used to find an optimum geometry of a specific model during wave flume tests.

In conclusion, the completion of this research creates a knowledge platform for finding the pneumatic power in OWC designs. This platform can be built upon to facilitate the validation of future OWC concepts and determine whether they are worthy for further research and development.

## 7. References

Ackerman, P.H. October 2009. *Air Turbine Design Study for a Wave Energy Conversion System*. Unpublished MSc Eng Thesis. University of Stellenbosch, Stellenbosch.

Dizadji, N. & Sajadian, S. E., 2011. Modeling and Optimization of the Chamber of OWC System. *Energy,* Volume 36, pp. 2360-2366.

Figliola, R.S & Beasley, D.E. 2006. *Theory and Design for Mechanical Measurements*. John Wiley & Sons, Inc.

Gunn, K, Stock-Williams, C. 2012. Quantifying the Potential Global Market for Wave Power. *Proceedings from the International Conference on Ocean Energy 2012*. Dublin, Ireland

Hayward, A.T.J. 1979. Flowmeters. The MacMillan Press LTD: London and Basingstoke

Heath, T.V. 2012. A review of oscillating water columns. *Philosophical transactions of the Royal Society A 2012*: 370, 235-245

ISO 5167-1:1991. 1991. Measurement of fluid flow by means of pressure differential devices Part 1. *International Organisation for Standardisation*

Mendes, A.C & Monteiro, W.M.L. [s.a]. *Performance analysis of a model of OWC energy converter in non-linear waves*. Laboratory of Fluid Mechanics and Turbomachinery, Universidad de Beira Interior.

Muetze, A & Vining, J.G. 2009. *Ocean Wave Energy Conversion – A Survey*. Electrical and Computer Engineering Department, University of Wisconsin-Madison.

OES-IA. 2009. *Ocean Energy Systems International Agreement: Annual Report 2009*.

Patterson, C, Dunsire, R, Hillier, S. 2010. *Development of Wave Energy Breakwater at Siadar, Isle of Lewis*

Ram, K, Faizal, M, Rafiudin Ahmed, M & Lee, Y.2010. Experimental studies on the flow characteristics in an oscillating water column device. *Journal of Mechanical Science and Technology* 24(10): 2043-2050.

Retief, G. de. F., Prestedge, G.K. & Müller, F, P, J, 1982. A Proposal for wave energy conversion near Cape Town. *18th ICCE conference* 1: 245-260, Cape Town, South Africa.83

Retief, G. 2006. Wave power in the Western Cape [Presentation].

Ross, D. 1979. Energy from the waves. Pergamon Press Ltd.: Oxford, England.

Sarmento, A.J.N.A. 1992. Wave flume experiments on two-dimensional oscillating water column wave energy devices. *Experiments in fluids* 12: 286-292

Thiruvenkatasamy, K. & Neelamani, S. 1997. On the efficiency of wave energy caissons in array. *Applied Ocean Research*, 19: 61-72.

Tseng, R, Wu, R & Huang, C, 1999. Model study of a shoreline wave-power system. *Ocean Engineering*, 27: 801-821.

Van Niekerk, J.L & Joubert, J.R. 2010. *Wave Energy Converters (WECs)*. Centre for Renewable and Sustainable Energy Studies.

Vining, J. 2005. *Ocean Wave Energy Conversion*. Advanced independent study report. University of Wisconsin, Madison.