Comparison of power takeoff between Fixed OWC and Backward Bent Duct Buoy OWC

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Abstract

This project compares power takeoff between fixed oscillating water column (OWC) and backward bent duct buoy (BBDB) OWC using OpenFOAM CFD. OWCs utilize wave-induced air pressure oscillations to drive turbines for electricity. Fixed and BBDB OWCs are studied using single chambers and evaluated for different cnoidal wave periods. Geometries were created in Salome, simulated with interFoam for fluid-structure interaction, and waveModels for wave generation. Paraview analyzed and compared results with literature. Future work could explore floating BBDB OWCs.

1. Introduction

The pursuit of renewable energy sources has led to innovative technologies harnessing ocean waves for electricity generation. The Oscillating Water Column (OWC) stands out as a promising solution, converting wave-induced air pressure oscillations into mechanical power for turbines. This report compares two OWC variations: the Fixed Oscillating Water Column (FOWC) and the Backward Bent Duct Buoy (BBDB) OWC. Advanced computational fluid dynamics (CFD) simulations using OpenFOAM software form the basis of this study. The Fixed Oscillating Water Column (FOWC) system features a stationary chamber submerged in the ocean. As waves interact with the chamber, air pressure fluctuations drive turbine-connected generators. Its simplicity has led to extensive research, yet optimizing its performance for varying wave conditions remains a challenge. The Backward Bent Duct Buoy (BBDB) OWC is an innovative variant. It integrates the chamber with a backward bent duct for improved airflow to turbines. This design aims to enhance energy capture and efficiency. The BBDB configuration allows flexibility in adapting to wave characteristics, potentially improving power conversion.

The study employs OpenFOAM, an open-source CFD toolbox, for comprehensive analysis. Simulations using interFoam and waveModels capture fluid-structure interaction and wave conditions.

2. Problem Statement

We have done a Comparative Analysis of Power Takeoff Systems for BBDB OWC and FOWC. The effectiveness of a wave energy converter(WEC) is closely tied to its power takeoff (PTO) system, which converts the mechanical motion of the water column into usable electrical energy. This study focuses on a comprehensive comparative assessment of the power takeoff performance between two specific types of Oscillating Water Column WECs: the traditional Fixed Oscillating Water Column and a novel geometric variation of the Backward Bent Duct Buoy (BBDB) Oscillating Water Column. It is important to note that in this study, the BBDB configuration has been examined solely in terms of its geometrical attributes and has not been rendered floatable.

3. Governing Equations

Continuity equation and momentum equation are the fluid flow governing equations used which are given as below,

$$\nabla . V = 0 \tag{1}$$

$$\rho(\frac{\partial V}{\partial t} + V.\nabla V) = -\nabla p + \mu \Delta V + \rho g \tag{2}$$

where, V is the fluid velocity, ρ is the fluid density, g is the acceleration due to gravity, p is the dynamic pressure and μ is the dynamic viscosity of the fluid.

3.1 Volume of fluid (VOF) method

OpenFOAM uses the volume of fluid (VOF) method to capture the free surface of the interface between the two phases air and water. In the VOF method, two phases have separate volume fraction (α). α =1 dictates the cell is full of water, if α =0, the cell is full of air and if 0< α <1, the cell is a mixture of air and water. The density ρ and viscosity μ in each cell is weighted by,

$$\rho = \alpha \rho_w + (1 - \alpha)\rho_a \tag{3}$$
$$\mu = \alpha \mu_w + (1 - \alpha)\mu_a \tag{4}$$

4. Simulation Procedure

4.1 Geometry and Mesh

The two-dimensional case study of OWC was simulated in this study. The numerical setup for the OWCs are shown in figure below. The numerical setup consists of a 2-D numerical wave flume 9 m long for FWOC and 10 m for BBDB OWC with an initial water depth of 0.6 m for FWOC and 0.62 for BBDB OWC. The position of the OWCs are shown in the figures below. A piston-type wave generator is set on the left-hand side of the numerical wave flume and a wave absorption boundary condition is placed on the other side to limit the presence of reflected waves in the flume. Geometry and Mesh both were created using Salome. Geometry was referred from paper[4]. The geometry was partitioned for enabling proper hexahedral meshing. For FWOC mesh size was taken 0.015 m for both 50 mm and 9 mm slots and for BBDB OWC mesh size was taken same as FOWC i.e., 0.015 m after some iterations.

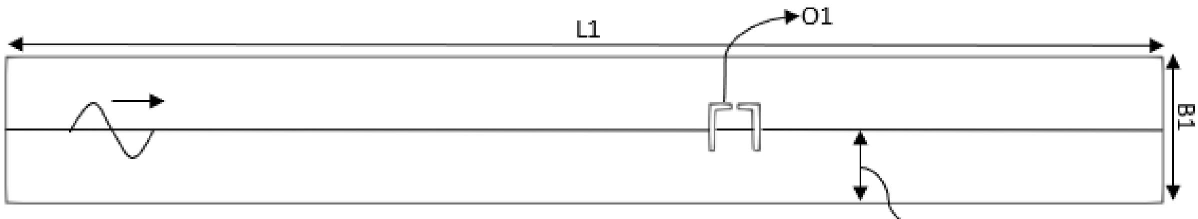


Fig 1:- Domain of Fixed OWC

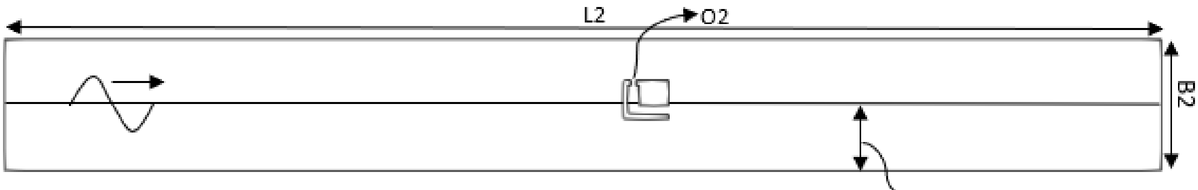


Fig 2:- Domain of BBDB OWC

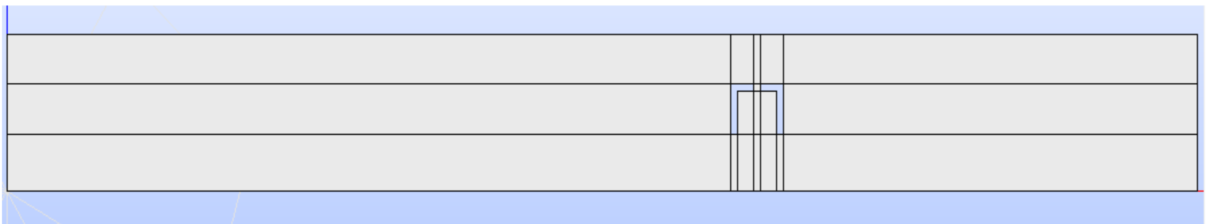


Fig 3:- Geometry of FOWC

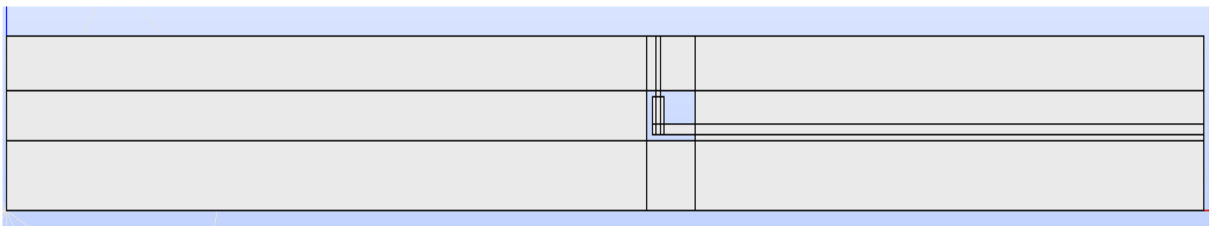


Fig 4:- Geometry of BBDB OWC

Fixed OWC		Backward bent duct buoy OWC	
L1	9m	L2	10m
B1	1.1m	B2	1.1m
O1	0.050m, 0.009m	O2	30mm
H1	0.6m	H2	0.62m

Table 1:- Domain Specifications

4.2 Initial and Boundary Conditions

Boundary conditions are set at the boundaries of the CFD domain in order to solve the governing equations. Table below lists the boundary conditions employed in the present study. The wave generation and absorption are made with the interFoam solver with different values specified at the inlet and outlet of the computational domain. Boundary conditions were same for both FWOC and BBDB OWC At the inlet, the volume fraction α and velocity are taken from cnoidal wave theory, and at the outlet, they are set to shallowWaterAbsorption model . The boundary conditions adopted in the study are given as below in the table. Inlet was taken as the left side of the domain and the right side as outlet. Bottom and the OWC part of the domain was given wall conditions and ground name was given to them. Top side of the domain was given atmosphere conditions and the sides were given as empty conditions as it is a 2D case study.

Boundary	Pressure	velocity	Volume fraction
inlet	fixedFluxPressure	waveVelocity	waveAlpha
outlet	fixedFluxPressure	waveVelocity	zeroGradient
ground	fixedFluxPressure	fixedValue	zeroGradient
top	totalPressure	pressureInletOutletVelocity	inletOutlet
sides	empty	empty	empty

Table 2 :- boundary conditions

4.3 Solver

The Solver utilized in the simulations is the OpenFOAM solver *interFoam*. It is an incompressible, transient, isothermal multiphase solver. The solver utilizes the Volume of Fluid (VOF) Method for tracking the free surface. The PIMPLE algorithm is run which is a combination of Pressure Implicit with Splitting of Operators (PISO) and Semi Implicit Method for Pressure Linked Equations (SIMPLE). The solver timestep is kept 0.01 s and the simulations are run for 70 s with 0.033 s write interval. The timestep is adjustable during runtime. The Max Courant Number and the Max Alpha Courant is set to 0.65.

TERMS		SCHEMES
Time		Euler
Gradient		Gauss linear
Divergence	div(rhoPhi,U)	Gauss linearUpwind grad(U)
	div(phi,alpha)	Gauss vanLeer
	div(phirb,alpha)	Gauss linear
	div(((rho*nuEff)*dev2(T(grad(U)))))	Gauss linear
Laplacian		Gauss linear orthogonal

Table 3:- Numerical scheme

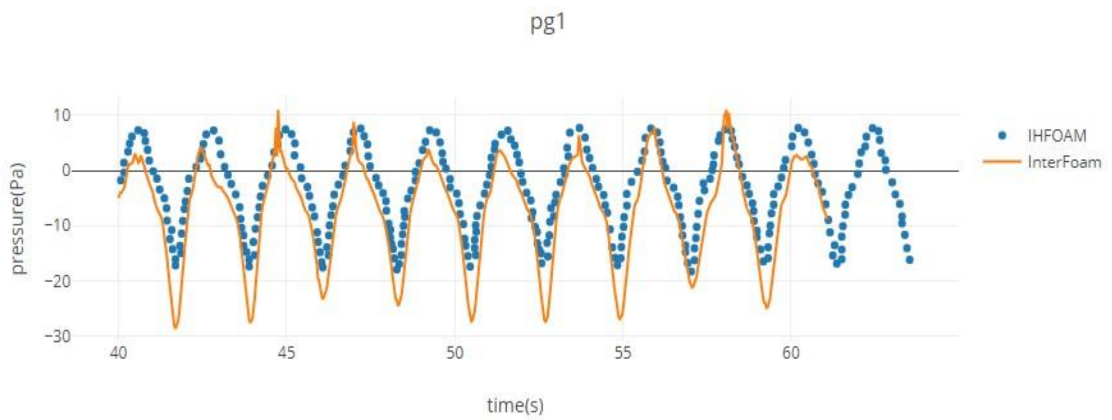
5. Results and Discussions

The aim of this section is to compare the powertakeoff between FWOC and BBDB OWC. The results of FWOC were validated by comparing with the finding from a relevant research paper[2]. Then Power takeoff of both the OWCs are compared.

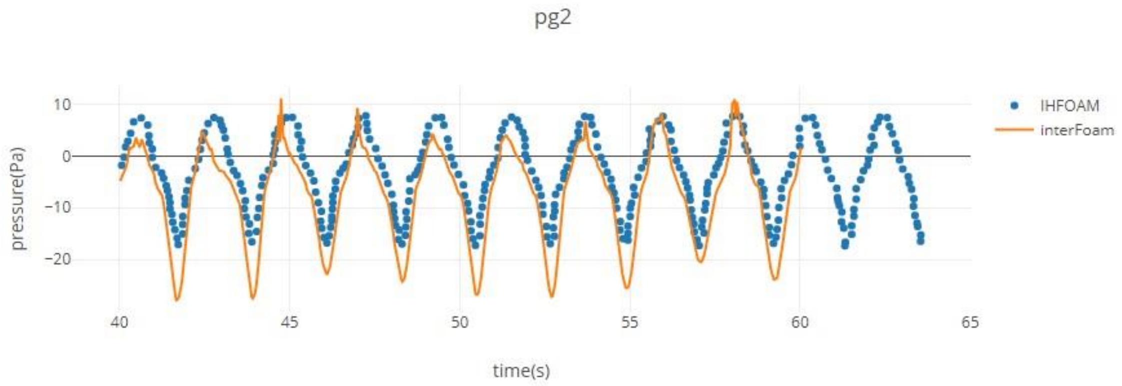
5.1 Model validation study

Fig below shows the comparison of pressure in wave chamber of our model with the findings of the paper[2] at two different time periods of wave i.e., 2.2 s and 3.2 s. Here PG1 refers to coordinates, (5.58m, 0.34m, 0.68m) and PG2 refers to coordinates, (5.715m, 0.34m, 0.68m). But in case of BBDB OWC pressure was observed in the coordinates, (5.405m, 0.25m, 0.7186m) and (5.475m, 0.25m, 0.7186m). Here in the referred research paper, they have used IHFOAM as the solver, but we have used interFoam. In the paper they have mentioned the model was able to predict the pressure behavior inside the chamber with certain quantitative differences between the experimental and numerical time series. The IHFOAM tends to slightly overpredict the maximum and minimum pressures. A too small air turbulent dissipation in the numerical model could be responsible for these differences, since very small differences on the free surface oscillation have been observed. Another aspect to point out is that the numerical model does not reproduce the slight irregularities experimentally recorded, especially around the maxima and the minima, where the model results are smoother in time. We can see our model slightly overpredicts the the minimum pressure from the model used in the paper and we can see some deviations, but overall shape of waveform is same as that of the reference paper. In case of free surface velocity, we have captured it by tracking $\alpha = 0.5$, using slice to get the plane inside the chamber and contour to map $\alpha = 0.5$ in the plane in Paraview software and it is found to be closely related to what is present in the paper. After getting the results they are plotted using online graph maker of plotly chart studio.

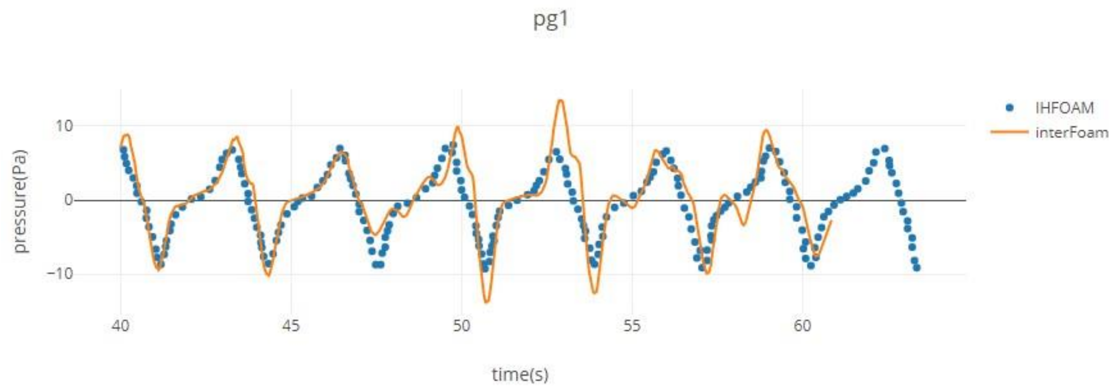
a)



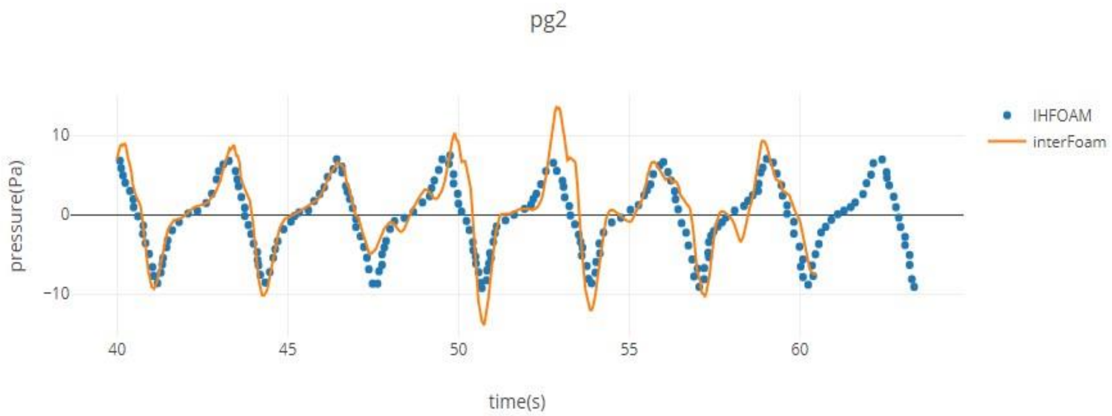
b)


pg2
pressure(Pa)
10
0
−10
−20
40
45
50
55
60
65
time(s)
IHFOAM
interFoam

c)


pg1
pressure(Pa)
10
0
−10
40
45
50
55
60
time(s)
IHFOAM
interFoam

d)


pg2
pressure(Pa)
10
0
−10
40
45
50
55
60
time(s)
IHFOAM
interFoam

e)

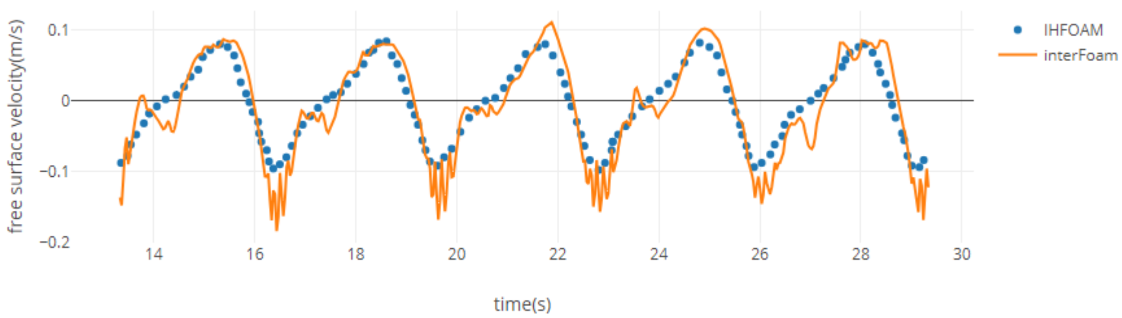
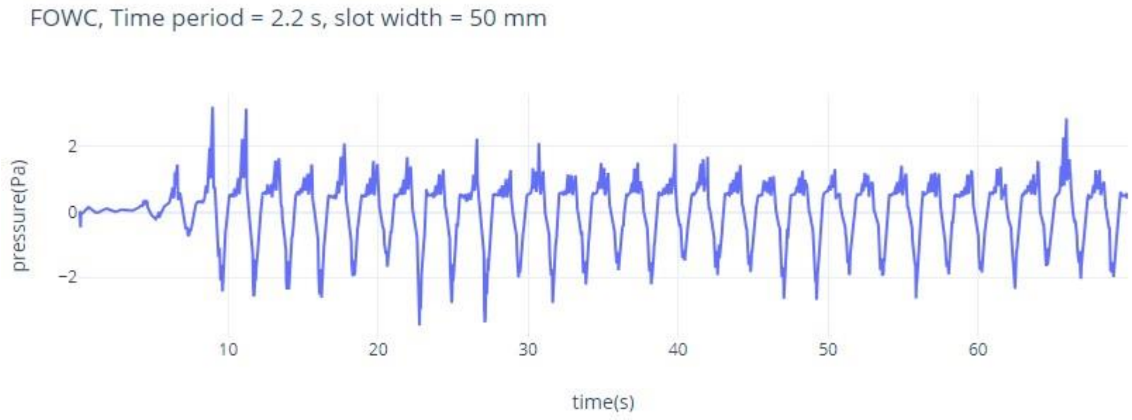

free surface velocity(m/s)
0.1
0
−0.1
−0.2
14
16
18
20
22
24
26
28
30
time(s)
IHFOAM
interFoam

Fig 5:- a)pressure at PG1 at time period of 2.2 s b) pressure at PG2 at time period of 2.2 s c) pressure at PG1 at time period of 3.2 s d) pressure at PG2 at time period of 3.2 s e) free surface velocity at time period of 3.2 s.

5.2 Power takeoff comparison between FWOC and BBDB OWC

a)



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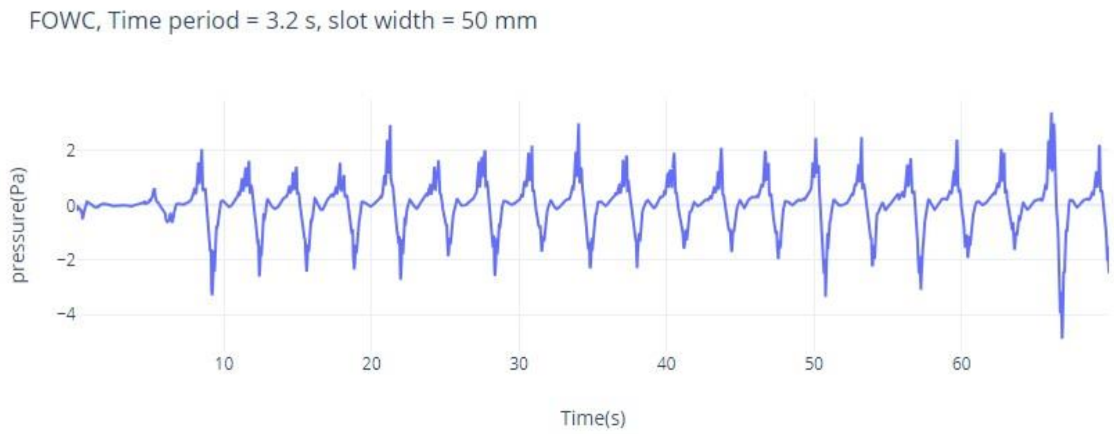
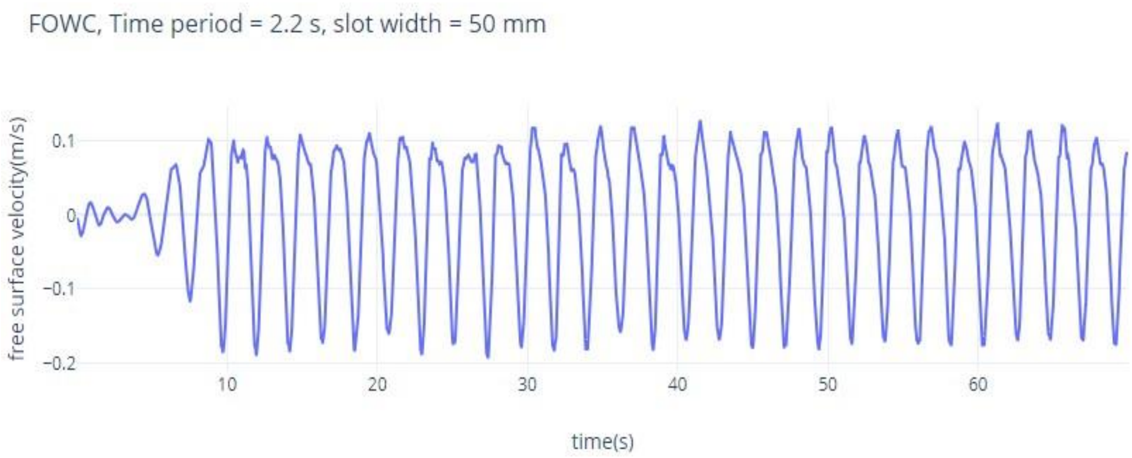


c)



d)

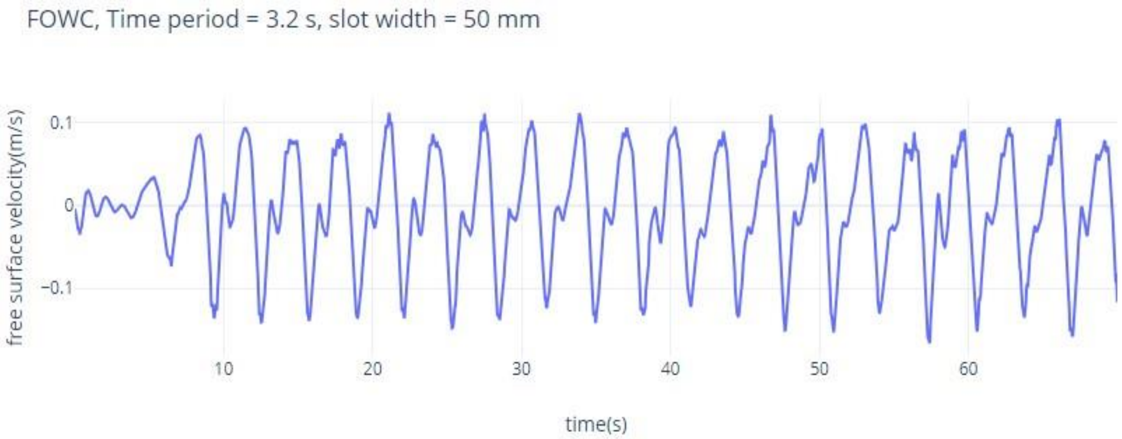
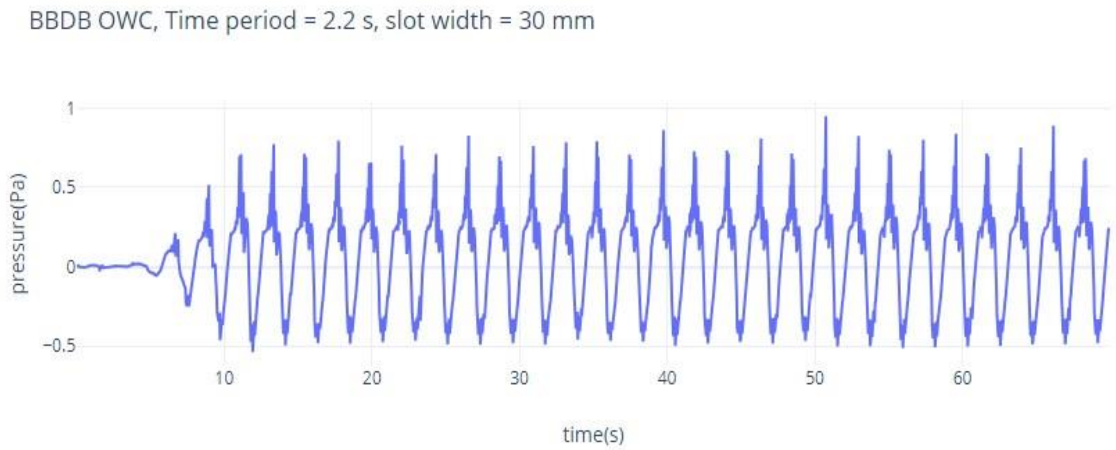
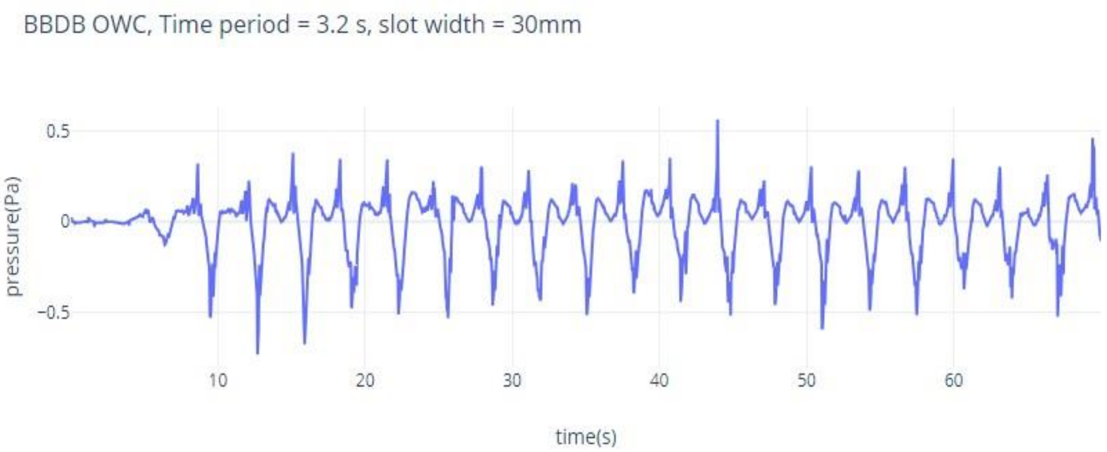


Fig 6:- a),b),c),d) are pressure and free surface velocity plots of FOWC at 2.2 s and 3.2 s respectively.

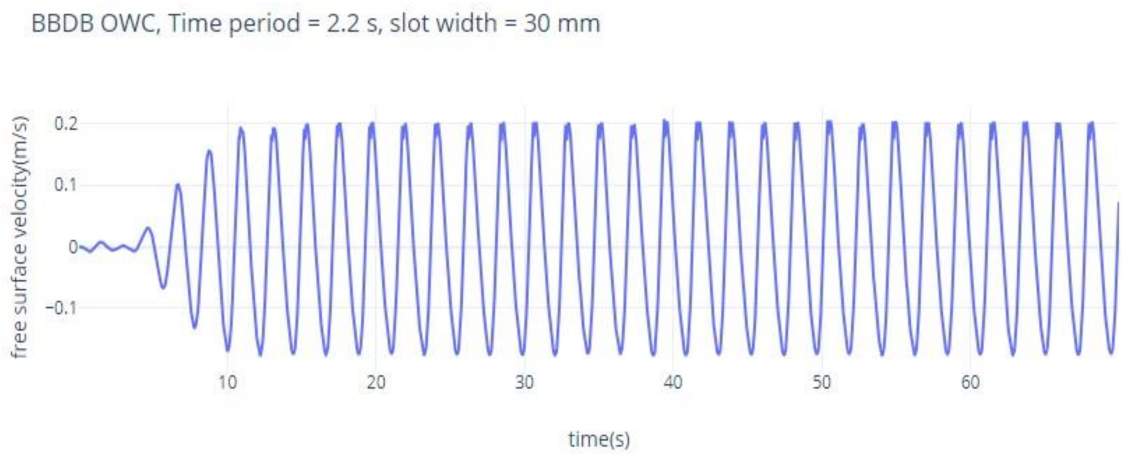
a)



b)



c)



d)

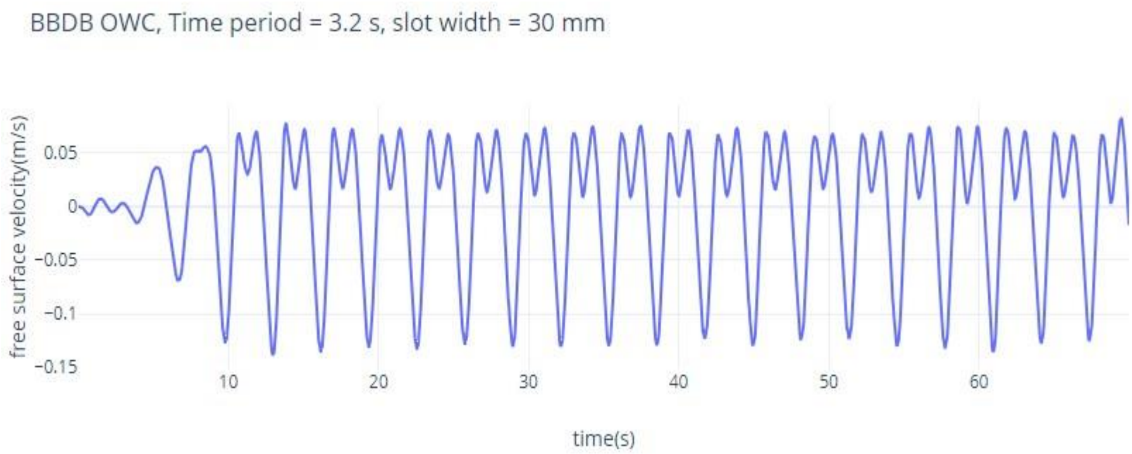


Fig 7 :- a),b),c),d) are free surface velocity and pressure plots of BBDB OWC at 2.2 s and 3.2 s respectively.

The efficiency of the WECs with PTO is highly related to the rate of energy flux converted by the device. The inlet energy (Pin), Eq. (5) is water particles' energy extracted by the Fixed-OWC (Pout), Eq. (8). The portion of energy extraction versus primary input energy is called efficiency (η); all these values are calculated by implementing the following equations form paper[3] as:

$$P_{in} = \frac{\rho_w g h^2 \lambda}{16T}\left[1 + \frac{4\pi d/\lambda}{sinh(4\pi d/\lambda)}\right] \tag{5}$$

where h and λ are the wave height and length and d is the water depth,

$$P_{out} = \frac{1}{T}\int_0^T |P(t)| \left|\left(\frac{d\eta}{dt}\right)\right| A_{owc} dt \tag{6}$$

where P(t), $\left(\frac{d\eta}{dt}\right)$, A_{owc} are instantaneous pressure inside the chamber, inst. free surface velocity inside the chamber and area of the chamber respectively,

$$P_{out} \approx \frac{A_{OWC}(|P(t)_1||V_{fsv1}|\delta t_1 + |P(t)_2||V_{fsv2}|\delta t_2 + |P(t)_3||V_{fsv3}|\delta t_3 + \ldots\ldots\ldots\ldots)}{T} \tag{7}$$

where $P(t)_1$, V_{fsv1}, $P(t)_2$, V_{fsv2}, $P(t)_3$, V_{fsv3} are average pressure inside the chamber and average free surface velocity inside the chamber for the time δt_1, δt_2, δt_3 respectively,

$$P_{out} \approx \frac{\delta t(A_{OWC})(|P(t)_1||V_{fsv1}| + |P(t)_2||V_{fsv2}| + |P(t)_3||V_{fsv3}| + \ldots\ldots\ldots\ldots)}{T} \tag{8}$$

Since we have recorded our data in equal timesteps that is 0.033 s so δt is same for all. Hence we can take it out as δt,

$$\eta = \frac{P_{out}}{P_{in}} \tag{9}$$

where η is the efficiency of the OWC.

5.2.1 Calculation of efficiency for FOWC :-

For 2.2 sec time period,

We have ,

$\rho_w = 997\ kg/m^3, h = 0.08\ m, \lambda = 4.90\ m, T = 2.2\ s, d = 0.6\ m$

So, $P_{in} = 14.7477\ watts$

Now $P_{out} = 0.016823\ watts$

Hence, $\eta = \frac{P_{out}}{P_{in}} = 1.141 \times 10^{-3}$

For 3.2 sec time period,

We have ,

$\rho_w = 997\ kg/m^3, h = 0.08\ m, \lambda = 7.48\ m, T = 3.2\ s, d = 0.6\ m$

So, $P_{in} = 16.90681\ watts$

Now $P_{out} = 0.010582\ watts$

Hence, $\eta = \frac{P_{out}}{P_{in}} = 6.26 \times 10^{-4}$

5.2.2 Calculation of efficiency for BBDB OWC :-

For 2.2 sec time period,

We have ,

$\rho_w = 997\ kg/m^3, h = 0.08\ m, \lambda = 5.225\ m, T = 2.2\ s, d = 0.62\ m$

So, $P_{in} = 15.86253\ watts$

Now $P_{out} = 0.001824\ watts$

Hence, $\eta = \frac{P_{out}}{P_{in}} = 1.15 \times 10^{-4}$

For 3.2 sec time period,

We have ,

$\rho_w = 997\ kg/m^3, h = 0.08\ m, \lambda = 7.615\ m, T = 3.2\ s, d = 0.62\ m$

So, $P_{in} = 17.17409\ watts$

Now $P_{out} = 0.000424\ watts$

Hence, $\eta = \frac{P_{out}}{P_{in}} = 2.467 \times 10^{-5}$

6. Conclusion

In conclusion, it is evident that the Forward Oscillating Water Column (FWOC) exhibits superior geometric efficiency when compared to the Backward Bent Duct Buoy (BBDB) Oscillating Water Column in harnessing ocean wave energy. This outcome aligns seamlessly with the observed phenomenon that the geometric design of FWOC minimizes obstructions to the vertical movement of the water column, resulting in reduced energy dissipation during the rise and fall of water, unlike the BBDB OWC. Further investigations involve assessing the efficiency of the floating BBDB OWC design to comprehensively understand its potential in ocean wave energy conversion.

7. Acknowledgements

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8. References

[1] OpenFOAM User Guide :- https://www.openfoam.com/documentation/guides/latest/doc/

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[3] Mobin Masoomi, Hamid Sarlak, Kourosh Rezanejad, “Hydrodynamic performance analysis of a new hybrid wave energy converter system using OpenFOAM”, Energy, vol 269, 2023.

[4] Sung-Jae Kim, WeoncheolKoo, Moo-HyunKim, “Nonlinear time-domain NWT simulations for two types of a backward bent duct buoy (BBDB) compared with 2D wave-tank experiments”, Ocean Engineering, vol 108, pp 584-593, 2015