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A review of numerical methods for studying hydrodynamic performance of oscillating water column (OWC) devices

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ABSTRACT

This paper provides a review of the numerical methods for studying hydrodynamic performance of Oscillating Water Column (OWC) wave energy converters (WECs), covering analytical methods, the frequency and time domain numerical models based on the potential flow theory, the Computational Fluid Dynamics (CFD) models based on the Reynolds-Averaged Navier-Stokes (RANS) equations and a meshless method, i.e., Smoothed particle hydrodynamics (SPH). This critical review aims to make systematic comparison between different numerical methods, identify the suitability of different method for different stages of OWC design, and provide recommendations for future numerical studies. While improving OWC through geometric modification of OWCs has been studied extensively, future studies should be more focused on the enhancement of wave condition, the effects of air compressibility in prototype and the effect of turbine properties on OWC.

1. Introduction

The energy consumption and environmental degradation nexus has been important since 1991 but was only paid attention to in the 2000s [1]. To promote the concept of sustainable development, many renewable energy technologies have been developed and utilised [2]. Many studies have been conducted to prove significant available amount of wave energies along shorelines that can be utilised. Wave energy converters (WECs) should be placed in the coastal areas where the wave energy are concentrated to under the action of refraction or shoaling [3]. A variety of wave energy flux forecasting method have been developed, including the probabilistic method based on a log-Normal assumption for the shape of predictive densities [4], the regression-based method [5] and the method using convolutional neural networks [6]. The environmental impact should also be considered when utilising Renewable Energy Sources (RESs) including wave energy [7]. The development of WECs has not been made to large commercial stages as much as wind and solar energy, mainly because converting the successes of theoretical, experimental and numerical studies of WEC prototypes to actual field deployment have been very difficult [8]. The use of both the simulations and laboratory tests will lead to higher efficiency in the nascent wave energy industry [8].

Oscillating Water Column (OWC) is one of the most studied, most efficient and reliable wave energy wave energy harvesting devices [9, 10]. Many prototype OWCs have been constructed [11]. OWC devices are partially submerged hollow structures with an opening to the sea below the free surface of water, as illustrated in Fig. 1. The vertical oscillation of the water column inside the chamber drives the air through the turbine that generates the energy. In addition to the rectangular OWCs shown in Fig. 1, many other geometries of OWCs are also proposed and investigated. The hydrodynamic performance of OWC has been extensively investigated both experimentally and numerically, aiming to improve the hydrodynamic efficiency of the OWC. In this paper, only hydrodynamic performance of OWC is discussed and the efficiency of the OWC refers to the hydrodynamic efficiency.

The research of OWC has been summarized in some recent review papers. Different review papers are focused on particular designs or parts of OWC including multi-chamber OWC [12], Turbine analysis [13, 14], OWC control [15], Computational Fluid Dynamics (CFD) models based on Navier-Stokes equations [16], OWC geometric factors [17], integration of OWC with breakwaters [18] and real fluid effects and challenges [19].

The hydrodynamic efficiency can be measured by the capture width ratio (CWR), which is the ratio of the power absorbed by a WEC to the wave power that passes through the device [20]. It is defined as

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$$\varepsilon = \frac{P_T}{P_w B} \tag{1}$$

where P_T is the power absorbed by the WEC, P_w the wave power per unit width in the wave crest direction, and B is the characteristic dimension of the WEC, usually the width of the device. CWR is also referred as hydrodynamic efficiency in many studies of OWC. The wave power calculated based on the second order Stokes wave theory is:

$$P_w = \frac{\rho g H_0^2}{16}\frac{\sigma}{k}\left(1 + \frac{2kh}{\sinh(2kh)}\right) \tag{2}$$

where ρ and g are the water density and gravitational acceleration, respectively. σ and k are the angular frequency and wave number of the waves, respectively. h is the water depth and H_0 is the wave height. The power absorbed by an air turbine is determined by:

$$P_T = Q_T \Delta p \tag{3}$$

where Δp is the difference between the air pressures at the inlet and outlet of the turbine, and Q_T is the air volume flow rate through the turbine. The principal aims of hydrodynamic studies of OWCs are to accurately calculate Δp and Q_T.

Many improved OWC devices have been proposed, studied, or constructed to improve the performance of OWC, mostly through geometric modification. Table 1 lists some typical devices that have been proved to be able to improve the hydrodynamic performance of OWC. The two-dimensional (2-D) OWCs and three-dimensional (3-D) OWCs listed in Table 1 are sketched in Figs. 2–4. The hydrodynamic performances of all the methods listed in the table have been studied using numerical methods. When these methods are implemented in prototype, the cost and safety must be considered in addition to the hydrodynamic performance.

With the rapid development of computer science, numerical methods have been increasingly applied to evaluate the hydrodynamic performance of OWCs. Early numerical methods were mainly based on the potential flow theory where the viscous effects and the turbulence of the flow are neglected. Although the potential flow theory overestimates the hydraulic power generated by OWCs because the energy dissipation due to fluid viscosity is not considered. However, it can be useful for optimizing the OWC design. Some very efficient theoretical methods based on the potential flow theory for predicting the hydrodynamic efficiency of OWC with simple geometries have been developed. Because theoretical methods can be used for optimizing design quickly, they can be used as the effective tools for the first-step design before the refined analyses are conducted.

Table 1
Methods of improve the performance of OWC.

Method	Key findings
Multiple-chamber 2-D offshore OWC	Dual-chamber-dual-turbine OWC improves hydrodynamic efficiency more than a OWC with dual chamber sharing single turbine. Three chamber OWC further improve efficiency than dual chamber one [143]. Rezanejad et al. [144] experimentally revealed that the multiple chamber OWC has improved hydrodynamic performance in a broad range of wave periods covering the most probable sea states in Portuguese oceanic area.
U-OWC	The longer eigenpriod of U-OWC than conventional OWC makes it works better with swells and large wind waves and its larger amplitude of the pressure fluctuations makes it performs better with small wind waves [145].
Hybrid OWC and a floating oscillating buoy (OB)	The combined wave energy harvested by the OWC and OB is greater than that harvested by either OWC or OB alone [146,147].
Multiple-Chamber cylindrical OWC	The effective frequency bandwidth of the dual-chamber OWC-WEC is broader than that of the single-chamber OWC-WEC [57].
Front wall geometry modification	A L-Shaped front wall could improve performance for long waves by reducing the natural frequency of the device [148]. An elliptical front wall can increase the efficiency by 25 % [149].
OWC bottom geometry modification	A convex arc bottom geometry of OWC performs better than other bottom geometries [150]. Hayati et al. [151] improved the performance of OWC using a bottom step.
Oscillating front wall	The performance can be improved by pitching and surging front wall [42,44,45].
Bottom plate on a floating OWC	The optimal length of the bottom plate length was found to be within the range of 2–2.5 times the chamber length [142,152].
Projecting seawalls	Power can be extracted not only from the incident wave but also from the wave which is reflected from the wall [153].
Wave energy converging	[87] used parabolic side walls to converge wave energy towards the OWC.
Integration of OWC into breakwater	Integration of OWC into breakwaters is cost-effective design in addition to enhance energy harvesting comparing with offshore OWC [18, 154–156].
Coupling of a OWC and a floating cylinder	The hybrid device has higher efficiency than an OWC only or a floating cylinder only [157].

Most recent numerical studies are based on computational fluid dynamics (CFD), where the real fluid is considered. In CFD studies, numerical wave takes (NWTs) with OWCs are established to investigate the

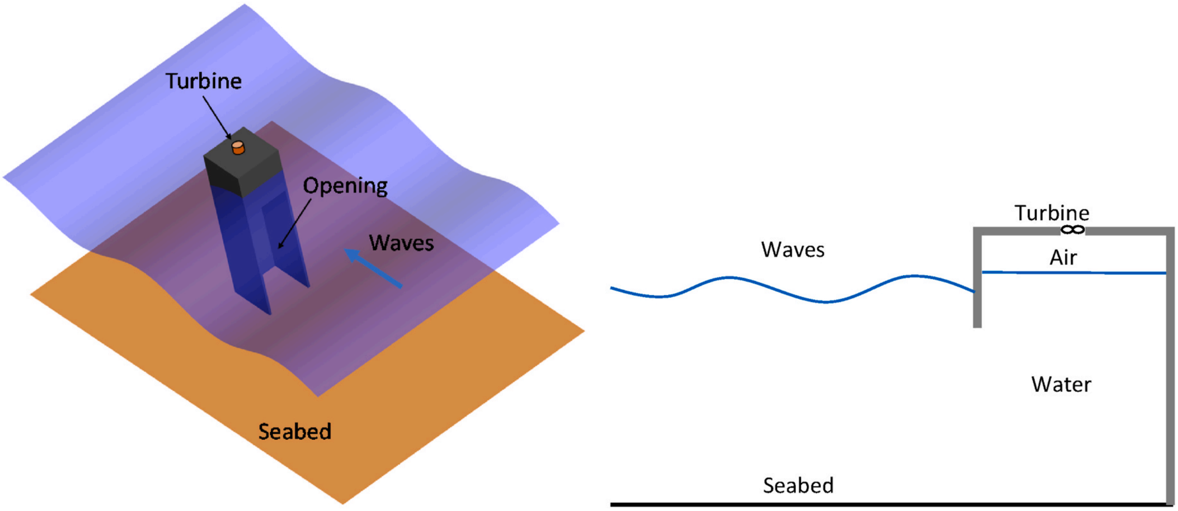


Fig. 1. Sketches of OWC devices. Left: three-dimensional offshore turbine; Right: two-dimensional land-fixed turbine.

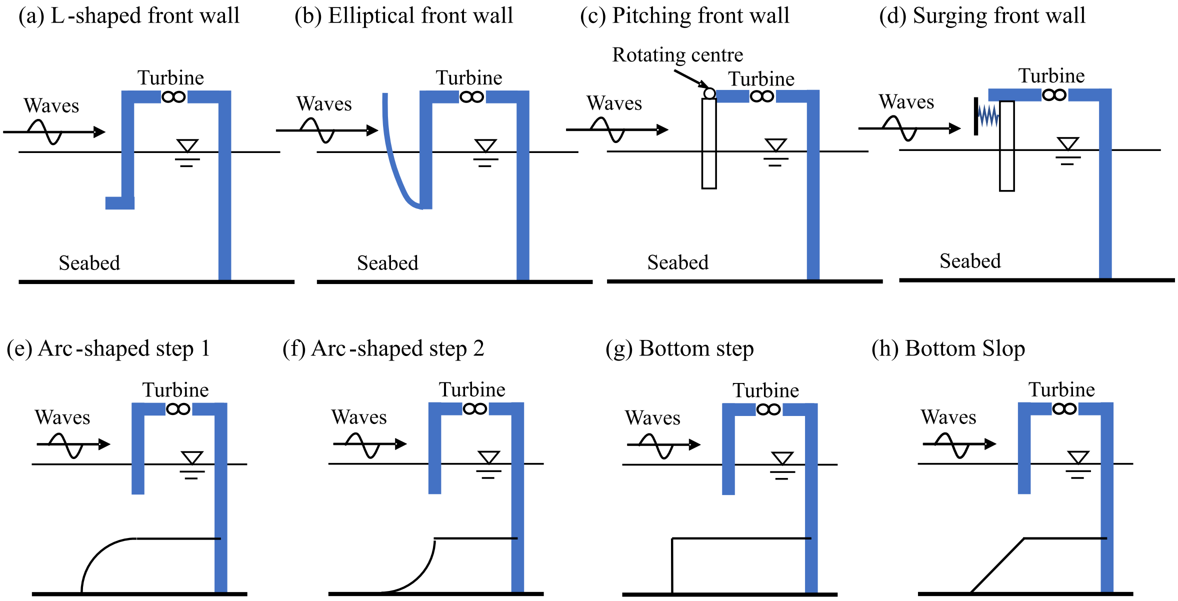


Fig. 2. Sketches of proposed front walls and bottoms steps for improving 2-D OWC performance.

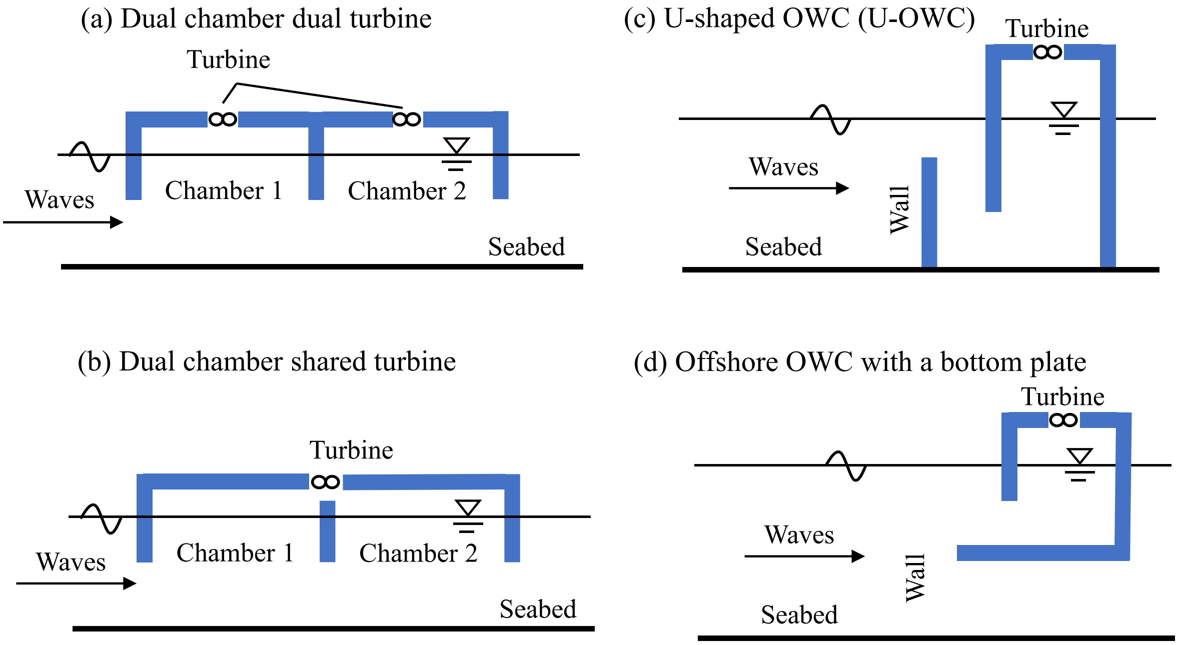


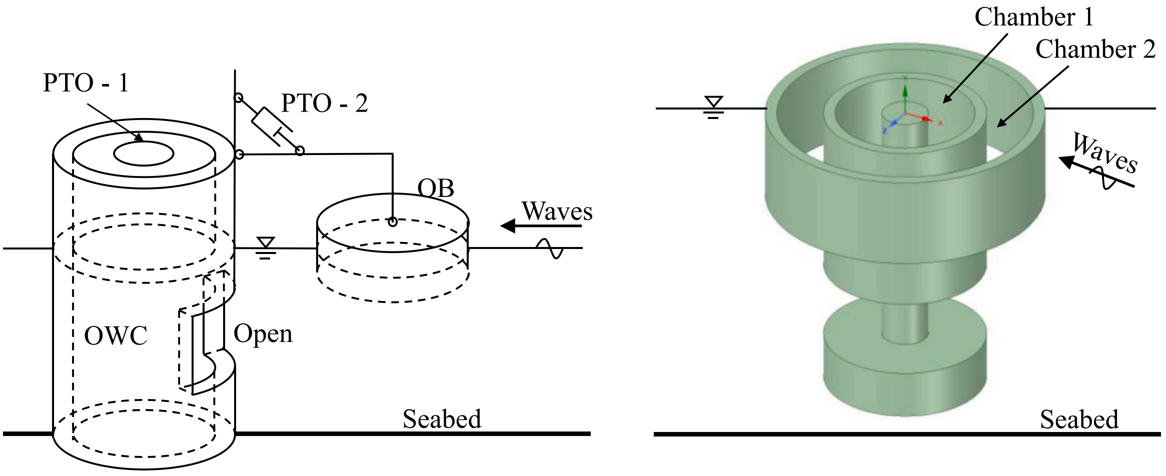
Fig. 3. Sketches of dual-chamber OWCs, U-Shaped OWC and OWC with a bottom plate.

interaction between waves and OWCs and calculate the hydrodynamic efficiency. Windt et al. [21] conducted review of CFD based Numerical Wave Tanks (NWTs) for studying different types of wave energy converters (WECs), including Point Absorber (PA); Terminator; Attenuator; oscillating wave surge converter (OWSC), OWC and Pressure Differential (PD).

The aim of this paper is to comprehensively review the numerical methods that have been used for studying the hydrodynamic performance of OWC, including theoretical methods based on the potential flow and linear wave theory, numerical models based on Boundary Element Method (BEM) and CFD based methods. The purpose of this paper is to compare the efficiencies and effectiveness of difference methods rather than presenting detailed discussion on the research outcomes derived from these methods. The rest of the paper is arranged as follows. Section 2 introduces the typical turbines that are used for OWCs and how they are modelled in experimental and numerical studies; Section 3 reviewed the research based on the potential flow theory. There are three types of numerical method in potential flow theory: theoretical method, BEM in frequency domain and BEM in time domain, and they are discussed in section 3.1 to 3.3, respectively. Section 4 presented a review on single- and two-phase CFD models and Smoothed particle hydrodynamics (SPH) method. Finally, the conclusions are made, and the proposed future studies are given in Section 5.

2. Wells and impulse turbine

Wells and impulse turbines are the two main types of self-rectifying air turbines for OWC, and they have been studied extensively [22]. The Wells turbine, while reaching only a moderately high peak efficiency as compared with conventional turbines, can operate in reciprocating flow



(a) Hybrid OWC and a floating oscillatory buoy (Cui et al., 2021)

(b) Dual chamber cylindrical OWC (Ning et al., 2018)

Fig. 4. Sketches of improved 3-D OWCs.

without the need of a rectifying valve system. The performance of Wells turbine can be found in the review paper [23]. The Wells turbine is known to exhibit an approximately linear relationship between the turbine pressure drop $\Delta p(t)$ and the flow rate $Q_T(t)$ [24]. Falcão [10] summarized that the Wells turbine is the most frequently proposed and used air turbine for OWC due to its (i) high blade to air-flow velocity ratio, (ii) a good peak efficiency and (iii) relatively cheap to construct. The weak points of the Wells turbine are: (i) low or even negative torque at (relatively) small flow rates; (ii) drop (possibly sharp drop) in power output due to aerodynamic losses at flow rates exceeding the stall-free critical value; (iii) aerodynamic noise; (iv) relatively large diameter for its power. Impulse turbines can keep their average efficiency level practically unchanged within a wide range of sea states, much more than Wells turbines. However, that efficiency level is relatively modest unless movable guide vanes (pitching or axially sliding) are employed, a more expensive and mechanically more complex solution [22].

The relationships between the pressure and flow rate of Wells turbines and impulse turbines are approximately linear and quadratic, respectively [24,25]. In experiments, porous media were commonly used to simulate a turbine with a linear relationship between the air pressure and flow rate for the Wells turbine, and orifices were used to simulate the quadratic relationship between pressure and flow rate for impulse turbines [26]. The numerical results and experimental data of flow past a slot showed pressure and flow rate follows a quadratic relationship [27]. However, Carlo et al. [28] reported a linear relationship between the pressure for an orifice and air velocity in their study through experiments and numerical simulations, mainly because the relationship is dependent on the size of the orifices. Simonetti et al. [29] showed a good quadratic relationship between the pressure and the flow rate through an orifice of a OWC model.

Due to the difficulty in scaling down Wells turbines, flow through porous medium or flow through a very narrow slot on the ceiling of the OWC chamber were used in many experimental and numerical studies. Similarly, the flow through impulse turbines was simulated by flow through an orifice in majority studies of OWC.

Fig. 5 shows an example of the measured efficiencies of single-, dual- and triple-chamber OWCs measured in the experiments by Zhao et al. [30]. The OWCs are same as the one in Fig. 3 (a) but different number of chambers. Chambers 1, 2 and 3 are the chamber that facing the waves, the middle chamber, and the rear chamber, respectively. In the

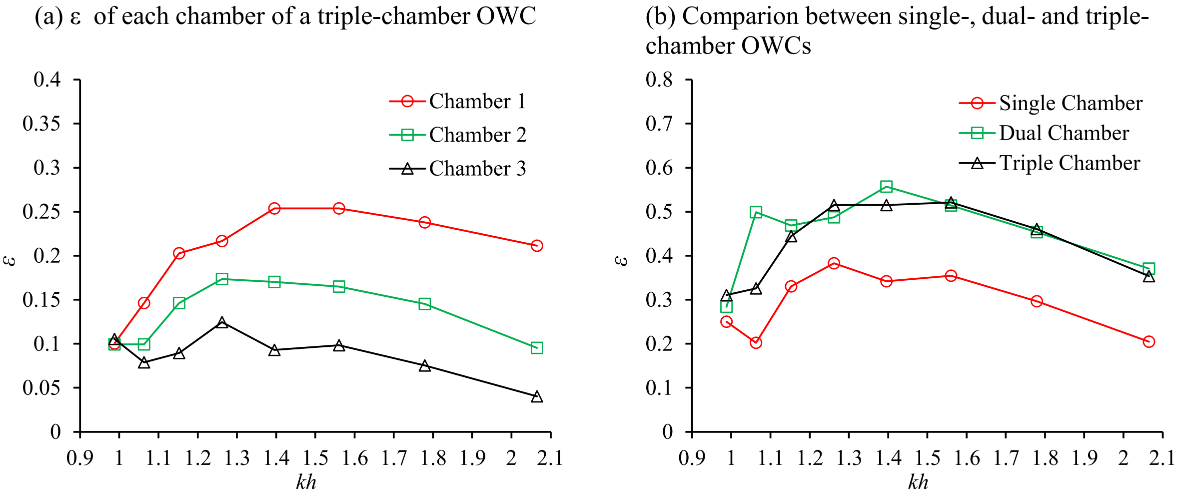


Fig. 5. Comparison between the hydrodynamic efficiencies of single-, dual- and triple-chamber 2-D OWCs [30]. The parameters of each OWC are: Water depth = 0.6 m, Wave height = 0.05 m, Draft of vertical walls = 0.2 m, Chamber height = 0.99 m including draft, Vertical wall thickness = 1 cm, Opening ratio of orifice = 1.5 %. Total OWC length = 0.62 m (single-chamber), 0.63 m (dual-chamber) and 0.64 m (triple-chamber).

experiments, orifices were used to represent impulse turbines. Zhao et al. [30] conducted an extensive study with wide range of parameters, but the data of one case with orifice opening ratio of 1.5 % are shown in Fig. 5. The orifice opening ratio is defined as the ratio of the opening area of the orifice to the total ceiling area of the OWC chambers. The variations of the hydrodynamic efficiency ε with kh in Fig. 5 follow the similar trend with those find in other studies for other types of OWCs. ε increases with the increase of kh and peaks at certain kh value, then it decreases with the increase of kh. It can be seen in Fig. 5 (b) that multiple-chamber OWC improves the hydrodynamic efficiency but increase chamber number from 2 to 3 does not make further improvement. Many numerical studies have been conducted to investigate the improvement of OWC performance through various strategies. In the following sections, the numerical models that were used will be reviewed.

3. Potential flow theory

Potential flow theory assumes the water flow to be inviscid, irrotational and incompressible. It can predict wave diffraction around structures by neglecting viscous effects, which are important when the ratio between the wave height and the dimension of a structure is large [31]. Based on the potential flow theory and linearizing the problems, efficiently analytical solutions can be developed. Given the periodic nature of the waves, many numerical methods based on the potential flow theory were developed in the frequency domain. Time-domain fully nonlinear wave models based on potential flow theory have also been developed for studying OWCs. The inability of the potential flow theory to model viscous effects were overcome by adding some artificial damping terms in the free surface boundary conditions in some studies. Because the numerical models based on the potential flow theory are more efficient in terms of calculating speed than the viscous flow models, they are still widely used in the past decades. In this section the review of the potential flow theory is divided into three sub-sections, i.e., analytical models, frequency-domain models and fully nonlinear time-domain models in sections 3.1 to 3.3, respectively.

3.1. *Analytical models*

Analytical models developed for evaluating the hydrodynamic efficiency of OWC can be used to conduct extensive parametric studies with affordable computing time. They are mostly developed by assuming the flow to be potential flow, the waves to be linear and relationship between the pressure drop and flow rate through turbines to be linear. Analytical formulae were generally derived by asymptotic expansions or eigenfunction expansion of the equation that satisfy the boundary conditions.

Evans [32] derived approximate solutions of wave-energy absorption of a float OWC connected to a spring-dashpot system using matched asymptotic expansions and assuming no spatial variation of free surface within the air chamber. Sarmento and De Falcao [33] developed an analytical method for predicting the efficiency of a 2-D OWC, where the linearized compressibility effect is considered. Because the energy dissipation due to the viscosity of the water and turbulence is neglected, the best efficiency predicted by this theory can be 100 % for incompressible air. Evans and Porter [34] developed an efficient and accurate method for predicting the efficiency of a 2-D OWC using potential wave theory. Malmo and Reitan [35] developed analytical formulae based on the matching of eigenfunction expansion for calculating the behaviour of OWC in a channel and in front of a reflecting wall. Martins-rivas and Mei [36], Martins-Rivas and Mei [37] and Lovas et al. [38] developed a theoretical methods for calculating the efficiency of the circular OWC installed on a straight coastline, on the tip of a breakwater and on the corner of a cornered coastline, respectively.

Analytical methods can quickly identify optimised design by comprehensive study with wide parametric space, although they cannot predict the hydrodynamic efficiency accurately due to their inability to consider energy dissipation due to friction, viscosity, and turbulence etc. In 2010s and 2020s, increasing number of analytical models have been developed for hydrodynamic design of complex OWCs.

Analytical models have been implemented to investigate the improvement of 2-D OWC hydrodynamic performance through modifying front wall [39] and using multiple chambers [40,41]. They have also been developed to optimize OWCs by moving OWC walls in various ways, including pitching front wall [42,43] and surging front and back walls [44,45]. The motion of the whole OWC under the action of waves can also be considered in analytical models. Wang et al. [46] analytically investigated a 2-D OWC with heave motion in front of a vertical breakwater and examined the effect of gap resonance. Zheng and Zhang [47] developed analytical solution of 2-D hybrid OWC consisting of a fixed inverted flume with long length and a bottom hole, and a long floating cube hinged with the flume. Zhao et al. [48] developed an efficient semi-analytical model for solving the problem of water wave interaction with OWC array with perforated wall and used this model to investigate the wave absorption.

Malara and Arena [49] developed an analytical model for analysing 2-D U-shaped OWC under random waves. It was found that the inner and outer chambers mainly contribute to the efficiency of wave energy conversion for different frequency domains. He et al. [50] derived an analytical solution of a 2-D rectangular offshore OWC to study the effects of the front and back wall drafts on the hydrodynamic efficiency. It was found an increase in the back wall draft increases the hydrodynamic efficiency. Konispoliatis and Mavrakos [51] derived an analytical solution of an array of oscillating water column (OWC) devices that is floating independently in finite depth under the action of regular water waves. They studied the effects of the effects of the spacing between the devices on the radiated waves from each OWC device. Scandura et al. [52] developed an analytical solution based on the linear irrotational wave theory that can consider nonlinearities due to not small oscillations of the free surface in the air chamber and to the air transformation, as well as those related to the characteristics of the air turbine.

Analytical solutions 3-D OWCs based eigen-function expansion fewer than 2-D solutions and mostly for circular shaped OWCs. The analytical models for cylindrical OWCs include those for one circular OWC [53,54], wave farms with multiple circular OWCs [55], cylindrical OWC with a solid centre part [56] and dual chamber cylindrical OWC [57,58]. Zheng et al. [59] developed an analytical model based on the eigen-function matching method for analysing OWC with a circular chamber and linear relationship between pressure and flow rate of Wells turbine.

3.2. *Potential flow theory in the frequency domain*

Analytical methods can only be available for OWCs with simple geometries. When complex OWCs are analysed, it is necessary to perform numerical analysis. The numerical methods in frequency-domain are more efficient than time-domain methods because they only calculate the solution under steady state conditions. Frequency-domain analysis can be the first step to validate the design under various operational sea conditions [60]. However, it is only accurate for the cases with small amplitude waves under linear potential flow assumption. The linear relationship between the air turbine pressure drop Δp and flow rate through turbine Q_T of Wells turbines enable the problem to be linearized. For simple geometry, the solution of potential flow theory in frequency-domain is very close to the analytical solution [61].

Most of the frequency domain studies are conducted using Boundary Element Method (BEM), because it reduces the cost of calculating by converting the integration over the fluid volume to the integration over the boundary. To linearize the problem, the pressure and flow rate of the turbine followed linear relationship in the frequency domain models. Liu et al. [62] suggested that higher-order boundary element method (HOBEM) is preferable compared with constant panel method because it can achieve accurate solutions with smaller number of elements and less computer time.

Delauré and Lewis [63] developed a steady-state potential flow BEM model for simulating 3-D OWC, where the integration equation is solved by a first-order mixed distribution panel method. Rezanejad et al. [64] and Rezanejad et al. [61] demonstrated that the BEM solution are the same with the analytical solution. Cong et al. [65] developed a frequency domain 3-D BEM model for evaluating the hydrodynamic performance of floating OWC that moves in waves. They found that floating OWCs could expand the frequency range of efficient conversion and improving the device's adaptability to variable oceanic environments. Mohapatra et al. [66] used the frequency domain BEM to investigate the effect of bottom geometry of OWC on the hydrodynamic performance. Gomes et al. [67] used commercial BEM software WAMIT to study the impact of the diameter of the floater, the submerged length, and the air chamber height on the power extraction of an axis symmetric OWC with a Wells turbine. Trivedi and Koley [68] used a 2-D BEM model to investigate the hydrodynamic performance under irregular incident waves. Trivedi and Koley [69] used a 2-D BEM model to investigate the improvement of the hydrodynamic performance by using a U-shaped OWC. Belibassakis et al. [70] used BEM to investigate the varying water depth on the OWC performance. Brito-Melo et al. [71] investigated an OWC using a 3-D BEM model for varying water depth three-dimensionally. While majority of the studies in frequency domain have been conducted using BEM, Nader et al. [72] developed a finite element method (FEM) for studying the efficiency of an array of circular OWC devices and proved the accuracy of FEM.

Coupled methods have been developed by utilising the eigen expansion method's efficiency and the BEM method's capability of dealing with complex geometry. The implementation of the eigenfunction expansion increased the computing speed and ensured that the open boundary condition is fully satisfied. Count [73] used an eigenfunction expansion suitable for the inner region of OWC and 3D boundary integral method outside the OWC to predict the hydrodynamic performance. Josset and Clément [74] developed a 3-D hybrid model where the computational domain is divided into an outer zone and an inner zone. The incident, diffracted and radiated waves in the outer zone are solved once for all and the inner zone are solved by time-domain BEM method. Koley and Trivedi [75] developed a 2-D coupled model where BEM is used near a OWC and eigen-function expansion is used in the far field to analysis an OWC with undulated seabed. Medina Rodríguez et al. [76] and Medina Rodríguez et al. [77] implemented the coupling between the eigenfunction expansion method (EEM) and BEM method in the study of the effect of obliqueness of the wave direction on the hydrodynamic efficiency of a land fixed OWC. EEM-BEM coupled method was also used to analyse multiple chamber OWC under oblique waves [78].

3.3. Fully nonlinear wave model based on the potential flow theory in the time domain

The frequency domain potential flow theory is limited to linear, small amplitude waves. OWCs need to be placed in locations with strong waves that are fully nonlinear for extracting large amount of power. Many fully nonlinear BEM transient wave models in the time domain have been developed to simulate wave interaction with OWCs and calculate hydrodynamic efficiency. Fully nonlinear BEM models can use any relationship between the pressure and flow rate through the air turbine, including linear relationship that represents Wells turbines and quadratic relationship that represents Impulse turbines.

To enable the potential flow theory to consider the energy dissipation due to the viscosity and turbulence of the fluid, an artificial damping term can be implemented in the fully nonlinear wave models [79–81]. However, the damping coefficients that determines how much energy dissipated need to be carefully calibrated through experimental data before it is used. When the scale of the OWC changes, the damping coefficients need to be recalibrated.

Both 2-D and 3-D HOBEM fully nonlinear wave models have been developed [81–83] and used to investigate the improvement of the hydrodynamic efficiency of OWCs through various strategies including dual-chamber 2-D OWC [58] and 2-D OWC with U-shaped chamber [84]. Zhou et al. [85] evaluated hydrodynamic performance of a land fixed OWC under irregular waves using HOBEM. Cheng et al. [86] studied the characteristics of a hybrid oscillating water column-oscillating buoy wave energy converter integrated into a π-type floating breakwater using HOBEM. In the 3-D BEM study by Hasanabad [87], parabolic side walls were used to converge wave energy to the OWC. Trivedi and Koley [69] developed a dual boundary element method (DBEM) to simulate the interaction between waves on two layers of water with different densities, which can occur due to reasons such as mixing of fresh river water with the saline sea water, and solar heating of the upper layer water. Cheng et al. [86] investigated the improvement of the OWC efficiency by placing an oscillating buoy inside the OWC chamber through numerical simulations using HOBEM. It is found that the oscillating buoy can improve the OWC performance especially for long waves. Finite Element Method (FEM) is less used than BEM in fully nonlinear wave models based on the potential flow theory. Kim et al. [88] and Kim et al. [89] developed FEM models based on the potential theory for predicting the hydrodynamic efficiency of a 2-D inclined OWC.

4. CFD models

The CFD models can offer more in-depth analysis of the hydrodynamics in the chamber and its surroundings than the models based on potential theory with the sacrifice of computational cost, as well as the complex geometries, because complex physics in OWC device including turbulence and associated energy dissipation caused by viscous effects are considered [90]. Potential flow theory has shown that OWC can absorb all the incident wave power theoretically, provided optimum values of the complicated OWC geometries [91]. This is unrealistic because some energy was lost to dissipation due to the fluid viscosity, which can be captured using CFD models.

Navier-Stokes are the fundamental equations for simulating real flow of Newtonian fluid. To resolve whole range of spatial and temporal scales of the turbulence using Direction Numerical Simulations (DNS) is impractical even in the small-scale experimental condition. Large eddy simulations (LES) that use sub-grid-scale (SGS) model to simulate small scale eddies cost much lower computational cost than DNS but are still unaffordable for many engineering cases of OWC [21]. Majority of CFD studies on OWC have been conducted by solving the Reynolds-Averaged Naveir-Stokes (RANS) equations and turbulence equations, i.e., k-ε and k-ω equations. Researchers have conducted both experiments and CFD simulations of OWC and demonstrated the validation of CFD in the studies of OWC performance by comparing numerical results with experimental data [92–96]. Opoku et al. [16] provided a review of CFD models for modelling OWCs and focused on their review on the comparison between different CFD solvers (software). In this section, the CFD models are classified based on the methods of modelling the wave surface and turbine.

The k-ε and k-ω turbulence models are the most popularly used ones and they provide good prediction of fully turbulent flows. However, the standard k-ε and k-ω models failed to predict the flow correctly near walls, where there is a laminar layer and viscous effects are stronger than the Reynolds stress [97]. To overcome this problem, many low Reynolds number k-ε models [98–101] and k-ω [102–105] have been developed. Re-Normalisation Group (RNG) k-ε was developed to account for different length scales of turbulence [106,107]. The RNG model can be integrated directly to a solid boundary without the need for ad hoc wall damping functions [108]. The most popularly used k-ω model is the shear stress transport (SST) one developed by Menter [109]. The SST k-ω model uses a blending function to switch to k-ω in the near wall region for predicting the viscous sub-layer and to k-ε in the free-stream region.

When RANS equations are used to model ocean waves, it has been noticed that the turbulence models (k-ε and k-ω) overpredict the turbulence, as a result the waves decay fast while they are propagating [110,111]. Larsen and Fuhrman [112] developed an improved turbulence models that avoid limited the excessive production of turbulence using a Reynolds Stress limiter. This model has been successfully used in the simulation of OWC [113]. Zhan et al. [114] developed a Hybrid realizable k−ε/laminar method in the application of 3D heaving OWCs, where a laminar zone was used in front to the OWC to avoid wave decay. In this section, all the CFD models that are reviewed are the models based on RANS equations except otherwise specified.

4.1. Two phase CFD models

Many CFD models are two phase models where water flow below the wave surface and the air flow through the turbine are simulated simultaneously. To simplify the problem, the air flow through the air turbine is simplified as air flow through an orifice for impulse turbines or air flow through porous medium for Wells turbines in most of CFD studies. This type of CFD models are two-phase models since both water and air flows are simulated. The turbine characteristics (represented by orifice) in these models are dependent on the diameter and length of the orifice or porous medium. The OWC power is then calculated by the pressure drop and the flow rate through the orifice. The method of modelling impulse turbines using orifices is the same as that used in most of the experimental studies. The free surface of the water waves can be tracked using the method of Volume of Fluid (VOF). In 2-D simulations, a slot (small gap) on the ceiling of the OWC devices is equivalent to the orifice in the 3-D studies. Most of the studies in Table 2 used orifices to represent turbines and only two used porous media. Considering the analogy between the pressure-flow relationships of orifices and impulse turbines, the outcomes of the studies in Table 2 that used orifices can be implemented in OWCs with impulse turbines. A variety of k-ε/k-ω models have been used in the numerical models in the table. Majority of the studies use software used the fluid simulation software ANSYS Fluent or the open-source software OpenFORM. Some studies who used in-house codes, which allow the developers also the users have flexibility to make modifications. OpenFORM has been used to investigate large-scale case of an array of 3-D OWCs by Mayon et al. [115].

4.2. Single-phase CFD models

Huang and Huang [116] and Luo et al. [117] used an artificial sink term that follows the Darcy-Forchheimer law in two-phase CFD models to simulate the energy absorbed by the turbine and concluded that method can reach satisfactory solutions with only cost 1/25 simulation time compared with the orifice-flow method because the simulation of flow through orifice using refined mesh is avoided. Some CFD models are one phase models where only the water flow phase is simulated, while the air pressure inside the chamber is assumed to be constant that can be calculated according to the volume change rate of the air in the chamber using:

$$\Delta p = -K_{t1} Q_T \tag{4}$$

for Wells (linear) turbines or

$$\Delta p = -K_{t2} |Q_T| Q_T \tag{5}$$

for impulse (quadratic) turbines. The air pressure determined by the

Table 2
List of two-phase CFD studies where the turbine is modelled by either porous media or orifice.

Turbine model	References	Turbulence model	Software	OWC type	Aim of study
Porous media	Kharati-Koopaee and Fathi-Kelestani [158]	k-ω	ANSYS Fluent	2-D land fixed	Influence of wave steepness at various chamber lengths and bottom slopes.
Porous media	Kamath et al. [159]	Lor Re k–ω	REEF3D	2-D land fixed	The effects of wavelength and wave steepness
orifice	Kuo et al. [160]	RNG k-ε	Flow-3D	2-D land fixed	The relationship between the wavelength ratio and the power produced by air
Slot	Yamaç and Koca [150]	k-ε	ANSYS Fluent	2-D land fixed	The effects of different types of steps on the bottom
Slot	Elhanafi et al. [161]	SST k- ω		2-D land Fixed	Energy balance analysis
Slot	Chen et al. [162]	SST k- ω	OpenFOAM	2-D land fixed	influence of the front wall draught and the chamber width on the wave energy conversion efficiency of the onshore OWC device
Slot	Zhang et al. [163]	NS equations	In-house code	2-D land fixed	The effects of front wall draught and vortices
Slot	Vyzikas et al. [164]	Standard k-ε	OpenFOAM	2-D Land-fixed OWC	The validation of RANS CFD models and water sloshing effect
Orifice	Ranjan and Roy [165]	Standard k-ε	ANSYS Fluent	3-D fixed OWC with Parabolic bottom profile	The effects of Orifice Ratio and Relative Opening
Slot	Qu et al. [149,166]	RNG k-ε	In-house code	2-D Offshore OWC	The effect of the elliptical front wall
Slot	[167]	k-ω	InterFOAM	2-D Trapezoidal OSC	The effect of geometric parameters
Slot	Qu et al. [168]	RNG k-ε	In-house code	A row of 3-D rectangular OWC with a constant spacing between them	The effect of Chamber width
Slot	Masoomi et al. [169]	standard k-ε	OpenFOAM	2-D rectangular OWC	The effects of vertical plates in the chamber
Slot	Masoomi et al. [170]	standard k-ε	OpenFOAM	2-D Hybrid system	Improvement of efficiency by a combined OWC and a point absorber
Orifice	Simonetti et al. [171]	LES	OpenFOAM	3-D three-chamber OWC	The effects of air compressibility
Orifice	Xu and Huang [172]	k-ω	OpenFOAM	3-D circular floating OWC	The effect of water sloshing in OWC
Slot	Iturrioz et al. [90]	SST k-ω	OpenFOAM	3-D rectangular OWC	Validation of OpenFOAM using Experimental data
Orifice	Zaouf et al. [173]	standard k-ε	ANSYS	3-D circular OWC	optimal size of the power takeoff for various chamber upper surface
Slot	Bouali and Larbi [174] Bouali and Larbi [175]	standard k-ε	ANSYS	3-D rectangular OWC	The effects of front wall geometry, The effects of the Power Take-off (PTO) model, the geometry, and the wave conditions
Orifice	Elhanafi et al. [176,177]	SST k-ω	Star–CCM + CFD	3-D OWC	3D effects and correlation between wave height and lip submergence
Orifice	Mayon et al. [115]	k-ω	OpenFOAM	3-D OWC	Performance improvement by a parabolic-wall energy concentrator.
Porous media	[178]	standard k-ε	FLUENT	3-D OWC	The effect of integration of the OWC with breakwater.

above two equations is used as the boundary condition on the water surface when wave induced water flow is simulated. The compressibility of the air can be considered in the single-phase model by using aerodynamics models [74]. Single-phase models are much faster than the orifice-flow methods because the air flow phase through the turbine or orifice is not simulated. They can be used to simulate OWC whose relationship between the pressure and flow rate through the turbine is known, for example the linear relationship for Wells turbine [113,118,119], the quadratic relationship for a turbine, or combined linear and quadratic relationship [117], or any known relationship between Δp and Q_T. Table 3 lists some single-phase models for simulating OWC. Due the high efficiency of the single-phase models, most studies in Table 3 conducted comprehensive parametric study to find out the best performance. In addition, single phase models can be easily to be used to compare the performance of different types of turbines. Teixeira et al. [120] used a 2-D RANS model to simulate a 2-D land fixed OWC equipped with a Wells turbine and an impulse turbine. The best power of the Well's turbine is found to be slightly higher than the impulse turbine. Palmer et al. [121] investigated dual-chamber OWC and reported that dual-chamber, dual-turbine configuration overperforms the configuration of dual-chamber sharing a single turbine. Zhao et al. [122] found that for a circular OWC in a wave flume, the higher harmonics of the wave surface varies significantly in the OWC chamber and numerically identified the significantly reduction of CWR due to transverse sloshing.

The third type of CFD models are the fully integrated models where simulations of the wave motion and real turbine are fully coupled [123–125]. Without make any simplification on the turbine, this type of methods reflects the operating condition of real OWC devices but the cost of computing time increases significantly [125].

All the above reviewed CFD models have been rigorously validated against experimental study. Figs. 6 and 7 are some examples of the comparison between the CFD results with the experimental data. In Fig. 7, B and L are the chamber length and the wavelength, respectively. In the BEM method in Fig. 6, an artificial damping factor is added in the potential flow theory to account for the energy damping due to the viscosity of the flow. Without using this article damping factor, the efficiency of the OWC would be overestimated by BEM [126]. The single-phase CFD model predicted the hydraulic efficiency well for the land fixed and offshore OWC in Figs. 6 and 7, respectively. However, it appears that the two-phase model results are closer to the experimental data at larger B/L values in Fig. 7.

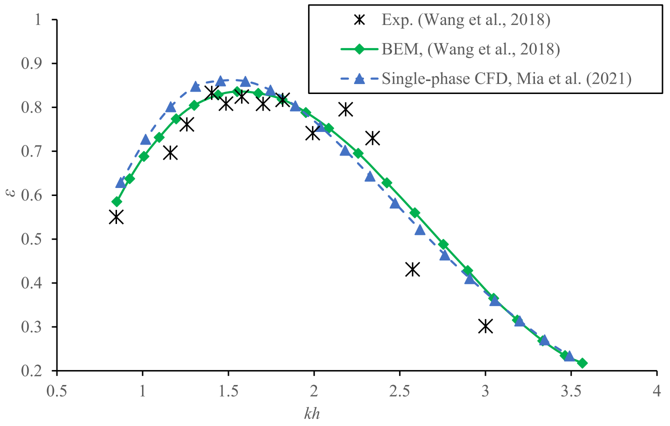


Fig. 6. Comparison of the BEM and the Single-phase CFD results of the hydrodynamic efficiency with the experimental data of a two-dimensional land fixed OWC shown in Fig. 1. The dimension of the OWC and the wave parameters can be found in Ref. [126].

4.3. Smoothed particle hydrodynamics (SPH)

Recently, Smoothed particle hydrodynamics (SPH) has been increasingly used in the reserch on OWC. It is a meshfree, Lagrangian, particle method, which is advantageous over conventional Eulerian methods in the aspect of interface treatment [127,128]. Although there are concerns about its convergence and accuracy, successful application of SPH in complex flows and multiphase flows with good accuracy has been reported in literature [127]. Some Arbitratry Lagrangian Eulerian (ALE) method was used in the studies of OWC [113] but they still cannot handel overly distorted mesh for large deformation of the computational domain. The Lagrangian nature of SPH is its advantages over traditional mesh-dependent Eulerian methods. Ramezanzadeh et al. [129] investigated the improvement of an OWC using dual chamber using SPH. Crespo et al. [130] used SPH to investigate 2-D and 3-D OWCs in prototype sizes. Quartier et al. [131] conducted detailed validation of SPH in the simulation of OWC using experimental data. Soleimani et al. [132] used a weakly compressible SPH (WCSPH) model to simulate a 3-D rectangular OWC and investigated the piston motion of waver in the chamber. Zhu et al. [133] invested the effects of wall thickness and damping coefficient on the performance of and Didier et al. [134] invetigated the fluid force on the front wall and the wave height amplication of OWC.

Table 3
Single-phase CFD models.

Turbine type	References	Turbulence model	Software	OWC type	Aim of study
Linear	Torres et al. [179], Torres et al. [180]	standard k-ε	ANSYS Fluent	2-D Rectangular land fixed OWC	The effects of turbine coefficient and size
Linear	Samak et al. [148]	k-ε	ANSYS Fluent	2-D rectangular land fixed OWC	Improvement using a L-shaped front wall
Linear	Gaspar et al. [181]	k-ε	ANSYS Fluent	2-D land fixed	OWC with inclined chamber walls
Linear	Mia et al. [113]	SST k-ω	In-house code	2-D rectangular land fixed OWC	Scaling effect
Linear	Mia et al. [143]	SST k-ω	In-house code	2-D Offshore OWC	Multiple chamber
Linear	Mia et al. [182]	SST k-ω	In-house code	2-D elastically supported floating OWC	The effect of motion
Linear	Teixeira et al. [118]	standard k-ε	ANSYS Fluent	3-D Land-fixed OWC	The influence of the chamber geometry and the turbine characteristic relation in the device performance
Linear	Wiener et al. [119]	standard k-ε	FLENT	2-D Land-fixed OWC	Optimal Sizes of Wells Turbine and Chamber
Linear	[121]	SST k-ω	In-house	2-D Land-fixed OWC	Improvement through dual chamber
Linear	Teixeira and Didier [183]	k-ε	ANSYS Fluent	3-D Land-fixed	Difference between irregular and random waves
Quadratic	Zhao et al. [122]	SST k-ω	In-house	3-D Offshore OWC	The effects of wave flume wideth on the OWC

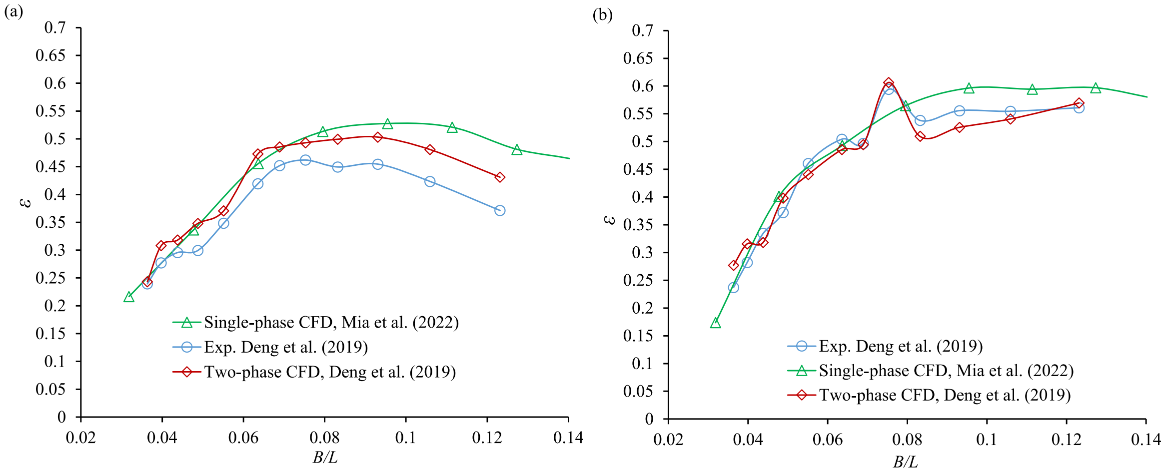


Fig. 7. Comparison of the single- and two-phase CFD results of the hydrodynamic efficiency with the experimental data of a two-dimensional offshore OWC with a bottom plate shown in Fig. 3 (d). The length of the bottom chamber is twice the OWC chamber length. See Ref. [142] for rest parameters. (a) Orifice opening ratio = 0.3 %; (b) Orifice opening ratio = 0.65 %.

Some SPH models are single-phased. Zhu et al. [133] developed a single-phase SPH model where the flow through air turbine is modelled by Pneumatic model. In some single-phase SPH models, the power take-off (PTO) systems were numerically modelled by addinga force on a plate floating on top of the free surface inside the OWC chamber [131, 135]

To overcome its weakness, SPH model was coupled with other models in the studies of OWC. He et al. [136] developed a SPH-FDM coupled method to simulate the performance of OWC. This method utilised the FDM's advantage of local mesh refinement and SPH's capability of dealing with multi-phase interface and moving boundary. The SPH-FDM solution was in a very good agreement with the experimental data. The SPH method and a potential-flow-theory based wave model were coupled together in the numerical investigation of OWC through U-shaped chamber by Zhu et al. [137]. This model overcame the inefficiency of SPH by potential flow theory.

5. Discussion and conclusions

A comprehensive review of existing numerical methods for studying the hydrodynamic performance of OWCs is conducted. The review covers the models based on the potential flow theory including analytical, frequency domain and time domain methods, CFD models including single-phase and two-phase models and SPH models that is meshless.

Although the numerical methods based on the potential flow theory cannot consider the effects from viscosity of the fluid and turbulence, they are still popularly used in 2010s and 2020s due to their high efficiency, especially the analytical models and frequency domain models. Potential flow theories can accurately find out resonance frequency or best design quickly, although they overestimate the hydrodynamic efficiency. In some fully nonlinear time domain potential flow theory, some artificial damping coefficients are added into the free-surface boundary conditions inside the OWC chamber to account for the energy dissipation due to viscosity of the fluid. However, these artificial damping coefficients calibrated using particular experimental cases cannot be directly used in other cases. As a result, it is recommended to use potential flow theory to do the preliminary study before refined CFD study and experimental study in a real engineering case.

The RANS equations are the governing equations for solving the water and air flows in nearly all the CFD models because their higher efficiency than DNS or LES. k-ε and k-ω models are predominantly used in the CFD studies of OWC. Many numerical validations have been conducted to prove that both single- and two-phase models have been proved to be able to simulate wave interaction with OWCs with satisfactory accuracy. Both models based on CFD and potential flow theory have been used to explore the potential of improvement of OWC through various strategies listed in Table 1. The SPH methods is a meshless Largrangian method that can consider compressibility of the flow. They are specifically suitable for highly nonlinear free-surface wave problems that is difficult to simulate using mesh-based method [138].

After reviewing previous numerical studies of OWC, authors identified the following aspects that need to be addressed in future hydrodynamic studies.

1. More hydrodynamic studies should be conducted to compare between the performances of Wells and impulse turbines. Majority studies based on two-phase models used orifices that represent impulse turbines, while majority studies based on single-phase models were focused on linear turbine that represent Wells turbine. The comparison between these two turbines was discussed in very few studies.
2. Most of the numerical studies have been performed in the experimental model scales, where the air compressibility is low. Disregarding air compressibility introduces errors in the resonant period and wrong efficiency of OWCs [113,139,140]. This makes it necessary to conduct numerical studies under prototype scales where the compressibility is high. In addition, the validation of the numerical methods in the protype scales are rare mainly because lack of experimental data of large scale OWCs.
3. In addition to the method of modifying OWC chamber geometry for the improvement of OWC efficiency, the harvested energy can also be increased by changing wave conditions. One example is focusing waves towards OWC chamber is another way to increase harvested wave energy [87,115,141]. The studies on this aspect are much less than those on geometric modification of OWC.

CRediT authorship contribution statement

Ming Zhao: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Dezhi Ning:** Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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