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Effect of wind conditions on the performance of an Oscillating Water Column energy converter

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ABSTRACT

Local atmospheric conditions surrounding an off-shore Oscillating Water Column device — OWC hereinafter —, in particular wind action, may affect OWC performance and efficiency, specially over long harvesting intervals, i.e. yearly energy production. This work proposes an experimental study of a simple off-shore OWC where different ambient conditions are compared. More specifically, it proposes a set of experimental tests in laboratory wave flume, under both calm and external wind conditions, which represent a more realistic situation in full-scale prototypes. The results show that the external wind modifies the ambient conditions by changing the temperature, humidity and pressure values of the air surrounding the OWC device, affecting the density and the thermodynamic balance. This affects negatively the OWC performance, reducing the maximum pneumatic power by up to 15%, which can be extrapolated to a reduction of 3% in the total amount of annual energy produced.

1. Introduction

Given the need to reduce energy dependency on fossil fuel sources, the oceans appear as a potential source of energy with continuous availability for primary energy conversion, World Energy Council [1], Falnes [2], Cruz [3]. The Oscillating Water Column (OWC) is one of the most developed technologies for wave energy converters (WEC). This is evidenced by the implementation of several OWC power plants worldwide, such as PICO (Portugal) — with installed capacity of 400 kW, Falão et al. [4] — or LIMPET (Scotland). Even some of them have been connected to the grid, like Mutriku (Spain), with an installed capacity of 296 kW, Torre-Enciso et al. [5], Gabriel Ibarra–Berastegi et al. [6]. The most remarkable feature of the OWC converter is its simplicity, where the turbine is the only moving part of the device, Gato et al. [7], Raghunathan [8]. On the other hand, those devices have some weaknesses, such as the low efficiency, The Carbon Trust [9], Aderinto and Li [10], or the fairly high Levelized Cost of Energy (LCOE), de Andres et al. [11], Magagna and Uihlein [12], which must be improved to make the OWC technology attractive for the investors and society.

The theoretical framework of the OWC device is based on the radiation–diffraction problem. This problem has been analytically solved, Evans [13], Sarmento and Falcão [14], and studied for different boundary conditions, Martins-Rivas and Mei [15], Martins-Rivas and Mei [16], Mendoza et al. [17], Fox et al. [18]. Others authors have tried to improve the efficiency of the OWC devices by developing different control strategies and management, Sarmento et al. [19], Falcão and Justino [20], Falcão et al. [21], as well as studied the interaction between the OWC devices with the environment and its mutual influence, Mendoza et al. [22], Medina-López et al. [23], Simonetti and Cappietti [24], the development of floating devices to eliminate the problem of its installation in deep waters, Alves et al. [25], Gomes et al. [26], new types of turbines, Lopes et al. [27], Morais et al. [28], and even the relation between the electricity and hydrogen production, Huertas-Fernández et al. [29]. The theoretical development of OWC devices has been complemented with numerical simulations to study the devices under controlled conditions. Some of that research has focused on the aerodynamic and hydrodynamic coupling, Teixeira et al. [30], Zhang et al. [31], the implementation of an Actuator Disk to represent the turbine in a more realistic way, Moñino et al. [32], the consideration of non-linear effects to improve the OWC efficiency, Luo et al. [33], or the implementation of a wave-to-wire model to re

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List of Symbols

Latin symbols

A_b:	Turbine blades area – [m^2]
$C_{p,a}$:	Specific heat under constant pressure for dry air – [J/kgK]
$C_{p,v}$:	Specific heat under constant pressure for water vapour – [J/kgK]
e:	Vapour pressure – [Pa]
e_0:	Partial saturation pressure – [Pa]
e_s:	Saturation pressure – [Pa]
F_{drag}:	Drag force on the turbine blades – [N]
h_w:	Water depth – [m]
L:	Latent vaporization heat – [J/kg]
MW_a:	Molar weight of the air – [kg/mole]
MW_w:	Molar weight of the water vapour – [kg/mole]
N_{rpm}:	Turbine rotational speed – [r.p.m.]
p:	Static pressure – [Pa]
$p_{c,a}$:	Critical pressure for air – [Pa]
$p_{c,v}$:	Critical pressure for water vapour – [Pa]
p_{tot}:	Total pressure – [Pa]
r:	Mixing ratio – [–]
r_w:	Ratio between the power output of the full–scale OWC device and the OWC scaled device – [–]
R_a:	Air constant – [J/kgK]
R_v:	Water vapour constant – [J/kgK]
S_{blades}:	Surface of the blades of the turbine – [m^2]
T:	Temperature – [K]
T_0:	Reference temperature – [K]
$T_{c,a}$:	Critical temperature of the air – [K]
$T_{c,v}$:	Critical temperature of the water vapour – [K]
u:	Air velocity – [m/s]
v_{wind}:	External wind velocity – [m/s]

Greek symbols

ΔL:	Work done by/on the system – [J]
ΔQ:	Heat transfer by/on the system– [J]
ΔU:	Internal energy variation of the system– [J]
ϵ:	Ratio of the gas constants for dry and water vapour – [–]
λ:	Geometric scale ratio – [–]
ρ_a:	Dry air density – [kg/m^3]
ρ_{mix}:	Air mixture density – [kg/m^3]
ρ_v:	Water vapour density – [kg/m^3]
σ:	Turbine solidity – [–]

Abbreviations

$LCOE$:	Levelized Cost of Energy
OWC:	Oscillating Water Column
RH:	Relative humidity – [–]
WEC:	Wave Energy Converter

produce the overall OWC performance, Henriques et al. [34], among others.

Thermodynamics are a key factor in OWC performance. In fact, the theoretical and numerical OWC framework has been extended with experimental tests under controlled conditions to check different aspects

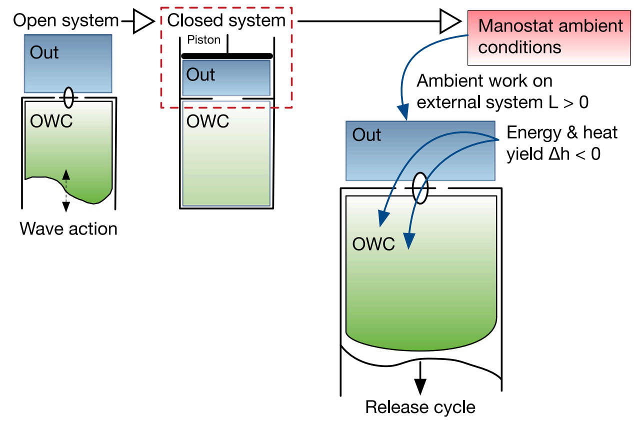

Fig. 1. Schematic representation of the performance during the release phase.

in performance, Cui et al. [35], Rezanejad et al. [36], López et al. [37], also considering Thermodynamics in some cases. Experimental research has focused on the air compressibility assuming an adiabatic process, Sheng et al. [38], Sheng and Lewis [39]. Further research has studied the thermodynamic process under a relaxation of the adiabaticity, considering only the compression phase as adiabatic process, Falcão and Henriques [40]. The differences obtained between the theoretical and the real efficiency might be explained by the implementation of the real-gas model due to the variation in the air density induced by moisture, Medina-López et al. [41], Medina-López et al. [42], Medina-López et al. [43]. In addition, the thermodynamics processes are influenced by the characteristics of the turbine, since the turbine acts like a restraint of the air-system, Moñino et al. [44], Molina-Salas et al. [45], affecting the polytropic exponent value and, consequently, the air polytropic process. Recently, authors of the present research have come up with the differentiation of the air compression and expansion processes into an *active compression* and *passive release* processes respectively, Molina-Salas et al. [46]. The influence of the thermodynamics processes affects the overall efficiency and, thus, the LCOE values, Molina-Salas et al. [47]. This influence can be more or less noticeable depending on the wave climate conditions, Gonçalves and Teixeira [48].

Associated to the experimental tests, scale-effects problems must be considered. Those scale-effects have been studied, Weber [49], Dimakopoulos et al. [50], and theoretical corrections have been developed to extrapolate results obtained, Falcão et al. [51]. Usually, scale-effects problems arise when moving from the scale of a prototype to the scale of the test model, Falcão and Henriques [52]. Nevertheless, the authors of the present research have recently pointed out that, in the case of the thermodynamic processes, the phenomena accuracy decreases upward scaling from model to full-scale prototype, Molina-Salas et al. [53].

The experimental tests performed in the laboratory might be a somewhat idealized representation of the full-scale reality, with the Thermodynamics playing an essential role, as it is more accurately described at the model scale. One of the phenomena that may not be accurately represented in the laboratory experimental tests is the environmental conditions, and more specifically the wind around the OWC device. In previous research, authors have pointed out that there is no mixing between the air inside and outside the chamber, Molina-Salas et al. [47], Molina-Salas et al. [46]. Nevertheless, the external wind can induce some energy exchange between the OWC air system and the atmosphere surrounding the OWC, which can affect the thermodynamics processes and, in consequence, the overall efficiency of the device. To take into account the environmental conditions in the OWC thermodynamic system, the first step is the *transformation* of the open thermodynamics OWC system into a *virtually* closed one, Kestin [54].

With this transformation, the First and Second Principles of Thermodynamics can be properly applied, and the thermodynamics processes can be adequately studied. This methodology has been followed up in previous researches, Falcão and Justino [20], Josset and Clément [55], Molina-Salas et al. [46]. Therefore, its analysis might help to justify the low efficiency obtained in the real model OWC devices.

The objective of this research is to study the influence of the environmental conditions on the OWC performance following a Thermodynamic focusing. This research analyses the influence of the wind conditions around the OWC device in the performance of the converter, based on experimental tests and previous theoretical analysis. This paper is organized as follows: in the first place, a theoretical development of the influence of ambient conditions in the thermodynamics processes is developed. In second place, the experimental setup of the tests performed is described. Afterwards, the results obtained of the experimental tests are analysed and discussed. Finally, the conclusions of this research are summarized, and the possibles future researches are exposed.

2. Theoretical background. A qualitative approach

The first step to understand the influence of ambient conditions in the OWC efficiency is to analyse its performance, which is governed by the wave action inside the OWC chamber. As it has been pointed in Section 1, each cycle induced by the wave action can be divided in two phases: an *active* phase of compression, and a *passive* phase of release back to the initial conditions, Molina-Salas et al. [46]. During the *active* phase, the water level inside the chamber rises and compress the air–system, which means that the system receives some amount of energy in form of work — $\Delta L > 0$. Given that the variation of the internal energy of the system during this phase is null — $\Delta U = 0$ —, some amount of energy is rejected in the form of heat — $\Delta Q < 0$. In addition, considering the *virtually* closed system, an extra energy flow appears to satisfy the First Principle of Thermodynamics — see Kestin [54], and compare equation (17) in Molina-Salas et al. [46] with the First Principle of Thermodynamics for a close system ($dU = dQ + dL$) —. One part of this energy is transmitted to the turbine — useful energy — and other part is exchanged with the environment — wasted energy. During the release phase, when the water level decreases, a Joule's expansion occurs, where $\Delta U = \Delta L = \Delta Q = 0$ in the air system inside the chamber. For that reason, in this phase, it is the air outside the chamber that transmits some amount of energy, in one hand, to the turbine, and on the other hand, to the air system inside the chamber, restoring the initial conditions. This energy transmission is due to the action of the air surrounding the OWC device, which performs like a manostat.

It is important to highlight the influence of the turbine performance on the air-system. As it has been pointed by the authors — see Molina-Salas et al. [45] —, the turbine acts as a restrain for the system, isolating the air-system inside the chamber and preventing the thermodynamic exchange between air variables inside and outside the chamber. This fact helps to explain the aforementioned differences between the *compression* and *release* phases. A more intuitive evidence of this isolating effect can be observed in Section 4, where it is shown that there is no effective mixing between the air inside and outside the chamber as it would be expected — see Molina-Salas et al. [47] —.

Therefore, according to the physical interpretation of the compression and release phases and the turbine isolation effect, the influence of the ambient conditions on the OWC performance can be explained. During the compression phase the air subsystem inside the chamber yields an amount of energy onto the turbine. The air inside the chamber drives the turbine during this phase, which is essentially isolated from the ambient conditions by the walls of the OWC device and by the restraint imposed by the turbine rotation. Thus, the ambient conditions do not affect the efficiency of the device during compression. However, during the release phase the air system inside the chamber does not exchange any amount of energy since $\Delta L = \Delta Q = 0$ — passive expansion —, nor yields any amount of energy onto the turbine. In consequence the turbine performance is driven by the air outside the chamber, which transmits some amount of energy to it. For that reason, the efficiency of the turbine during the release phase is mostly influenced by the ambient conditions surrounding the OWC device. A schematic representation of this phase is shown in Fig. 1.

Focusing on the thermodynamic balance, although there is no significant mixing between the air subsystem inside the OWC chamber and the air subsystem outside the chamber and surroundings — Molina-Salas et al. [46] —, there is some energy exchange between both subsystems through the enthalpy budget. During the compression phase, the enthalpy of the air inside the chamber decreases, which means the air yields some amount of energy to the turbine and to the external subsystem. During the release phase, the enthalpy of the internal subsystem increases, revealing that it is the external subsystem that yields some energy to the internal one and to the turbine, as it has been pointed out previously.

Moreover, the real-gas model allows a more complete description of the gas system performance. This model modifies the ideal-gas model because the air system is a mixture of dry air and water vapour. The characteristics of the air–water vapour mixture depends on the vapour fraction present in dry air. Following Medina-López et al. [41], this fraction can be calculated starting from the Clapeyron–Clausius law:

$$e_s = e_0 \cdot exp\left[\frac{L}{R_v}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right] \tag{1}$$

where $e_0 = 611$ Pa is the partial saturation pressure at $T_0 = 273$ K, $L = 2,5 \cdot 10^6$ J/kg is the latent vaporization heat, and $R_v = 461$ J/(kg·K) is the water vapour constant. The saturation pressure represents the equilibrium state for which no more vapour is present in dry air without further condensation. This value only depends on the temperature. The real vapour pressure, e present in the air can be calculated through the saturation pressure and the relative humidity (RH) measured as $e = RH \cdot e_s$. Thus, knowing both the vapour pressure and the air–water vapour pressure, p, the mixing ratio, r, can be defined as a fraction between both pressures. Finally, the air–water vapour mixture density, i.e. the real gas density, can be calculated as:

$$\rho_{mix} = \rho_a \frac{1 + r}{1 + r/\epsilon} \tag{2}$$

where ρ_a is the density of the dry air, defined as $\rho_a = p/(R_a \cdot T)$ and $\epsilon = R_a/R_v = 286.7/461 = 0.622$ is the ratio of the gas constant for dry air and water vapour respectively.

In conclusion, any change in the conditions of temperature and/or relative humidity in the outer region, would affect the air–water vapour mixture density and, in turn modifying the OWC gas system performance and its efficiency through the performance during the passive release cycle. A decrease in gas density means less mass flow passing through the turbine, so the drag force on the rotor blades decrease, let us recall $F_{drag} \propto \rho_a S_{blades} u^2$. In consequence, the power captured by the turbine decreases, and so the efficiency.

3. Experimental set up

Experimental data have been collected in the wave flume of the Hydraulics Laboratory in the School of Civil Engineering of the University of Granada (Spain). The dimensions of the wave flume are 10 m long and 1.5 m wide, with a flat bottom and a water depth of $h_w = 0.45$ m. At the beginning of the wave flume, a paddle system for the wave generation is installed. On the other side of the flume, and with the aim to eliminate, or at least, to reduce the reflected waves, a dissipative beach is built. The dissipative beach is built by a metal-grilled structure with a 2.5 : 1 slope, covered by a layer of concrete cubes 0.075 m wide. This configuration allows the wave to pass through it, so one part of the wave energy is transmitted through the beach, other part is absorbed by it, and other part is reflected and absorbed

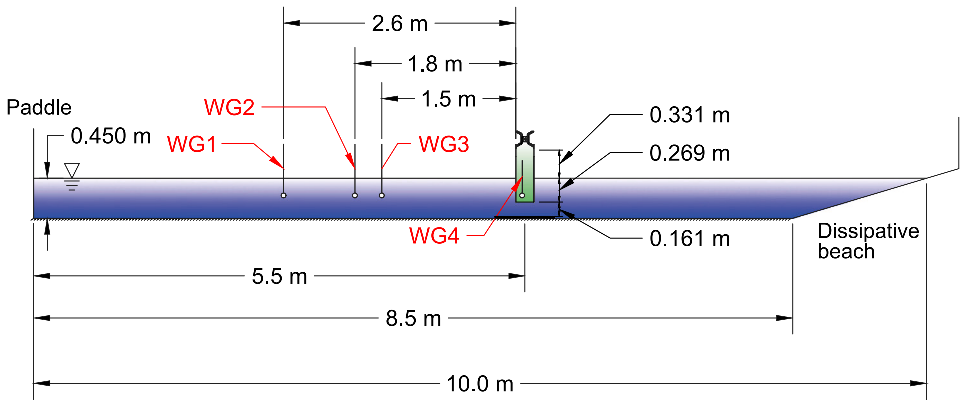

Fig. 2. Scheme of the wave flume used during the experimental tests.

later by the paddles through their reflected wave absorption system. Nevertheless, the reflected wave is not important for two reasons. On one hand, the amount of energy reflected is not high enough to change significantly the generated waves. And on the other hand, the focus of the research is the interaction between the air-system of the OWC and the water-surface elevation inside the OWC device. For this purpose, a wave-gauge level is placed inside the OWC chamber. Fig. 2 shows a scheme of the described wave flume.

The OWC device is modelled by a vertical steel cylinder, 0.20 m diameter and 0.60 m high. The base of the cylinder is located at 0.269 m under the still water surface, and the wave energy is transmitted inside the cylinder by a 0.161 m high gap placed at its base. The turbine is placed on the top of the cylinder, inside of cone-shaped trunks that allow a smooth transition between the sections of the chamber and the turbine. The turbine is a Wells turbine, with 6 divergent paddles with a NACA0022 profile, whose area is $A_b = 1.32 \cdot 10^{-4}$ m^2. The external and internal diameter of the turbine is 0.045 m and 0.0225 m respectively, which renders a turbine solidity of $\sigma = 0.6508$. The performance of the turbine shows a linear relationship between pressure drop and both air-flow and rotational speed. It is important to point out that the objective of this research is to study the influence of the ambient conditions on the air-system compression/release cycles rather than its influence on the turbine performance. For that reason, the turbine has been used as a restrain of the system, with the aim to reproduce adequately the air-system performance. The turbine size has been fixed to match the chamber size and to ensure an adequately performance of the OWC air system, rather than considering possibles scale-effects.

For the purpose of the present research, the variables measured are temperature (T), relative humidity (RH), air velocity (v), static and total pressure (p and p_{tot}). All those variables have been measured both inside and outside of the OWC chamber. The turbine rotational speed (N_{rpm}) is also measured. For pressure observation, a total of 11 pressure taps have been used, 4 of them placed inside the OWC chamber, 4 at the outlet of the turbine, and the remaining 3 placed outside the chamber. The location of measuring gauges is shown in Fig. 3, where *P1, P2, P5, P6* and *P9* represent the pressure taps measuring static pressure, *P3, P7* and *P10* represent the pressure taps measuring the total pressure pointed downside, and *P4, P8* and *P11* the total pressure pointed upside. Water elevation has been recorded with four water-level gauges, three of them placed between the paddle system and the OWC device, and the last one placed inside the OWC chamber. This configuration allows to measure the wave-energy transmitted inside the chamber, and to relate the air-volume and air-pressure inside the chamber, which is a key factor to represent the polytropic process. The sampling frequency of all the devices have been chosen considering the Nyquist Theorem. All the devices are connected to an acquisition system, which is configured at 50 Hz. Wave gauges location is shown in Fig. 3. The schematic representation of the OWC chamber and the gauges used during the test is shown in Fig. 3.

Table 1
Test runs for regular waves (water depth $h_w = 0.448$ m).

Test	Wave height H_s [m]	Wave period T_z [s]	Wave number kh [–]
1	0.10	2.12	0.68
2	0.08	1.01	1.87
3	0.08	1.34	1.21
4	0.08	1.68	0.90
5	0.10	1.68	0.90
6	0.10	2.02	0.72
7	0.10	2.35	0.61
8	0.15	2.02	0.72
9	0.15	2.35	0.61
10	0.15	2.69	0.52

4. Result and discussion

A total of 10 tests were conducted in the wave flume with regular waves. The wave characteristics of those tests are shown in Table 1. Next, the tests have been repeated under the same conditions, but modifying the conditions of the external air subsystem by adding an external wind of v_{wind} = 1.5 m/s, equivalent to a wind speed of fairly 4.5 m/s $\simeq$ 17 km/h in the case of a full-scale prototype with a 1:10 scale factor. The external wind has been generated with fan connected to a frequency converter, see Fig. 3. The relationship between the vertical air velocity of the air through the turbine and the wind velocity is around 0.15, similar to the normal situations that can be found in an hypothetical full-scale prototype, Falcão et al. [21], Henriques et al. [34], Falão et al. [4]. These tests have been planned to compare the results over a wide range of relative depth values. The air properties considered during the data analysis are shown in Table 2. It is assumedI for the purpose of this research that the turbulence generated by the fan is essentially developed and homogeneous. In fact, turbulence conditions may have a clear impact on the turbine performance — see Raghunathan [8] as example —, so this may be considered as one limitation of this research.

The distinction between compression and releases phase has been set on the basis of the pressure time series, following an essentially harmonic behaviour — see Fig. 4 —. Therefore, knowing the maximum and minimum pressure states inside the OWC chamber, the compression and release phases can be identified, e.g. from minimum to maximum and from maximum to minimum pressure states respectively. Given that the temperature and relative humidity time series are essentially constant, their values can be considered as reference parameters for each test. The same consideration applies to the density of the air mixture. The values of those variables are shown in Fig. 4 for one of the tests indicated in Table 1 for clarity of details. The rest of cases conducted show the same behaviour without losing of generality.

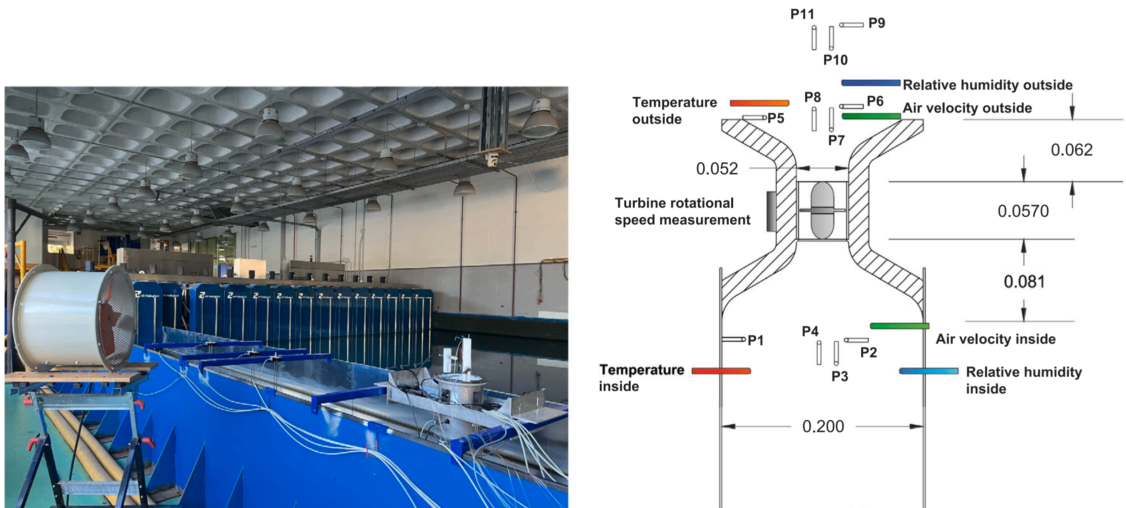

Fig. 3. (a): Experimental set-up. (b): Gauges distribution (dimensions in meters).

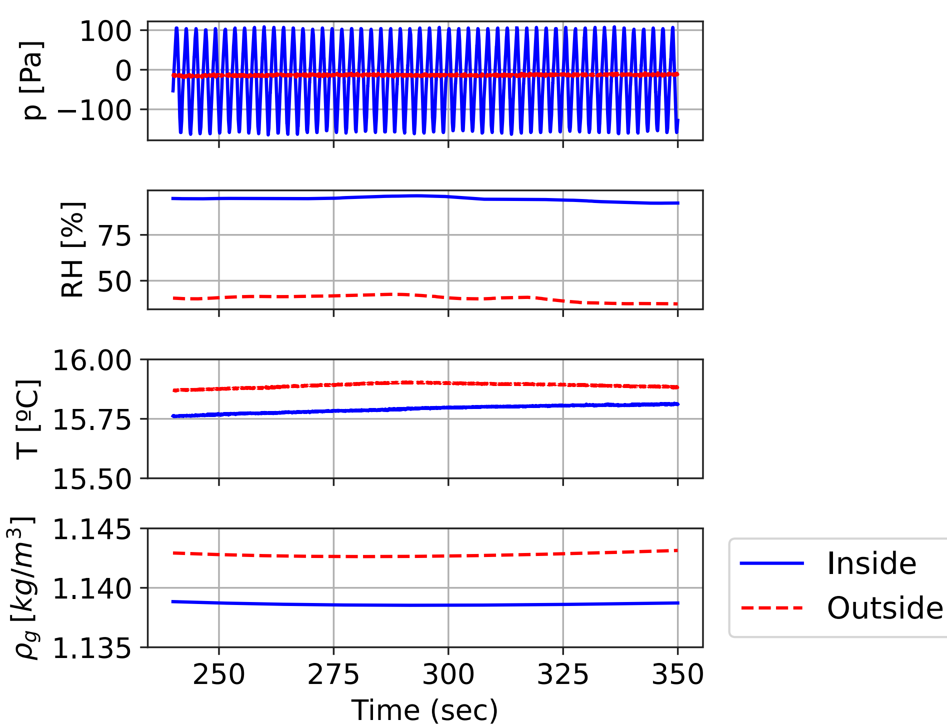

Fig. 4. Thermodynamics variables both inside and outside the OWC chamber (Data for test 1 in Table 1, without external wind).

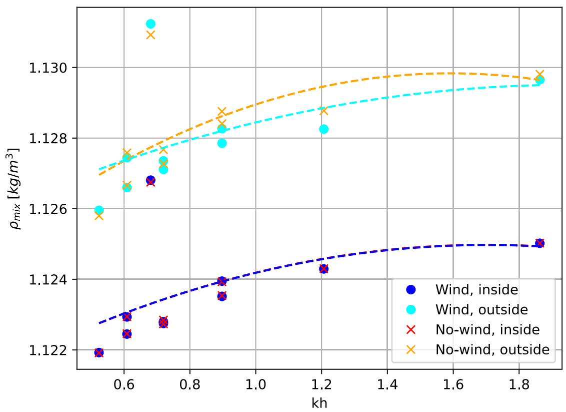

Fig. 5. Comparison of the air-density inside and outside the chamber, and with and without external wind.

Table 2
Dry air and water vapour properties.

Property	Value	Units
Air properties		
R_a	286.7	J/kg K
$C_{p,a}$	1010	J/kg K
ρ_a	1.25	kg/m³
MW_a	0.0288	kg/mole
$T_{c,a}$	132	K
$p_{c,a}$	$3.771 \cdot 10^6$	Pa
Water vapour properties		
R_v	461	J/kg K
$C_{p,v}$	1093	J/kg K
MW_v	0.0182	kg/mole
$T_{c,v}$	647	K
$p_{c,v}$	$2.2089 \cdot 10^7$	Pa

Furthermore, the external wind affects the ambient conditions of the OWC, and more specifically the air density. Fig. 5 shows the density calculated for the cases listed in Table 1, both inside and outside the OWC chamber, and both without and with external wind. According to the results, the outer air–water vapour mixture density decreases due to the presence of wind around the turbine outlet. The external wind induces a decrease in the local temperature around the OWC outlet, while at the same time reduces the external local air mixture pressure, as expected from the Venturi effect associated to the narrowing of stream flow lines in the vicinity of the OWC structure. This temperature and pressure reduction decreases the vapour saturation pressure according to expression (1), which implies a reduction of the vapour pressure in the air–water vapour mixture. Therefore, the mixing ratio decreases and, in consequence, the air–water vapour mixture density decreases as well. The mixture density reduction affects the turbine performance and the OWC overall efficiency as it is discussed ahead. It is worth recalling that according to Section 2, the air mixture inside the chamber is not essentially affected by outer conditions, since the turbine helps to isolate the system — see Fig. 5 —.

The external wind condition also affects the thermodynamic balance. Heat and kinetic energy budgets can be expressed through the enthalpy variation, which represents the energy exchanged between the system and the environment. The enthalpy budget in the air-subsystem inside the chamber — represented in Fig. 6(a) — is not essentially affected by the external wind, in fact due to the turbine isolation effect. Nevertheless, the subsystem outside is affected by the external wind — Fig. 6(b) —. Although during the compression phase the air mixture inside the chamber drives the turbine performance — the mixture not being affected by the external wind —, during the release phase the air mixture outside the chamber drives the turbine, and this is affected by external wind condition. From a purely thermodynamic view parallel to the density calculation, it is seen from Fig. 6(a) that the enthalpy of the internal subsystem is the same under both external conditions (wind/no-wind), which means that it always receives the same amount of energy from the external subsystem. Since the enthalpy yield from the external subsystem during release phase is required both to restore the energy in the internal subsystem and to drive the turbine, then it is clear that in the case of external wind condition with associated decrease in temperature, there will be less availability for the turbine driving, once the required amount of enthalpy has been used to restore the internal system.

In addition, the thermodynamic efficiency of the OWC device in both situations can be analysed through the isentropic efficiency, which represents the deviation of the process from the ideal isentropic one, i.e. the process where the entropy variation is null. The results obtained are shown in Fig. 7. During the release phase the isentropic efficiency is around 100%, which means that the process can be regarded as isentropic — see Molina-Salas et al. [46] and Section 2 —. However, during the compression phase, some amount of heat is exchanged, leading to a non-adiabatic process. Under external wind, the isentropic efficiency is lower, which means that the heat exchanged in this situation is higher. This can be due to the fact that the external wind extracts some amount of energy from the outer air subsystem — see Fig. 6(b) —. All in all, it seems clear that the external wind affects negatively to the OWC performance since affects the thermodynamic balance increasing the heat exchanged, and thus, reducing its reversibility and efficiency.

Finally, those effects contribute the pneumatic power of the OWC device, as it can be observed in Fig. 8. Although the average pneumatic power seems not to change significantly due to the modification of the ambient conditions, the maximum power that can be achieved with the OWC device is lower when there is external wind. The differences can be up to 15% in the case of the maximum power — the differences in the case of mean power can be up to 4.5% —, with consequences on the annual energy harvested. To estimate the theoretical annual energy production, let us considerer a full scale OWC device with 2 m diameter, which implies a scale factor $\lambda = 1/10$ with respect to the OWC device tested in the lab. For that scale factor, the ratio between the pneumatic power output of the prototype and the model is $r_w = \lambda^{7/2}$, according to Froude similarity, Molina-Salas et al. [53]. Now, let us consider the OWC device deployed in a Mediterranean area, where statically, in one year there would be 3000 h of waves with period around 7 s and 100 h of waves with period around 10 s — see Medina-López et al. [43] —. Extrapolating the results obtained in the present research, for the indicated climate conditions, and assuming a roughly 75% efficiency for the turbine electrical generator, the annual electrical energy output can be estimated in 1.62 MWh for the case where there is no external wind, and 1.57 MWh for the case with external wind. That means that the external wind causes a reduction of fairly 2.7% in the annual energy obtained.

5. Conclusions and future research

This research analyses how the modification of the external ambient conditions affects the OWC performance. More specifically, the influence of the wind around the turbine outlet, which can be considered as a common condition that may occur in full–scale OWC devices, is compared with the ideal no–wind situation. The main conclusions of this research are:

- The pneumatic power of the OWC device is affected by the change in the external ambient conditions, reducing the amount of energy that can be harvested with the OWC converter. This pneumatic power can be reduced up to 15% in some cases, which implies a total reduction of around 3% in the annual energy production.

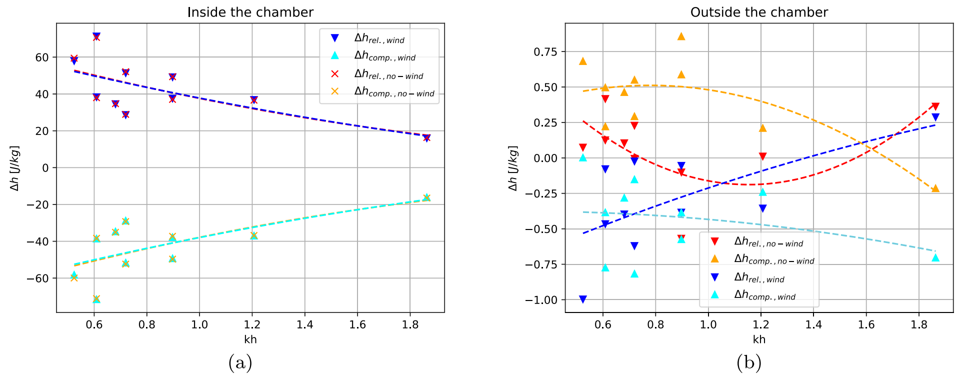

Fig. 6. (a): Enthalpy variation inside the chamber (with and without external wind). (b) Enthalpy variation outside the chamber (with and without external wind).

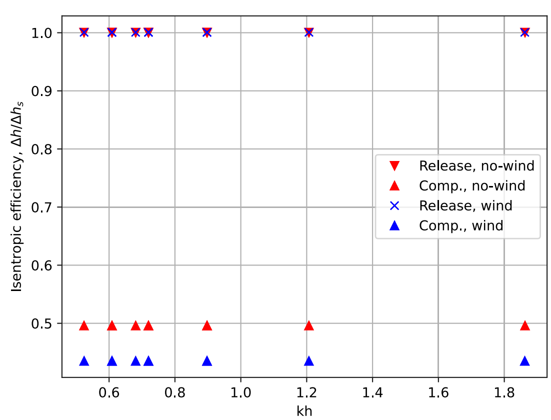

Fig. 7. Isentropic efficiency.

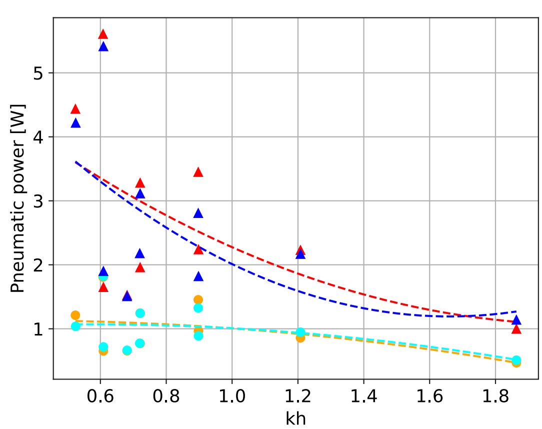

Fig. 8. Pneumatic power vs. relative depth.

- The external wind leads to a reduction in temperature and pressure, which implies a reduction in the outer air density. This density reduction affects the turbine performance only during the release phase, since during the compression phase the air inside the chamber drives the turbine rotation.
- The enthalpy balance in the outer subsystem is affected by wind, reducing both the amount of energy that this subsystem can yield onto the turbine and the isentropic efficiency. That enthalpy budget modification reduces the overall efficiency of the OWC device.
- The turbine has an isolating effect by preventing the thermodynamic exchange between air variables inside and outside the chamber. This isolation effects makes that the internal conditions of the OWC does not change although the external conditions change.

In order to keep studying the effect of the wind in the OWC performance, next steps are: (i) To apply a range of wind velocities to achieve a deeper analysis of its influence. (ii) To conduct tests under different outer conditions aside of wind, namely different temperatures and relative humidities. This would allow to have a wider knowledge about the influence of the ambient conditions in the OWC overall performance. (iii) To conduct irregular wave tests and to compare them with regular wave ones, in order to fine tune the expected range of OWC performance and energy harvesting. (iv) To isolate the turbine outlet from the atmosphere with the aim of preserving essentially constant ambient conditions. (v) To analyse the influence of the wind turbulence in the turbine performance.

CRediT authorship contribution statement

A. Molina-Salas: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **M. Clavero:** Writing – review & editing, Writing – original draft, Supervision, Project administration. **A. Moñino:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Conceptualization.

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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