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Numerical analysis of the effect of deflectors inserted inside the duct of an oscillating water column device with an existing Savonius turbine

Análise numérica do efeito de defletores inseridos no duto de um dispositivo de coluna de água oscilante com a inserção de uma turbina Savonius

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ABSTRACT

In this work, a comparison between three different configurations of deflectors inserted inside the duct of an oscillating water column device (OWC), where is attached a rotating Savonius turbine in the same domain, is done. In the first configuration, the numerical model is composed only by the Savonius turbine inside the OWC duct. In the second configuration, just one deflector is inserted upstream of the turbine region. In the third case, a second deflector is inserted, together with the first one, but downstream of the turbine. For every studied model, the geometry of the hydropneumatic chamber was varied by three values of the ratio H1/L1 (the height times the length). This geometric variation was performed according to the Constructal Design methodology. The purpose of this comparison was the evaluation of the OWC pneumatic power, the power coefficient, and the Savonius turbine power. The results indicated that for all the studied configurations, the ratio H1/L1 as well as the deflectors presence inside the OWC duct had an influence in terms of the performance indicators, especially regarding the pneumatic power, where variations up to 100 W were noticed.

Keywords: Oscillating water column; Savonius turbine; Deflectors; Turbulent flows

RESUMO

O presente trabalho apresenta a comparação de três diferentes configurações de defletores inseridos no duto de um dispositivo de coluna de água oscilante (CAO) com uma turbina Savonius em rotação inserida no domínio. Na primeira configuração, o modelo é composto apenas pela turbina no interior do duto do dispositivo. Na segunda configuração, ocorre a adição de um único defletor situado à montante da região onde se encontra a turbina. Na terceira configuração, é acrescentado um segundo defletor, juntamente ao primeiro, porém, situado à jusante da região da turbina. Para as três configurações, foi variada a geometria da câmara hidropneumática do dispositivo CAO em três valores da razão da sua altura pelo seu comprimento, H1/L1. Esta variação foi realizada através do método Design Construtal. A adição dos defletores no domínio em estudo teve como objetivo avaliar a influência sobre os resultados da potência pneumática do dispositivo, do coeficiente de potência e da potência da turbina Savonius. Os resultados indicaram que, para os casos estudados, a razão H1/L1 assim como a presença dos defletores em suas diferentes configurações influenciaram o comportamento dos indicadores de performance do estudo, especialmente em termos da potência pneumática, onde, variações de até 100 W foram observadas.

Palavras-chave: Coluna de água oscilante; Turbina savonius; Defletores; Escoamentos turbulentos

1 INTRODUCTION

According to Jenniches (2018), the transition from fossil fuels to renewable energy sources is a trend due to the need to diversify the energy matrix and the carbon emission reduction to the atmosphere. In this sense, the ocean wave energy conversion into electricity has been the subject of many scientific studies.

The Oscillating water column (OWC) device is one of the main way to convert the wave energy into electricity. According to Isoldi et al. (2018) the OWC converter is defined as a device with a hydropneumatic chamber where there are two openings, one in communication with the atmospheric air and the other one in communication with the sea water. When the sea waves pass through the OWC chamber, the water column inside the hydropneumatic chamber oscillates and then occurs a compression and a decompression air above the water free surface. In this sense, the air flows along the OWC duct, where is inserted a turbine which converts the rotational mechanical energy caused by the air flow in electrical energy. Several studies were made with simplifications to allow the achievement of recommendations in terms of the OWC design, such as Santos (2023), who studied a multiphasic problem (air and water), with geometric variation of a complete model containing an OWC device, inserted in a wave channel, with an existing Savonius turbine inside its chamber and rotating in a constant angular velocity. A ramp was positioned below the OWC device to dampen the effects of the waves on the system. Both geometries (OWC chamber and ramp) were varied to analyze the effects in terms of the pneumatic power and turbine power. This study concluded that the geometry variation is significant to improve a better performance for the OWC device and the turbine inserted.

Pinto Jr et al. (2019), for instance, evaluated the behavior of the OWC static pressure by varying the width of its duct, considering just the chamber and the duct regions of the device, and imposing a real condition of the sea state. A monophasic air flow was simulated for this work. This numerical modeling kind make possible to simulate longer physical times and to use real sea state data as a boundary condition for the study. In the work made by Letzow et al. (2020), the performance of an OWC device subject to variations in the geometry of its chamber and of a ramp positioned below the device was calculated using the Constructal Theory (Bejan, 2018). A wave channel and its interaction with the OWC device were considered, but an existing turbine inside the OWC duct was not modeled.

Research about wind turbine modeling have also been developed, including the Savonius turbine approach (Savonius, 1930). In the study by Akwa (2010), a computational model was validated, based on the experimental research carried out by Blackwell et al. (1977), where a Savonius turbine rotating inside a wind tunnel was analyzed. The OWC device was simulated inside a wind tunnel, i.e., with air flowing in just one direction inside the hydropneumatic chamber and passing through the turbine rotating with a constant angular velocity. Later, in the study by Santos et al. (2021), eight OWC duct position geometric variations, along the OWC device chamber, were analyzed.

The objective of this work is to analyze the performance of an OWC device with an existing Savonius turbine inside its duct where deflectors are inserted in order to modify the air flow that pass through the turbine. This kind of analysis has not yet been noticed in previous studies. The present study also investigates the effect of the ratio between the height and the length of the hydropneumatic chamber (H_1 / L_1) over the performance of the OWC device. In this sense, the study was subdivided into three different cases. In the first one, only the OWC device with an existing Savonius turbine is analyzed, i.e., without deflectors. In the second case, one rectangular obstacle (deflector) is added upstream of the Savonius turbine, inside the OWC duct. In the third case, two deflectors are added to the model, one upstream and another downstream of the Savonius turbine. For all the cases simulated, turbulent air flow was considered in a domain that simulates the OWC chamber and duct.

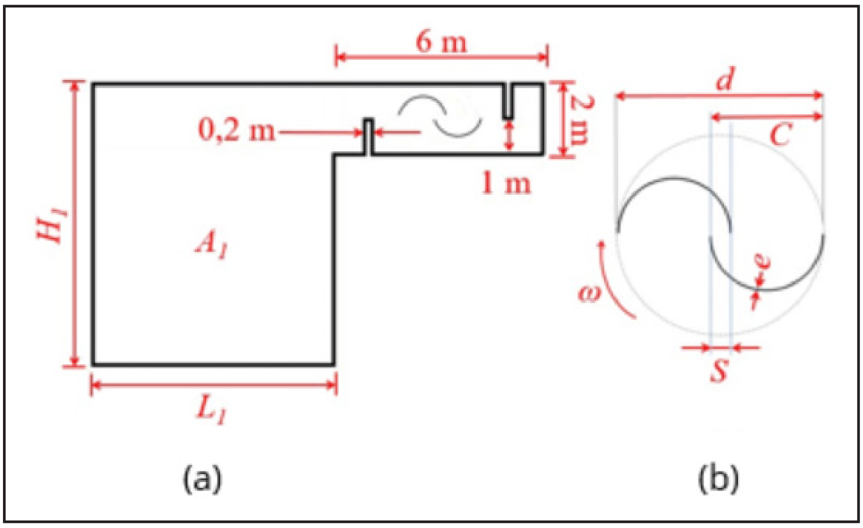
2 METHODOLOGY

In the present work, a two-dimensional computational model was carried out to simulate an OWC device with an existing Savonius turbine, using the Finite Volume Method (FVM) seen in Versteeg and Malalasekera (2007). This method converts the continuity and the momentum equations, in differential form, into algebraic equations, applying numerical methods to solve them. For the geometric evaluation the Constructal Theory was applied. This theory is based on the Constructal Law (Bejan, 2018). The Constructal law states that for a finite- dimension flow system to persist over time, its configuration must evolve freely in order to facilitate the access of the flow through the system. In this way, the Constructal Theory is applied to define the problem constraints (OWC duct area), the degrees of freedom (the ratio H_1/L_1) and the performance indicators (the pneumatic power and the turbine power) for the three different model configurations studied in this work. It is important to mention that the air flow inside the OWC device is considered incompressible and turbulent regime and the Savonius turbine is modeled by a rotational mesh, with a constant tip speed ratio of $\lambda = 1.5$.

2.1 Mathematical and Numerical Modeling

Figure 1 shows the OWC device and Savonius turbine dimensions used to evaluate the geometric configuration of the present work. The Savonius turbine dimensions were: d = 1.8 m for the turbine diameter, e = 0.0072 m for the blade thickness, S = 0.144 m for the distance between the blades and C = 0.972 m for the blade chord.

Figure 1 – OWC device and Savonius turbine dimensions: (a) OWC device dimensions and (b) Savonius turbine dimensions



Source: Authors (2024)

To determine the problem variables, using the Constructal Theory (Bejan, 2018), the chamber area $A_1 = H_1 \cdot L_1$ was considered as the constraint of the problem.

Turbulent and incompressible flows are modeled by the continuity and momentum equations in the x and y directions. According to Versteeg and Malalasekera (2007) these equations are given by:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

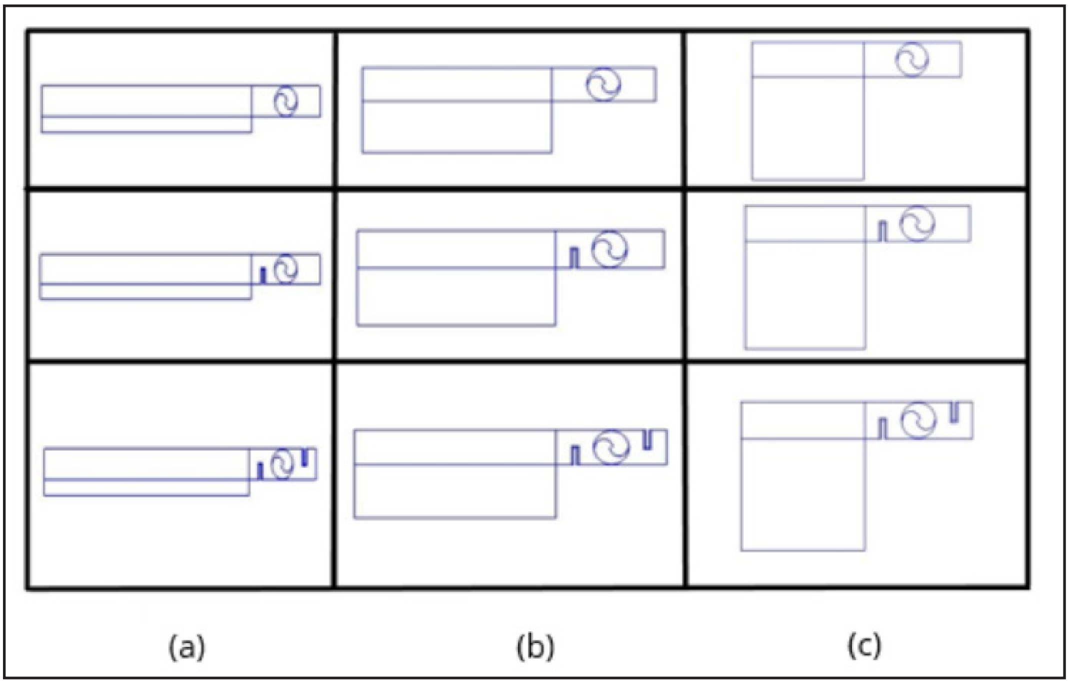
$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u u)}{\partial x} + \frac{\partial \rho v u}{\partial y} = -\frac{\partial p}{\partial x} + (\mu + \mu_t)\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho u v)}{\partial x} + \frac{\partial \rho v v}{\partial y} = -\frac{\partial p}{\partial y} + (\mu + \mu_t)\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

where x and y are spatial coordinates (m), u and v represent the time-averaged velocity components in the x and y directions (m/s), p is the pressure (N/m²), ρ is the air density (kg/m³), μ is the dynamic viscosity (kg/m.s) and μ_t is the turbulent dynamic viscosity (kg/m.s), which is obtained with the use of k – ω SST model (Menter, 1993; Menter et al., 2003).

Regarding the OWC geometric evaluation, nine variations were developed. The Fig. 2 illustrates all the geometry variations investigated here.

Figure 2 – OWC device geometric variations: (a) H_1/L_1 = 0.2; (b) H_1/L_1 = 0.5 and (c) H_1/L_1 = 1.2



Source: Authors (2024)

More precisely, Fig. 2(a) indicates a chamber with H_1/L_1 = 0.2, Fig. 2(b) configurations with H_1/L_1 = 0.5, and Fig. 2(c) cases with H_1/L_1 = 1.2. For each configuration of H_1/L_1 three different cases without deflectors, with one deflector and with three deflectors are investigated, completing the nine studied cases.

Regarding the power coefficient in wind turbines, which is the performance indicator of the present work, it can be given by (Custódio, 2009):

$$C_p = C_t \cdot \lambda \tag{4}$$

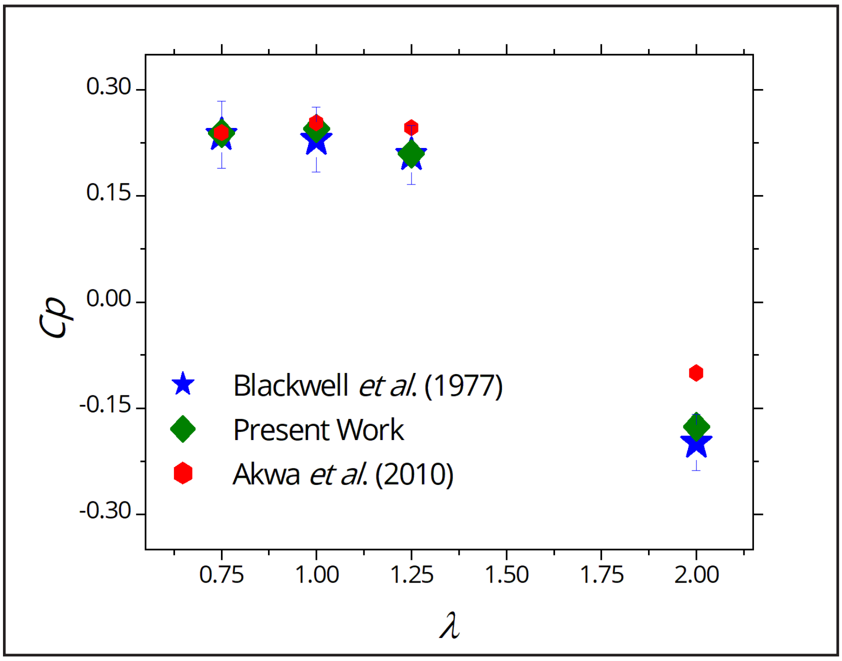
where C_t the torque coefficient, given by the torque calculated in the turbine as described in Santos (2023).

For the simulations, the commercial software Ansys FLUENT 2022 R1 was used to solve the equations, where the residuals solutions were considered converged at 1×10^{-5}, with a time step of $\Delta t = 0.00175$ s for a total simulation time of $t = 1.75$ s.

2.2 Computational model verification

According to Santos et al. (2021), the present work was also numerically verified about a Savonius turbine simulation modeled in an opened channel, exposed to a constant air flow in a turbulent regime. This verification was carried out by comparing the experimental study by Blackwell et al. (1977) and also the numerical study by Akwa (2010). Figure 3 illustrates the results obtained in the numerical verification. As can be seen, the present numerical model presented a close agreement with the numerical results of Akwa (2010) and experimental work of Backwell et al. (1977) indicating that the model is adequate for the recommendations obtained in the present study.

Figure 3 – Numerical verification of the present study



Source: Authors (2024)

3 RESULTS AND DISCUSSIONS

After the simulations of the nine different configurations, the quantitative results for the pneumatic power, *Pot*, in its different variations can be seen in Fig. 4. It is possible to notice that the deflector presence inside the OWC duct improve the *Pot* for the different ratios of H_1/L_1 comparing with the cases without the deflectors. For the best configuration, H_1/L_1 = 1.2 (OWC duct with two deflectors) presented a difference of 390 W compared to the worst case, H_1/L_1 = 0.2 (OWC duct without deflectors).

Figure 5 shows the results for the turbine power, $P_{turbine}$. It is possible to notice that the OWC chamber geometric variation influenced in the results more than the insertion of the deflectors, mainly for the ratios H_1/L_1 = 0.5 and 1.2, which conducted to a better performance. For the ratio H_1/L_1 = 1.2, the configuration without deflectors led to the highest magnitude of Pturbine = 436.23 W, which is not intuitively expected. This result can also be observed for the turbine C_p, shown in the Fig. 6.

Figure 4 – OWC pneumatic power for the different geometric variations

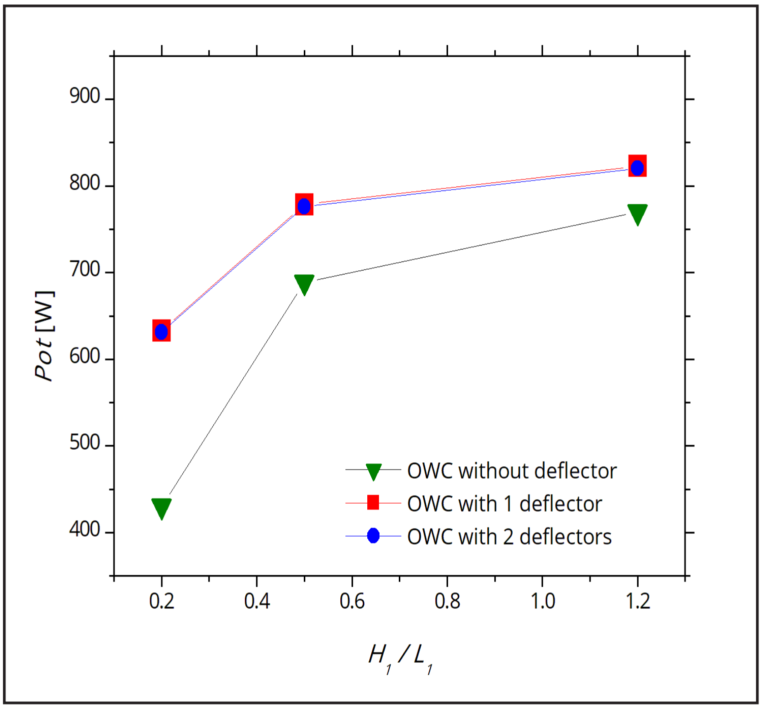


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Figure 5 – Turbine power for the different geometric variations

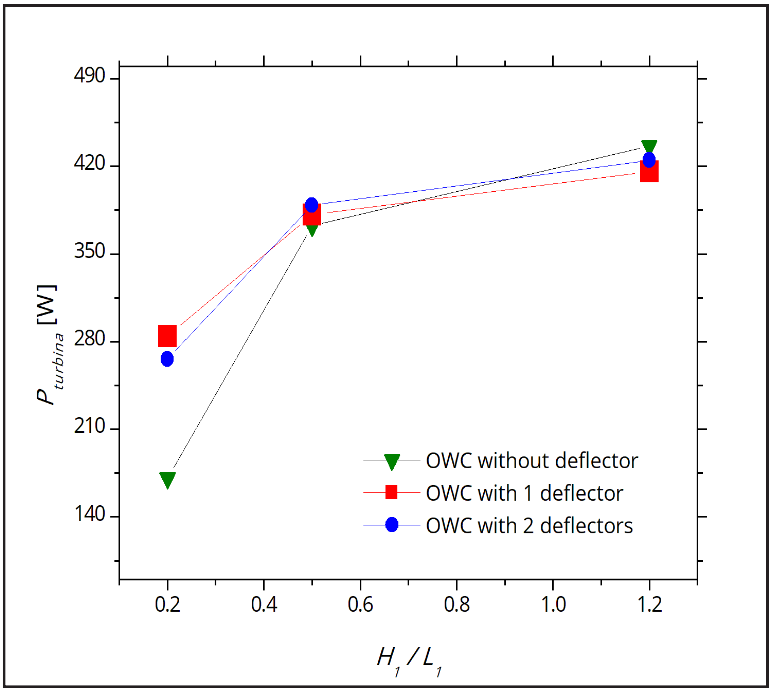

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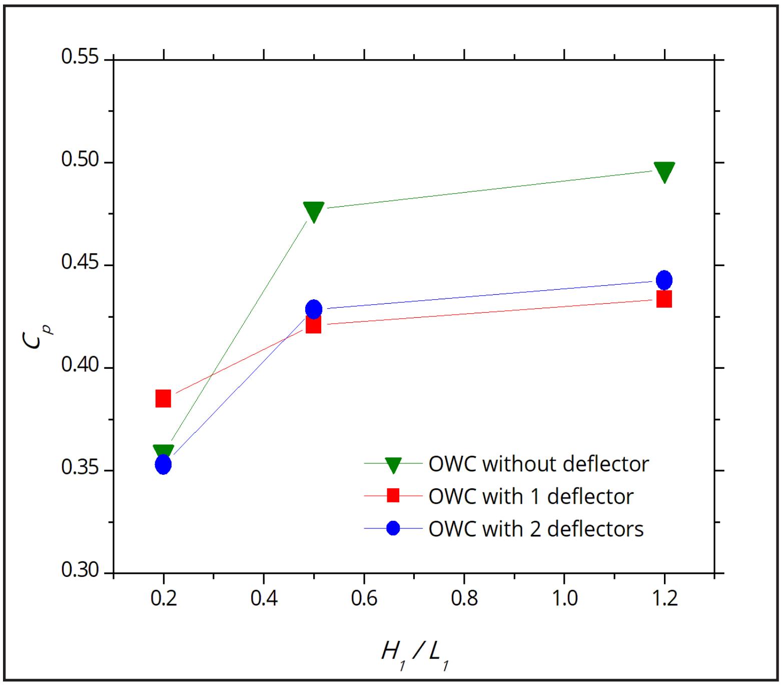
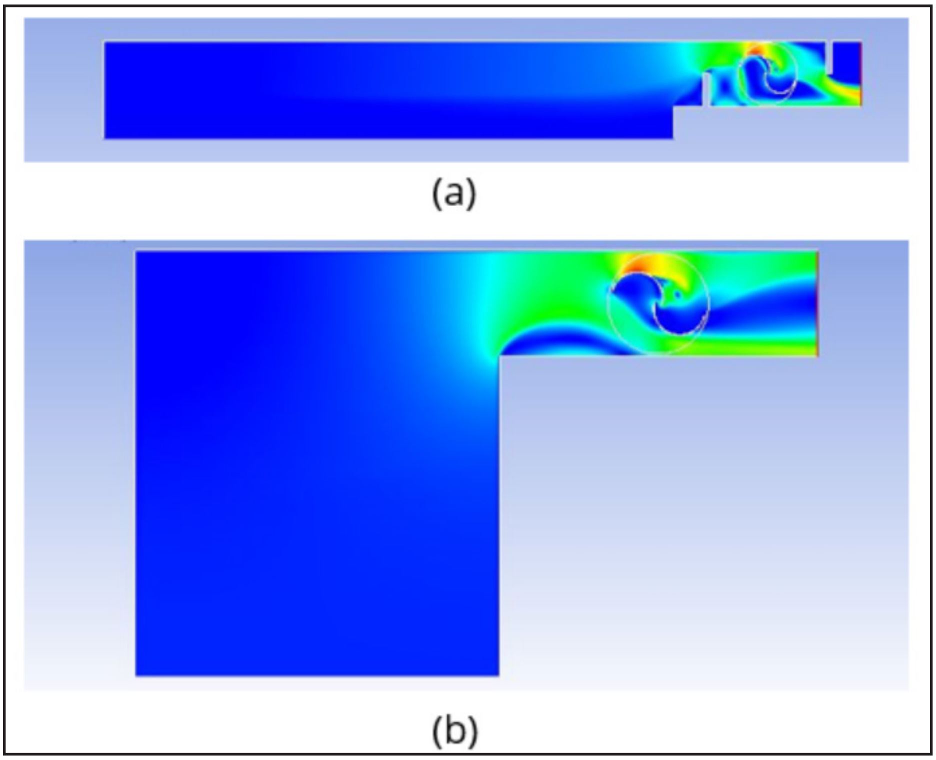
Figure 6 – Turbine power coefficient for the different geometric variations



Source: Authors (2024)

In general, the results show that the presence of the deflectors leads to a significant increase in the OWC device available power. However, this increase was not reflected in the mechanical power of the Savonius turbine intruded into the OWC duct. The results also indicated that the H_1/L_1 ratio has a significant influence on both pneumatic and turbine power, and with a similar behavior regardless of the presence or absence of deflectors inside the OWC duct. Figure 7 illustrates the velocity field obtained for the cases with the lowest and the highest C_p magnitude. For the present investigation, the detachment of the boundary layer for the optimal configuration case, Fig. 7(b), performed a similar function of the deflector, increasing the fluid dynamic performance since the mainstream impinges on the advancement blade. Here, the insertion of the first deflector for the ratio H_1/L_1 = 0.2 restricts part of the main stream and conducting to a decrease of the mechanical power in the turbine.

Figure 7 – Velocity fields for: (a) the worst performance of $P_{turbine}$, H_1/L_1 = 0.2 with two deflectors and (b) the best performance of $P_{turbine}$, H_1/L_1 = 1.2 without deflectors



Source: Authors (2024)

4 CONCLUSIONS

The present numerical study presented the geometric analysis of an OWC device with an existing Savonius turbine inside the duct. Three different configurations were developed: 1) the first case was available only the OWC device and the Savonius turbine (without deflectors), 2) at the second case, one deflector upstream of the Savonius turbine was added and, 3) at the third case, two deflectors (one upstream and another one downstream the turbine) were added inside the OWC duct. For each case, three different ratios of the height/length ratio of the OWC chamber were investigated, following the Constructal Theory. The main purpose of this work was obtaining recommendations about the influence of the ratio H_1/L_1 and insertion of deflectors on the available of the device and mechanical power in the turbine.

After all the simulations performed, it was concluded that there are significant differences in terms of the OWC performance, both due to the geometry variation of its chamber and due to the deflectors' presence inside its duct, as their presence alters the behavior of the air flow along the duct. For the present conditions, the use of the deflectors increased the available power of the device (*Pot*), but decreased the mechanical power in the turbine ($P_{turbine}$) for optimal configurations of the ratio H_1/L_1. This behavior was obtained due to the incidence of the main flow stream after the detachment of boundary layer in the connection between the OWC chamber and the duct where the turbine is inserted.

In future study, a wider range of geometric variations, new H_1/L_1 ratios or another variables will be indicated, which could serve as constructive recommendations for the OWC device.

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