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Validation and verification of numerical model for simulation of the operating principle of the oscillating water column device

Validação e verificação de modelo numérico para simulação do princípio de funcionamento do dispositivo coluna de água oscilante

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ABSTRACT

Initially, this work presents the validation of an axisymmetric computational model employing the Air-Methodology for the numerical simulation of a sea wave energy converter into electrical energy of the Oscillating Water Column (OWC) type, through experimental results of turbulent flow over a downward step; a characteristic that resembles the airflow within an OWC device. Subsequently, the model was verified with numerical results produced in a study where turbulent airflow over the downward step was simulated, and the validation of these results was also performed with the experimental data previously used. The model that uses $\kappa-\varepsilon$ standard for turbulence, Enhanced Wall Function as the wall function, and SIMPLE for pressure-velocity coupling, achieved a processing time of approximately 30 min and presented an average Mean Absolute Error (MAE) value of 1.25% during validation. In verification, the MAE was less than 4% for the *x*-component and less than 1.5% for the *y*-component.

Keywords: Computational modeling; Wave energy; Validation; Verification

RESUMO

Inicialmente, este trabalho apresenta a validação de um modelo computacional axissimétrico empregando a Metodologia Ar para a simulação numérica de um conversor de energia das ondas do mar em energia elétrica do tipo Coluna de Água Oscilante (CAO), através de resultados experimentais de um escoamento turbulento sobre um degrau descendente; característica essa que se assemelha ao escoamento do ar no interior de um dispositivo CAO. Posteriormente, o modelo foi verificado com os resultados numéricos produzidos em um estudo onde o escoamento de ar turbulento sobre o degrau descendente foi simulado e a validação destes resultados também foi realizada com os dados experimentais previamente usados. O modelo que utiliza $\kappa - \varepsilon$ padrão para turbulência, a *Enhanced Wall Function* como função de parede e o SIMPLE para o acoplamento pressão velocidade, atingiu um tempo de processamento de aproximadamente 30 min e apresentou um valor médio para o Erro Absoluto Médio (MAE) de 1,25% na validação. Na verificação o MAE foi inferior a 4% para componente *x* e menor que 1,5% para componente *y*.

Palavras-chave: Modelagem computacional, Energia das ondas; Validação; Verificação

1 INTRODUCTION

According to Jenniches (2018), the transition of the global electrical energy system to matrices based on renewable sources is one of the main trends today, since, in addition to reducing the emission of polluting gases generated by the current model, it allows not only the diversification of energy production but also its decentralization. At the same time, the extraction of energy from the sea waves presents itself as a possible alternative to the increase in demand for electrical energy, as its global resource is approximately 32,000 TWh/year on the high seas (Reguero et al., 2015).

Several technologies have been proposed for converting sea wave energy into electrical energy; however, there is still no consolidated technology. Among the proposed technologies, the Oscillating Water Column (OWC) converter is one of the most promising. These devices have been studied by several authors due to their robustness and simplicity, essential characteristics for energy extraction in an environment as hostile as the sea. It is worth noting that a large part of the wave energy converter prototypes deployed at sea and that effectively generated electricity are OWC devices (Falcão and Henriques, 2016).

The operating principle of OWC converters can be computationally modeled using different approaches, being possible to highlight the VOF Methodology, Piston Methodology, and Air-Methodology. The VOF Methodology uses the multiphase Volume of Fluid (VOF) model to simulate a wave channel where the converter is inserted, considering the interaction of the water and air phases in the generation of waves that impinge on the OWC device (Gomes et al., 2018; Marjani et al., 2008).

The Piston Methodology is based on the fact that the movement of the water surface inside the OWC converter can be treated as a flat piston moving vertically. This methodology uses a mobile mesh and does not require a wave channel (Marjani et al. 2008; Brendmo et al., 1996). Finally, the Air-Methodology, like the Piston Methodology, only considers the converter and the air flow inside it. However, in this approach, the air flow is reproduced through a sinusoidal equation, representing the variation in the vertical velocity of the air flow caused by the movement of the water surface at the entrance to the domain (Barakaz and Marjani, 2021; Conde and Gato, 2008).

In this context, the present proposal has as goal the validation and verification of an axisymmetric computational model using the Air Methodology for the numerical simulation of an OWC type converter. The validation was carried out using experimental data obtained by Driver and Seegmiller (1985), while the verification was carried out using numerical results produced by Conde (2007). Stands out, that the geometric shape of the OWC device studied in this work, for being symmetrical, allows the application of the axisymmetric boundary condition, resulting in a two-dimensional domain with a descending step. Inside it, a turbulent airflow is imposed, reproducing in an adequate way the characteristics of the problem studied both in Driver and Seegmiller (1985) and in Conde (2007).

2 THEORETICAL REFERENCE

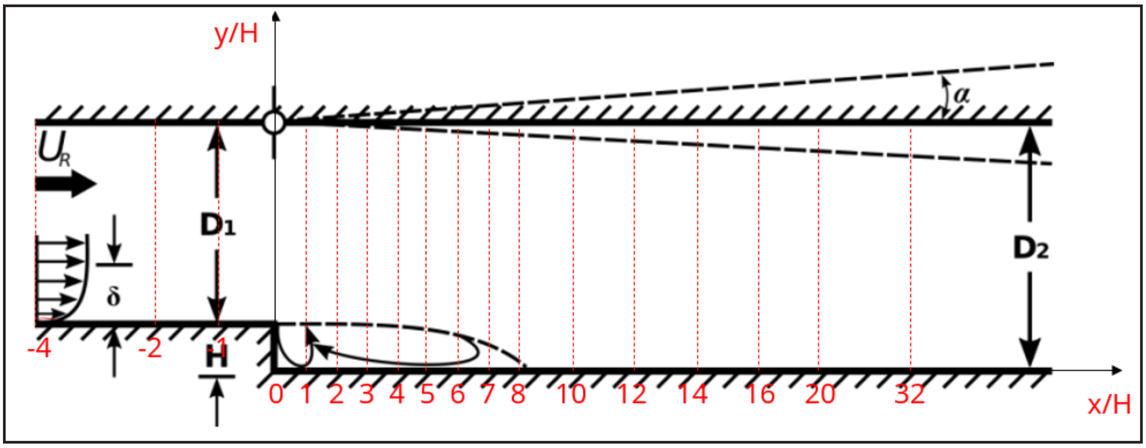
2.1 Oscillating Water Column (OWC)

According to Falcão and Henriques (2016), among the existing technologies for converting sea wave energy into electricity is the OWC device, which is fundamentally composed of a hydropneumatic chamber and a duct where a turbine and an electric generator are coupled. The chamber is opened below the free surface of the seawater, while the turbine duct is opened to the atmosphere. The oscillating movement of the free water surface within the chamber, generated by incident waves, can be considered as a piston-like motion that compresses and decompresses the air and causes an alternating airflow through the turbine, powering the electric generator.

2.2 Experimental study by Driver and Seegmiller (1985)

In Driver and Seegmiller (1985) an experiment was conducted on an internal turbulent, incompressible, and steady airflow over a descending step within a two-dimensional domain. The domain's geometry and the flow conditions are defined according to Case C30 from the Ercoftac Classic Database, as depicted in figure 1.

Figure 1– Flow geometry over a descending step



Source: Adapted from Driver and Seegmiller (1985)

As we can observe in figure 1, Driver and Seegmiller (1985) conducted measurements of the components of mean velocity and Reynolds stresses using Laser Doppler Anemometry (LDA) at various cross-sections.

The experimental tests conducted by Driver and Seegmiller (1985) were carried out in a wind tunnel with a cross-sectional area of 15.1 × 10.16 cm² (D_1 = 10.16 cm, D_2 = 11.37 cm). The descending step, with a height H = 1.27 cm, is positioned 1 m downstream from the tunnel's inlet section. In this section, an abrasive strip, 12.5 cm in length across the tunnel's entire width, was installed to ensure the complete turbulence of the boundary layer upstream of the step. The experiment was conducted at a constant, undisturbed flow velocity of *UR* = 44.2 m/s and at ambient pressure and temperature. These conditions correspond to a Mach number of M_a = 0.128. The boundary layer thickness at the wall was δ = 1.9 cm, and the Reynolds number was R_e = 5000, at the section located at a distance of 4*H* upstream of the step. This high Reynolds number was chosen to ensure that the boundary layer was fully turbulent upstream of the step.

2.3 Numerical study by Conde (2007)

Validation and verification of turbulent flow over a descending step were addressed in Conde (2007). To do so, simulations were conducted using the commercial code FLUENT, employing the Reynolds equations and the Spalart-Allmaras one-equation turbulence model. The convective terms were interpolated using the UDS and/or QUICK schemes.

For validation, simulations were conducted under three conditions based on the choice of interpolation schemes for the convective term: A - UDS scheme in the momentum equations and modified turbulent viscosity equations; B - QUICK scheme in the momentum equations and modified turbulent viscosity equations; C - QUICK scheme in the momentum equations and UDS scheme in the modified turbulent viscosity equation. The validation was performed by comparing the velocity component profiles and the evolution of pressure and wall shear stress obtained from approaches A, B, and C with the experimental results of Driver and Seegmiller (1985).

The verification process only considered the verification of calculations. As defined in Conde (2007), the verification of the calculations consists of determining an estimate of the error of a numerical solution for which the exact solution is usually unknown. The errors verified were: rounding, iterative and discretization.

Conde (2007) concluded in the validation that the turbulence model used is not the most appropriate to simulate this flow correctly. When higher order schemes are used for velocity components, the use of first order interpolation schemes to turbulent viscosity gives rise to the degradation of the convergence order. During verification, it was found that, for this error to be negligible in estimating the discretization error, it is necessary for the residual to be less than 10^{-5}. Adopting double precision reduces rounding errors. The iterative error was evaluated using the maximum and L_2 standards, concluding that the residual normalized is not a good estimate of the iterative error, which can be several orders of magnitude higher.

3 MATERIALS AND METHODS

For defining the computational approach, combinations were made among two turbulence models (standard *k-ε* and *k-ω* SST), three wall functions (Standard Wall Function, Scalable Wall Function, and Enhanced Wall Treatment), and four solution schemes for pressure-velocity coupling (SIMPLE, SIMPLEC, PISO, and Coupled), resulting in 16 different computational models (see table 1). All combinations from table 1 were simulated using the FLUENT software, which is based on the Finite Volume Method (FVM), and analyzed during the validation and verification processes.

The use of the Air-Methodology in the numerical simulation of an OWC type converter reduces the problem to a domain with only the geometric configuration in which turbulent internal airflow occurs, i.e., the chamber and turbine duct. In addition, the application of the axisymmetric condition in the computational modeling of the OWC converter enables the utilization of a two-dimensional domain with a descending step. Considering the converter's operating principle, it is possible to utilize a prescribed velocity as an inlet boundary condition in the domain to represent the piston-like motion caused by the incidence of waves inside the device (Conde and Gato, 2008; Gomes et al., 2009). At the outlet, imposing a prescribed pressure is an appropriate boundary condition since many OWC devices have one or more openings to the atmosphere through the turbine duct, where the pressure is atmospheric. Characteristics such as the domain shape, flow, and boundary conditions were defined based on the experiment conducted by Driver and Seegmiller (1985), which were then used in the validation process of the proposed computational model. Meanwhile, the numerical results from Conde (2007) were adopted for verification purposes.

Table 1– Tested numerical models

Model	Turbulence model	Wall function	Pressure-Velocity
1	*k-ε* Standart	Standart Wall Function	SIMPLE
2	*k-ε* Standart	Standart Wall Function	SIMPLEC
3	*k-ε* Standart	Standart Wall Function	PISO
4	*k-ε* Standart	Standart Wall Function	Coupled
5	*k-ε* Standart	Scalable Wall Function	SIMPLE
6	*k-ε* Standart	Scalable Wall Function	SIMPLEC
7	*k-ε* Standart	Scalable Wall Function	PISO
8	*k-ε* Standart	Scalable Wall Function	Coupled
9	*k-ε* Standart	Enhanced Wall Function	SIMPLE
10	*k-ε* Standart	Enhanced Wall Function	SIMPLEC
11	*k-ε* Standart	Enhanced Wall Function	PISO
12	*k-ε* Standart	Enhanced Wall Function	Coupled
13	*k-ω* SST	-	SIMPLE
14	*k-ω* SST	-	SIMPLEC
15	*k-ω* SST	-	PISO
16	*k-ω* SST	-	Coupled

Source: authors

3.1 Numerical and mathematical modeling

In the numerical simulations, carried out to choose the computational model, we considered the case in which the upper part of the domain, under which the flow occurs, is horizontal ($\alpha = 0°$, see figure 1) and the coordinates were non-dimensionalized by the step height H (see figure 2) and the velocity components by the input velocity UR. The origin of the reference frame was placed at the bottom corner of the step, thus, it was considered that horizontally, the domain extends between $-4 < x/H < 40$, and vertically between $0 < y/H < 9$, as indicated in figure 2. These parameters were also adopted by Conde (2007).

Figure 2 – Domain dimensions and boundary conditions

Source: authors

As an input condition, a prescribed velocity profile was imposed associated with profiles of the turbulence model components, namely the turbulence kinetic energy and its dissipation rate. These profiles were obtained through a nonlinear regression of the data provided by the Ercoftac Classic Database. The equations obtained through the nonlinear regressions for the velocity components in the *x* and *y* directions are, respectively:

$$-0.0022956663298533 \cdot x^4 + 0.0459133265968655 \cdot x^3 - 0.330137805122879 \cdot x^2 + 1.00571172139281 \cdot x - 0.0919694 \quad (1)$$

$$0.0000199245919909929 \cdot y^6 - 0.000597716715593032 \cdot y^5 + 0.00697960006443858 \cdot y^4 - 0.0399742729349031 \cdot y^3 + 0.115910848190383 \cdot y^2 - 0.156557872675175 \cdot y + 0.0771151900 \quad (2)$$

Similarly, profiles for turbulent kinetic energy, *k*, and its dissipation rate, ε and ω, respectively for the *k-ε* and *k-ω* models, were obtained. The equations used in the calculation of these components are presented in Wilcox (2006) and Fluent 12.0 User's Guide (2009), as follows:

$$k = \frac{1}{2}\overline{u_i'u_i'} = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2}\right) \quad (3)$$

It's important to highlight that the components *u'* and *v'* were also obtained through nonlinear regression, which determined the following equations for *u'* and *v'*, respectively:

$$0.000516272215904262 \cdot x^6 - 0.0154881661551041 \cdot x^5 + 0.210954169937989 \cdot x^4 - 1.63772240590646 \cdot x^3 + 7.37947196589691 \cdot x^2 - 17.7222089754555 \cdot x + 17.7175125944245 \quad (4)$$

$$-0.00131192632592806 \cdot y^6 + 0.0393577896838819 \cdot y^5 - 0.452382962188429 \cdot y^4 + 2.48802763946156 \cdot y^3 - 6.52185208317185 \cdot y^2 + 6.41345480846206 \cdot y + 0.606311602601004 \quad (5)$$

while the turbulent dissipation rate is given, respectively, for the *k-ε* and *κ-ω* models, by:

$$\varepsilon = C_\mu^{3/4} \frac{k^{3/2}}{l} \quad (6)$$

$$\omega = \frac{k^{1/2}}{C_\mu^{1/4} l} \quad (7)$$

where C_μ is a constant whose value, for the standard model, is 0.09, and *l* represents the turbulent length scale (FLUENT, 2012).

To insert prescribed speed, turbulent dissipation rate, and turbulent kinetic energy, a TableData file was created, with the positions of the mesh nodes along the *y/H* direction that belongs to the *x/H* = -4 cross section, together with the speed and turbulence information for each node.

Additionally, a prescribed pressure of 101325 Pa, representative of the atmospheric pressure, was imposed as outlet boundary condition. For the remaining boundaries, a wall condition was applied, meaning no-slip and impermeability.

For calculating the error, the Mean Absolute Error (MAE)) was used as a measure to quantify the error generated in the comparisons, given by (Hulland et al., 2010):

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|x_{ref,i} - x_{obt,i}\right| \tag{8}$$

where *n* is the total number of samples analyzed, *i* is the specific sample number being analyzed, x_{ref} represents the reference data, and x_{obt} represents the obtained data.

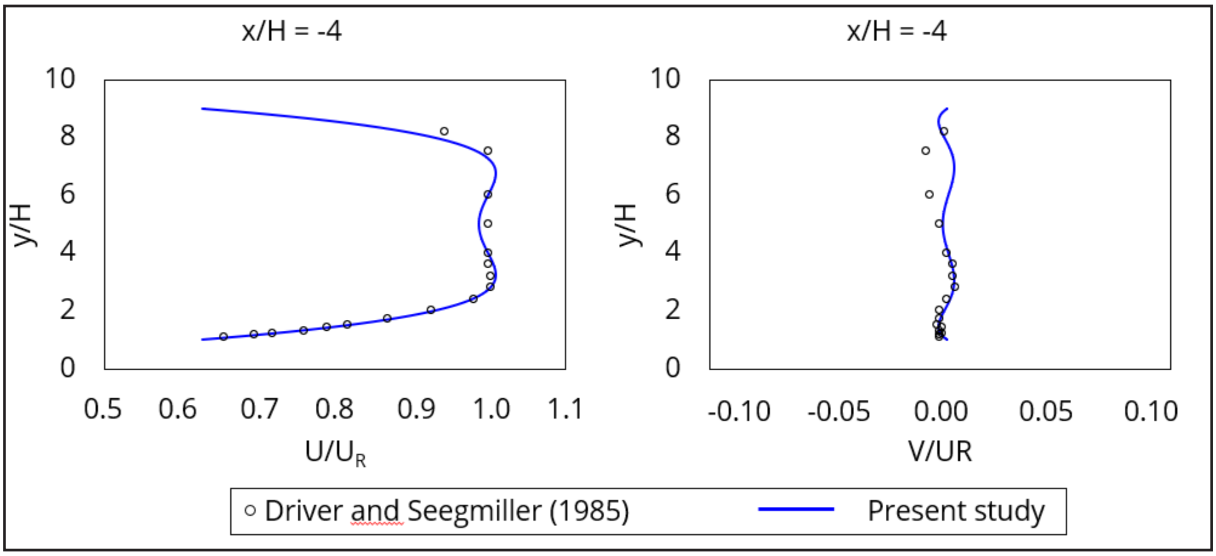
Regarding the mesh, it was constructed in Designer Modeler software and consists of structured quadrilateral cells with uniform spacing in the *x*-direction where 100 nodes were inserted, as recommended in Kim et al. (2007). Vertically, there are three parts: the upper wall region, lower wall region, and central region, each with 30 nodes, totaling 90 nodes in this direction. This discretization strategy for the walls was adopted to capture and correctly resolve the physics of flows, considering the separation of the boundary layer.

4 RESULTS AND DISCUSSION

In figure 3, the curves of the velocity components in *x* and *y*, obtained from equations through nonlinear regression, are compared with the experimental data of Driver and Seegmiller (1985) corresponding to the cross-section x/H = -4.

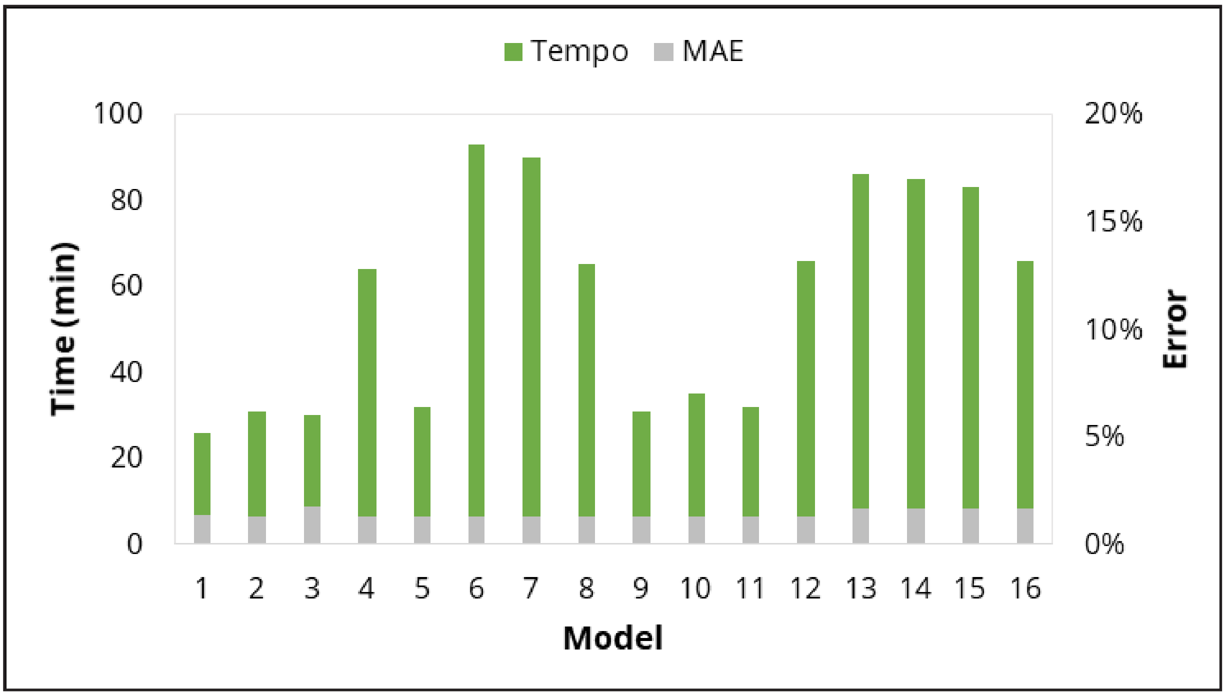
It can be observed in figure 3 that the curves show good agreement with the experimental data.

Figure 3 - Velocity components at the domain's inlet section



Source: authors

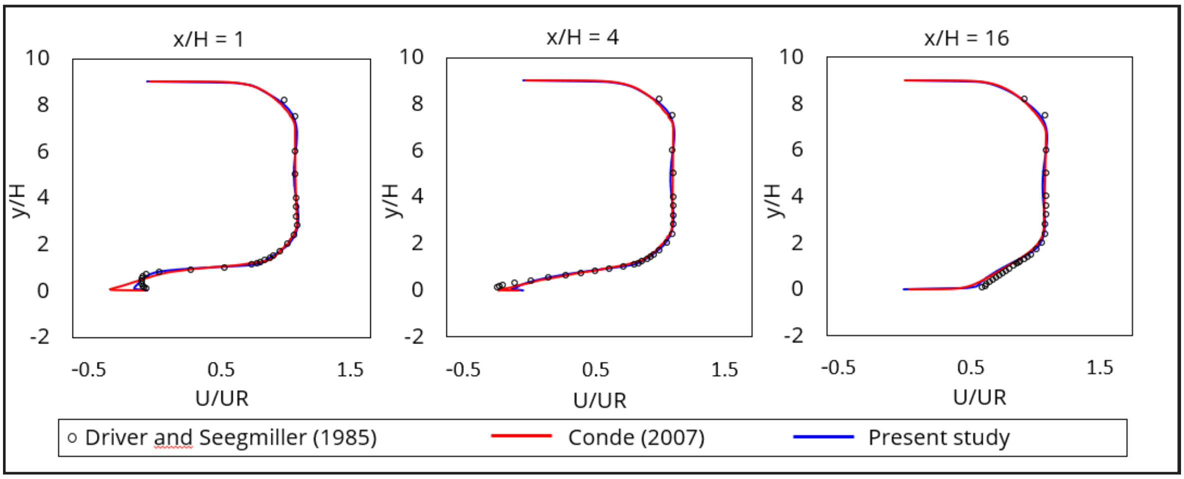
Figure 4 – Comparison among the models



Source: authors

It is noticeable in figure 4 that models 1, 2, 3, 5, 9, and 11 converged more rapidly, reaching approximately 30 min of processing time. It is also noticeable that all models achieved a similar MAE value, below 2%. However, models 9, 10, and 11, when their velocity results in *x* and *y* were compared to the experimental data, achieved the lowest error (1.25%), calculated using the *MAE* statistical indicator. Therefore, considering the shortest processing time (31 min), model 9 was selected and adopted for the verification stage against the work developed by Conde (2007). The horizontal velocity profiles are depicted in figure 5, showcasing the curves of the experimental data produced by Driver and Seegmiller (1985), numerical data from the work of Conde (2007), and the data from this study (using model 9) for the cross-sections of *x*/*H* = 1, 4, and 16. In a similar way

Figure 5 - Comparison among the horizontal velocity profiles



Source: authors

It is possible to observe in figure 5 a good agreement between the results of this study, obtained with model 9, when compared to the numerical solutions achieved by Conde (2007) and also with the experimental data of the Driver and Seegmiller (1985), it is noteworthy that the speed data from Driver and Seegmiller were included in figures 5 and 6 for the purpose of conference, since both the present study with Conde (2007) validated their experiments with such data.

To substantiate the accuracy of the verification, the MAE error was calculated between the present study and Conde (2007) for each cross-section presented in figure 5, and also between the present study and the experimental data of the Driver and Seegmiller (1985), which can be found in table 2. In table 2, there are also the MAE values for the velocity component in *x* an *y* for the same cross-sections.

Table 2 – MAE of velocity components from the present study in relation to numerical (Conde, 2007)and experimental(Driver and Seegmiller, 1985) data

x/H	MAE for *x* component		MAE for *y* component	
	Conde (2007)	**Driver and Seegmiller (1985)**	**Conde (2007)**	**Driver and Seegmiller (1985)**
1	3.63%	2.10%	0.13%	0.66%
4	2.95%	3.91%	0.19%	1.33%
16	0.04%	3.35%	0.00%	0.71%

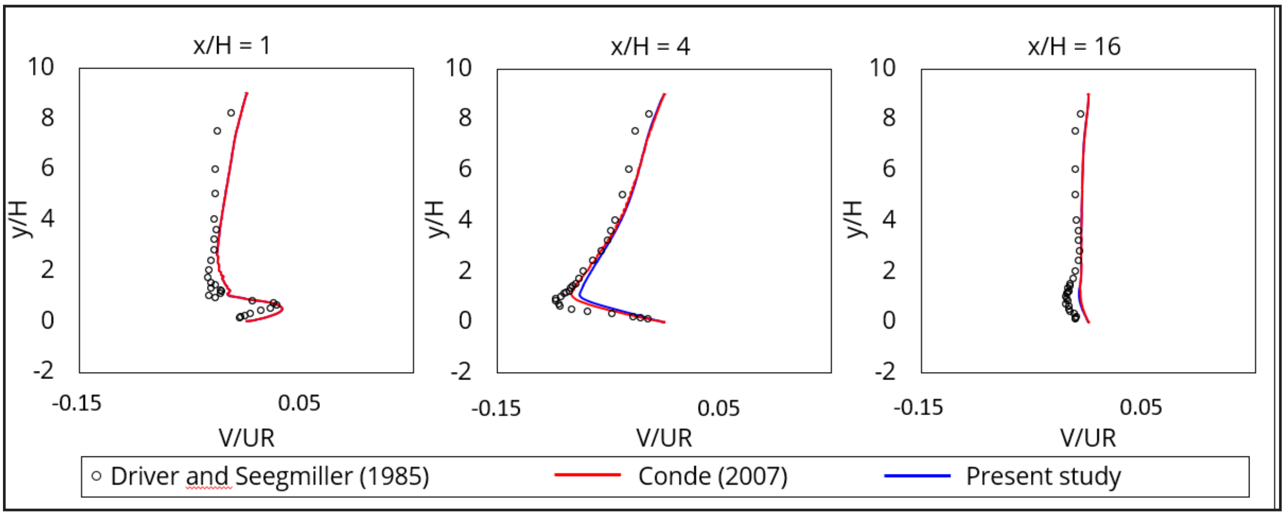
Source: authors

Table 2 shows that the error in the results for the *x* component of velocity in the present study is less than 4% when compared with the results of Conde (2007) and less than 0.2% for the *y* component of velocity. When comparing the results of the present study with the experimental data of Driver and Seegmiller (1985), the error remains less than 4% for the *x* component and less than 1.5% for the *y* component.

In a similar way, the results obtained for the vertical velocity components at the cross-sections where *x/H* = 1, 4, and 16 are displayed in figure 6.

Figure 6 shows how close the results of the present study are to the numerical results of Conde (2007), since in certain regions the curves overlap. In relation to the experimental data of Driver and Seegmiller (1985), the present study presents a more apparent difference in the cross section *x/H* = 4, however this difference is smaller at 1.5%, as can be seen in table 2.

Figure 6 – Comparison among the vertical velocity profiles



Source: authors

5 CONCLUSION

In this article, the validation and verification of an axisymmetric computational model were conducted to numerically simulate turbulent airflow in a two-dimensional domain containing a descending step. Inside an OWC device, turbulent airflow occurs when employing the Air-Methodology, and its shape resembles a two-dimensional domain with a descending step when the axisymmetric condition is applied.

In validation, model 9 stood out by achieving the lowest average MAE value of 1.25% and the shortest processing time of approximately 30 min when compared to the experimental data from Driver and Seegmiller (1985). Model 9 employs the standard *k-ε* turbulence model, Enhanced Wall Function as the wall function, and SIMPLE for pressure-velocity coupling. Thus, this computational model was used in the verification stage, where the results of the *x* and *y* velocity components, dimensionless by the reference velocity *UR* = 44.2 m/s, were compared with numerical data presented in Conde (2007), yielding an average MAE of 2.53%.

These results indicate that the proposed axisymmetric computational model has been validated and verified for unidirectional airflow. In future work, this computational model will be evaluated in the numerical simulation of airflow that alternates its direction over time.

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