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NUMERICAL SIMULATION AND SOLUTION VERIFICATION OF AN OVERTOPPING DEVICE

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Abstract. *This study refers to numerical simulation and solution verification of an equipment used to convert ocean wave energy to electrical energy. This equipment is an overtopping device, which forces the break of the wave over a ramp storing water in a reservoir to feed a set of low head turbines. Present paper contributes to the current state of art of ocean wave energy converters (OWECs) pointing OpenFOAM as a considerable tool to predict ocean wave comportment by comparing its results with ANSYS FLUENT ones. Therefore, it has been used the finite volume method applying volume of fluid methodology, modeling the problem as an unsteady 2D multiphase (air and water) flow. It has been estimated the total mass inside the reservoir of seven different ramp configurations (H/L) for a constant depth (5 m). Regardless of the differences between these software, this study presents the simultaneity of water overtopping for both solutions and similar trend lines regarding water storage in respect to H/L.*

Keywords: *Ocean energy, Renewable energy, Multiphase flow, VOF, OpenFOAM.*

1 INTRODUCTION

An overtopping device is a manner to classify Ocean Wave Energy Converters (OWECs) which concept is storing water arising from the wave overtopping to feed a set of low head turbines. An example of this equipment, the Wave Dragon (www.wavedragon.net), was built with two reflectors focusing the wave towards a ramp followed by a reservoir – the wave breaks on the ramp and fills up the reservoir. Although it has seemed promising, it is still in prototype stage (Kofoed et al., 2006, Tedd and Peter Kofoed, 2009), what motivates studies around its performance. In addition to that, points out the rise of numerical models usage in ocean field, amidst them there is the volume of fluid (VOF) (Hirt and Nichols, 1981), a technique used for immiscible multiphase systems which has the advantage that only one set of Momentum and Continuity equations is solved for all fluids. Fluid flow problems are unusually solved with the Finite Volume Method (Versteeg and Malalasekra, 2007), in this work, OpenFOAM and ANSYS FLUENT was applied to get the simulations results.

WECs have been deeply studied lately due to global efforts on renewable energy researches. In the context, Xie and Zuo (2013) reviewed dynamics characteristics about the three most major types of WECs (oscillating water column, overtopping and oscillating-body) and methods of control (latching control, declutch control, reactive control, model predictive control and state space control). Teixeira et al. (2013) used a numerical code (Fluinco) based on the semi-implicit Taylor-Garlekin method to study the interaction between ocean waves and an oscillating water column device (OWC), including aerodynamic effect inside its chamber, and compared these with ANSYS FLUENT results. Gomes et al., (2012) optimized a 2D laboratory scale OWC applying Constructal Design under ANSYS FLUENT simulations. In this context, mentions that OpenFOAM has been considered a good tool on wave phenomena applications (Higuera et al., 2013).

Although there are few analytic methods to calculate the overtopping of marine structures, there is lack of information about overtopping devices. How ever, numerical field has been presenting good related results. Liu, Z. et al. (2008) studied the overtopping device performance using ANSYS FLUENT. Goulart, (2014) have applied the Constructal Design in a 2D overtopping device model to find out the optimum ramp configuration for various depths. In his work, it has been used ANSYS FLUENT to register the total mass of water entering in the reservoir. Nam, B. W et al. (2008) carried out simulations using the commercial program FLOW3D based on the Finite Difference Method (FDM) to find the optimal design of a spiral-reef overtopping device. Jin, J. et al. (2012) performed a numerical study similar to Nam's, however, it was a 3D application. Beels, C. et al. (2010) used a numerical model called mild-slope to solve transient flow in Wave Dragon farm, concluding an efficient arrangement of five devices.

This study refers to numerical solution and results verification of an Overtopping device regarding the mass flow towards the reservoir. VOF model was used to formulate and solve the problem using ANSYS FLUENT and OpenFOAM with identical meshes and boundary condition. A more detailed view about the model is presented later on covering domain's dimension, solvers and interpolation schemes. The main goal of this study is to verify previous solutions obtained with ANSYS FLUENT by presenting OpenFOAM as an efficient tool for ocean engineering applications. After this brief introduction over the current numerical scenario of WECs follow mathematical and numerical modeling, problem description, and results.

2 MATHEMATICAL AND NUMERICAL MODELING

The wave modeling is considered here as an unsteady 2D incompressible laminar free-surface flow. Therefore, follow the governing equations of the problem, which are conservation of mass (continuity) (Eq. (1)) and conservation of momentum (Eq. (2), Eq. (3)):

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u)+\frac{\partial}{\partial x}(\rho uu)+\frac{\partial}{\partial z}(\rho uw)=F_x-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

$$\frac{\partial}{\partial t}(\rho w)+\frac{\partial}{\partial x}(\rho wu)+\frac{\partial}{\partial z}(\rho ww)=\rho g_z+F_z-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial z^2}\right) \tag{3}$$

where ρ is the fluid density (kg/m³); u is the velocity component in horizontal direction (x); w is the velocity component in vertical direction (z) (coincident with gravity direction); g is gravity acceleration (m/s²); F_x and F_z are external body forces (N); and μ is the dynamic viscosity of the fluid (Pa·s).

In agreement with VOF methodology, a transport equation for the volume fraction is solved within Eqs. (1)-(3). This equation is given by Eq. (4), where α is the volume fraction of the water phase.

$$\frac{\partial(u\,\alpha)}{\partial x}+\frac{\partial(v\,\alpha)}{\partial y}=0 \tag{4}$$

In VOF, only one set of momentum and continuity equations are solved for all fluids (in this case water and air), thus it is necessary to average density and viscosity in Eqs. (1) -(3), for that it is used Eqs. (5) and (6).

$$\rho=\alpha\rho_{water}+(1-\alpha)\rho_{air} \tag{5}$$

$$\mu=\alpha\mu_{water}+(1-\alpha)\mu_{air} \tag{6}$$

The computational domain is shown in Fig 1. In this figure, the tank, device and boundary conditions are schematically represented. Wave generation is obtained using a wave-function for the left (under water) boundary condition, which in this study is given by the second order Stokes theory velocity profile (Eqs. (7) and (8)) (Dean and Dalrymple, 1991). Where h is the water level (m), H the wave height (m), k is the wave number and σ is the frequency (1/s).

$$u=\frac{Hgk\cosh k(h+z)}{2\sigma\cosh(kh)}\cos(kx-\sigma t)+\frac{3H^2\sigma k\cosh 2k(h+z)}{16\sinh^4(kh)}\sin 2(kx-\sigma t) \tag{7}$$

$$w=\frac{Hgk\sinh k(h+z)}{2\sigma\cosh(kh)}\cos(kx-\sigma t)+\frac{3H^2\sigma k\sinh 2k(h+z)}{16\sinh^4(kh)}\cos 2(kx-\sigma t) \tag{8}$$

Equations (1)–(3) are solved by means of two CFD packages based on finite volume method, ANSYS FLUENT (ANSYS, 2009) and OpenFOAM (*OpenFOAM User Guide*, 2011), using the VOF method to model the interaction between air and water. Both solvers are pressure based, although the velocity-pressure coupling is performed by PISO algorithm in

FLUENT simulations and PIMPLE, that mixes PISO and SIMPLE (Jasak, H., 1996), in OpenFOAM. Table 1. shows the interpolation schemes used for pressure, momentum and volume fraction in FLUENT and OpenFOAM. Present solutions are considered converged when the residual values are lower than 10^{-6}.

Table 1. interpolation schemes for advective terms

Interpolation schemes	FLUENT	OpenFOAM
Pressure	PRESTO!	Gauss linear
Momentum	First order upwind	Gauss linear
Volume Fraction	Geo-reconstructed	Gauss Interfacecompression

All the simulations have been performed at Laboratory of Numerical Simulation of FURG (www.labsin.furg.br).

3 PROBLEM DESCRIPTION

Current computational domain has been conceptualized under Constructal Design (Bejan, 2012; Rocha et al., 2009), which states that fluxes systems that are free to vary its own geometry will do it maximizing the flux through the media. Thus, it has been given degrees of freedom to the device's ramp under one constrain (the ramp area must be constant) (Goulart, 2014). Fig. 1 shows the domain, its boundary conditions, and general dimensions.

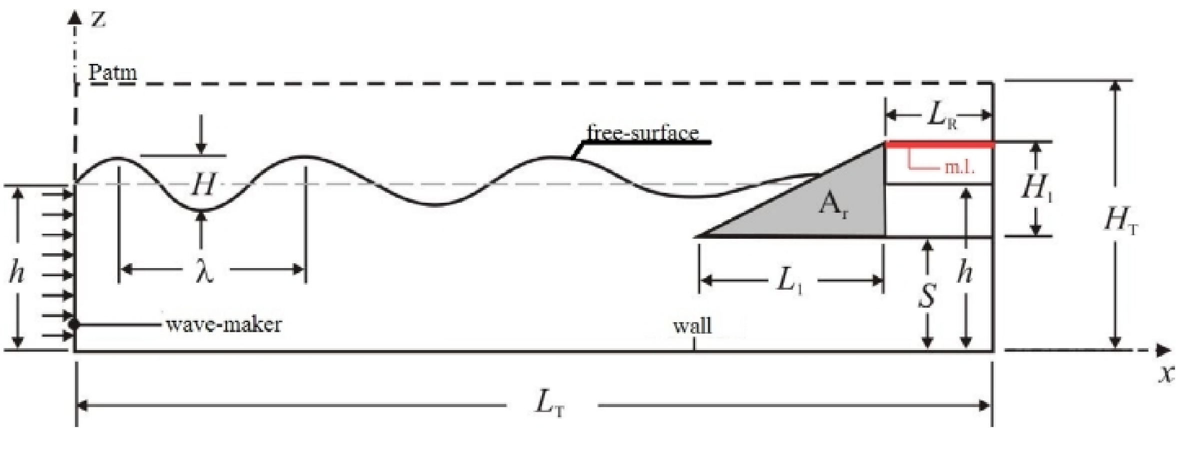

Figure1. The overtopping device domain with its general dimensions.

The domain is a three-hundred-twenty-seven-meter wave tank (L_t) with an overtopping device inside, with one constrain (A_r = 80 m²) and two degrees of freedom (L_1 and H_1). It is ten-meter depth (h) and the device is located five meters up the floor (S = 5 m). The reservoir positions coincides with the water level (h) and covers 20 m (L_r). The tank and the device have been set as wall no-slip boundary condition, with the wave-maker exception that is shown in Fig. 1., the total height (H_T) is 20 m and the tank is under atmospherics pressure (P_{atm}).

The device's dimensions are though treated in terms of its ratio (H_1/L_1). This paper considers the following ratios: 0.22, 0.24, 0.26, 0.28, 0.30, 0.32 and 0.34; resulting in seven different geometry results regarding the water flow in 94 seconds of simulation. These geometries has been selected considering their performance; the simulation duration takes into account the instant of water overtopping pause. In order to obtain the total mass inside the reservoir it is calculated the integral of the mass flow rate ($\dot{m}$) that is given by a monitoring line (m.l. at Fig. 1, marked in red) at the reservoir top by calculating Eq. (9) at each time-step; u_z is velocity in z direction, and a is the finite volume normal area. Once this methodology is applied, the velocity direction imposes negative signals to all posterior results which must be seen as absolute quantities; index "i" stands for a particular finite volume at the monitoring line.

$$\dot{m}=\sum_{i}^{n}\left(u_z\cdot\rho\cdot a\cdot\alpha\right)_i \tag{9}$$

Also important to be mentioned that Eq. (9) was implemented in OpenFOAM dictionaries, while in ANSYS FLUENT it has been set a monitoring line of mass flow rate in respect to flow time using its default option; both measures are compared in section 4.

4 DISCUSSIONS AND RESULTS

Firstly, Fig. 2 presents results of Courant Number (Co) independence referring to 100 seconds of simulation (next results are ninety-four-second simulation). Both software user's guide suggest setting Co = 0.5, although it has been noted a two-percent down variation on OpenFOAM results from Co = 0.5 to Co = 0.25 followed by a five-percent up variation from Co = 0.25 to Co = 0.125. Because of OpenFOAM results fluctuation are controlled and likely converged around Co = 0.5 (three-percent more or less), all the simulations were carried out with Co = 0.5. FLUENT results do not showed the same issue, being strait converged between Co = 0.5 and Co = 0.25.

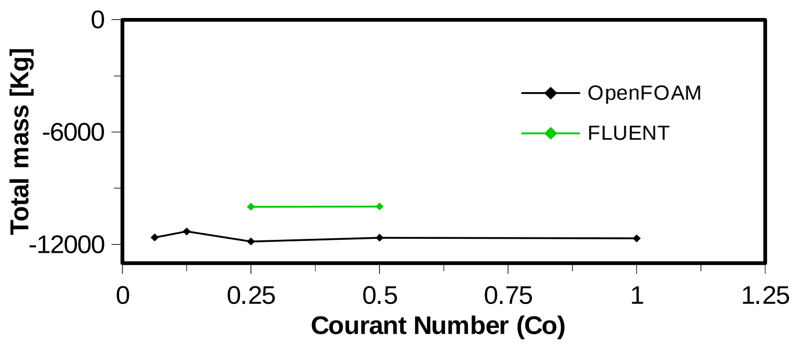

Figure 2. results independence of Courant Number

Figure 3 shows the simultaneity of water overtopping regarding the two software solutions. This verification, allied with Co verification, stands reliability to OpenFOAM solutions and also points out interesting aspects that must be more deeply studied, like the reason why FLUENT mass flow rate measures are more stable regarding reverse flow through the monitoring line than OpenFOAM ones. Although, reverse flow was observed during the simulations, owed to natural water behavior. When the water falls fast in the reservoir, hits against the walls, splashes out from the reservoir and falls back subsequently. When the water reenter in the reservoir it is recounted by the monitoring lines, this is notable in Fig. 3 by the minor precedent mass flow on OpenFOAM results in compresison with FLUENT's.

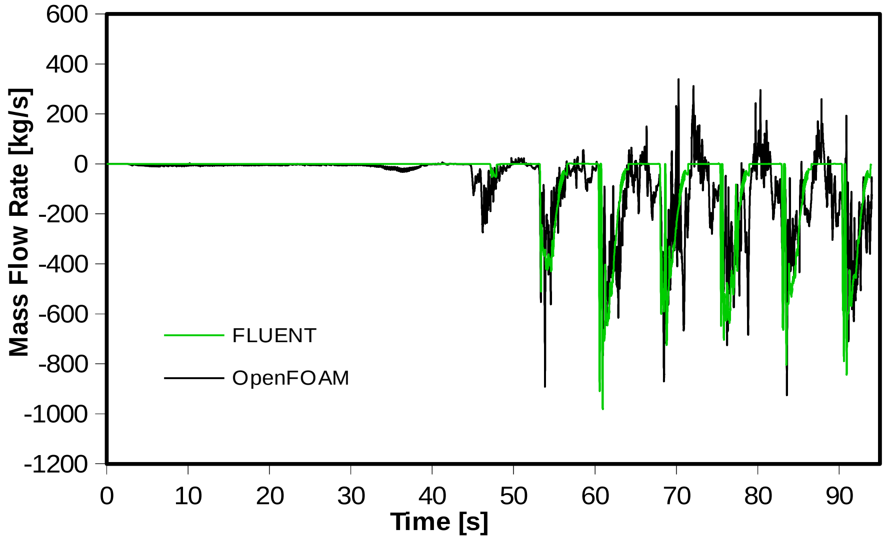

Figure 3. Water overtopping time series for FLUENT and OpenFOAM.

Results for all seven different studied geometries showed similar overtopping time series behavior. Fig. 4 shows the total mass inside the reservoir of each studied ramp geometry; these results were obtained integrating mass flow rate. In agreement with Goulart (2014) checks that the mass of water inside the reservoir gets lower when the ramp's ratio H/L gets higher. It is seen that absolute numerical solution between the two software diverges, and both of them presents point out of tendency (FLUENT in H/L = 0.28; OpenFOAM in H/L = 0.30). The similarity between their trend lines is a very appreciated result which indicates trustfulness on all presented results.

For currently unknown reasons, OpenFOAM total mass solutions are always greater than FLUENT's, indicating effect of software methodology particularities. Although this is not a concern once the solution verification is already done, but motivates further studies about interpolation schemes and mesh size for this specific application.

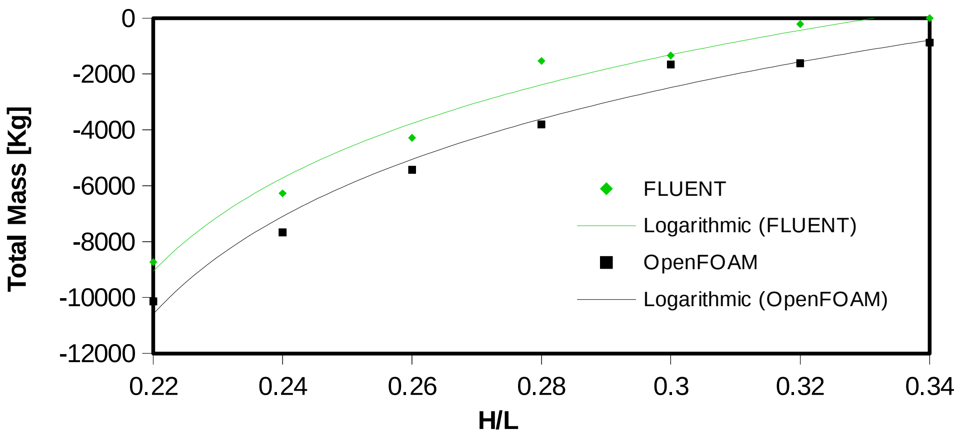

Figure 4. Absolute results of total mass inside the reservoir of all studied ramp geometries.

5 CONCLUSIONS

It was performed numerical simulations of an overtopping device by means of Constructal Design, so that, it was studied seven different ramp configurations (*H/L*: 0.22; 0.24; 0.26; 0.28; 0.30; 0.32, and 0.34) maintaining constant its area. Presented models are 2D unsteady laminar incompressible two-phase flow, in which applies VOF methodology to solve momentum and continuity equations for the two-phase system. Models were processed by ANSYS FLUENT and OpenFOAM with identical mesh and boundary condition set-up in order to verify previous results obtained with ANSYS FLUENT and present OpenFOAM as a powerful tool in ocean engineering research field. The general domain is constituted of an overtopping device contained in a wave-tank, both with real scale dimensions.

Results accuracy under Courant Number influence were tested showing acceptable fluctuation on OpenFOAM results (around 3% from results obtained with Co = 0.5) and FLUENT's strait convergence. This test were presented right before than simultaneity of water overtopping comparison, that measures mass flow rate towards the reservoir by monitoring line registrations, providing results reliability. Once it is seen convergence of overtopping time series and similar magnitude on both software solution, points out that OpenFOAM results seem respond reverse flow through the monitoring more instantaneously. The very last result topic presents the total water inside the reservoirs, what has been obtained by the integral of the mass flow rate. This final result agrees with mentioned studies related to the ramp inclination influence on water storage and demonstrate that OpenFOAM is an efficient toll that provides good results.

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