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Performance of Resonant Chambers in Oscillating Water Column Devices

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Research problem

The utilization of marine power potential in Colombia holds a great promise, and the oscillating water column (OWC) is one option that deserves to be explored. The wave energy conversion process using an OWC typically involves two stages: the conversion of wave power to pneumatic power in an air chamber, and the conversion of pneumatic power to electricity using a self-rectifying air turbine coupled to an electric generator. In order to improve the efficiency of the primary stage, this study is aiming at determining the hydrodynamic performance of an OWC air chamber using a numerical model based on the Reynolds Averaged Navier-Stokes equations and the Volume of Fluid approach for free surface simulation.

Keywords: Gravitational water vortex hydraulic turbine, runner, efficiency, hydropower

Material and methods

Objetive

The focus of this research is on conducting a numerical simulation of the OWC chamber in order to investigate the effect of the geometry on the OWC efficiency. For this purpose, a two-dimensional (2D) numerical simulation was carried out using the ANSYs Fluent software. The response variable was the efficiency of the OWC resonant chamber.

Introduction

An OWC is a highly efficient device used for capturing and extracting the wave energy having many advantages ascribed. It is a simple structure and easy to be manufactured. In addition, the generation of greenhouse gases or significant waste during its operation is limited. The basic design of an OWC consists of a partially submerged structure with a hollow bottom (wave resonant chamber) and an air chamber below the sea level. The movement of the waves creates pressure on the air inside the chamber, which in turn drives a Wells turbine that generates electricity.

The flowchart of study

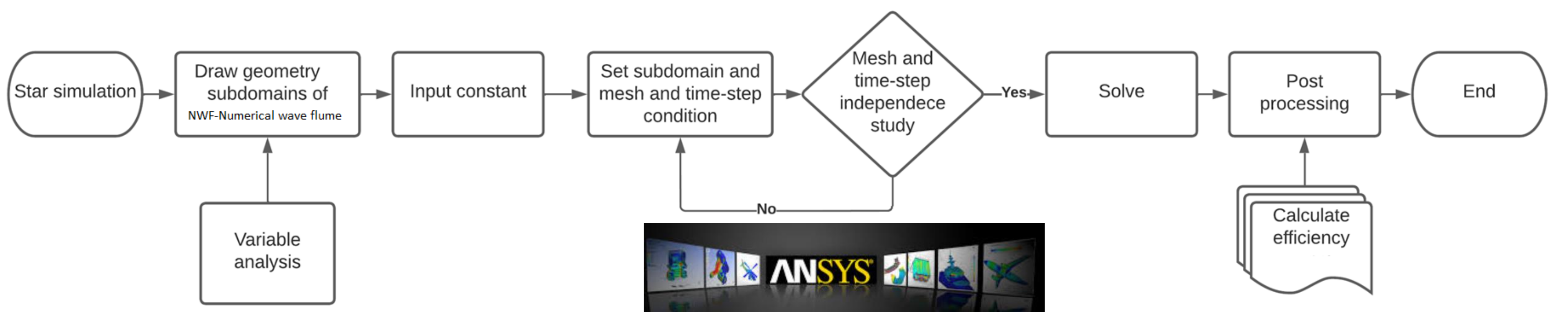
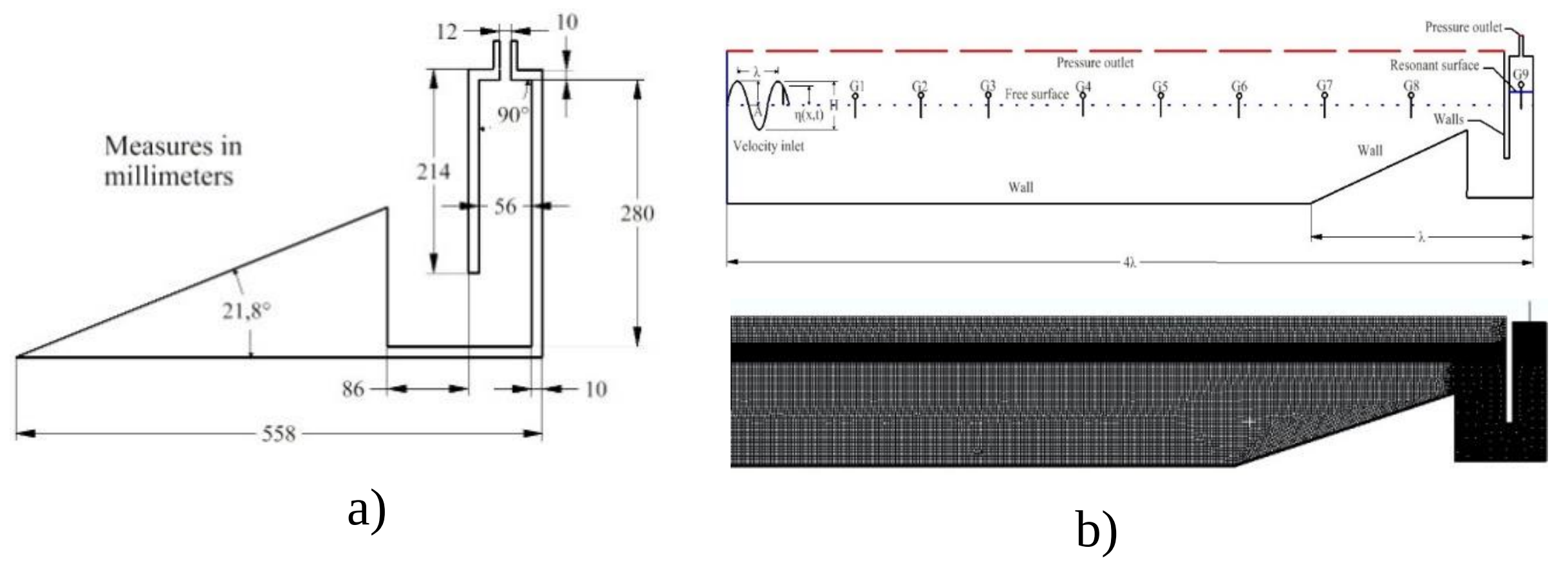


Figure 1. CFD package Ansys Fluent software



a)

b)

Figure 2. a) Geometry of the resonant chamber, b) computational domain

Water surface elevation $\eta(x,t)=\frac{H}{2}\cos(kx-\omega t)$ Equation (1)
Wave height (H), period (T), length (λ), amplitude (A)
Wave number (k)→2π/λ
Angular frequency (ω) →2π/T
Chamber efficiency (ε)
$\varepsilon=\frac{P_{out}}{P_{in}}$ Equation (2)
Incident wave power (P_{in})→ $P_{in}=EC_g$ Equation (3)
$E=\frac{1}{2}\rho g\left(\frac{H}{2}\right)^2$ Total energy per period (E) Equation (4)
$C_g=\frac{1}{2}\frac{\omega}{k}\left(1+\frac{2kh}{\sin(2kh)}\right)$ Group velocity (C_g) Equation (5)
Average pneumatic power obtained at the output of the device (P_{out})
$P_{out}=\frac{1}{T_{end}-T_{ini}}\int_{T_{ini}}^{T_{end}}\Delta P\, S_{schamber}\, V_{fs}\, dt$ Equation (6)
V_{fs} → Velocity of the free water surface
$V_{fs}=\frac{d[\eta(x,t)]}{dt}$ Equation (7)

To simulate the interface between water and air, the Volume of Fluid method was employed with a time-step of 0.001 and a maximum iteration limit of 35, using a convergence criterion of residuals of 10^{-6} [13]. The surface points were set to f=0.5. The regular wave generation was conducted at the left side boundary of the channel, with a wave H of 0.02 m and a λ of 1.47 m. Pressure outlet conditions at the top of the channel and at the air outlet in the resonant wave chamber were set to 0 Pa. The no-slip condition was applied to the bottom of the channel and the walls of the OWC to capture the boundary layer developed between them.

A 2D computational domain was used to perform a fluid dynamic analysis of the resonant wave chamber behaviour. The computational domain boundary conditions are defined in Fig. 1b. To evaluate the chamber efficiency (ε), the water surface elevation and the chamber efficiency are monitored.

Results and discussion

Fig. 3 displays the results of comparing the numerical and analytical assessments of the elevation of the unconfined water surface. The analytical solution was computed using Equation (1).

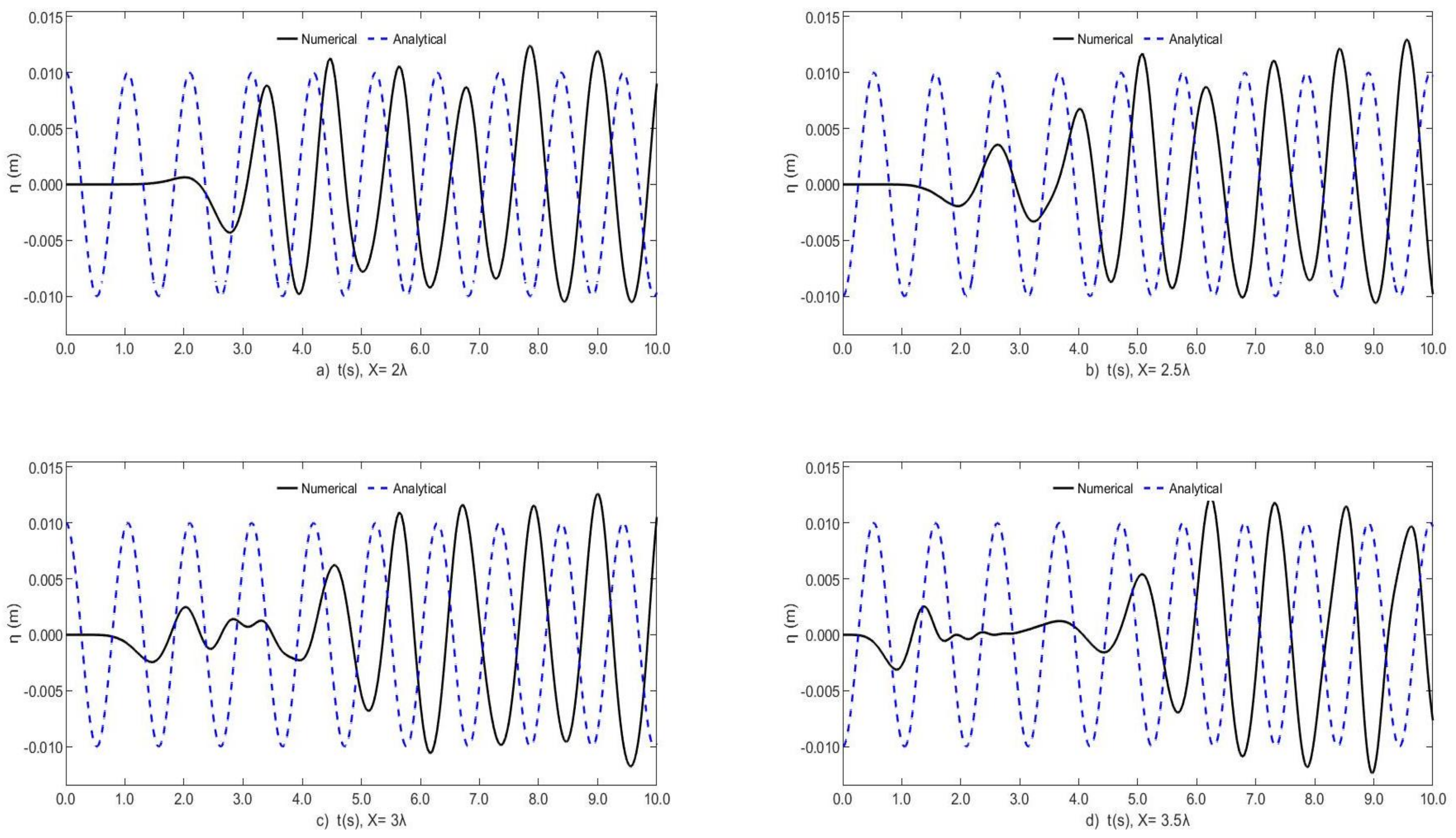


Figure 3. Comparison between the numerical and analytical results to validate the wave for a height (H) of 0.02 m at several distances from the wave generator, including a) X= λ, b) X=1.5λ, c) X=2λ, d) X=2.5λ, e) X=3λ, and f) X=3.5λ

The simulation results at t=15.34 s is presented in Fig. 4. In the figure, the phase contour is illustrated in blue and red colours representing air and water, respectively. The plot highlights the flow characteristics and behaviour of the resonant chamber.

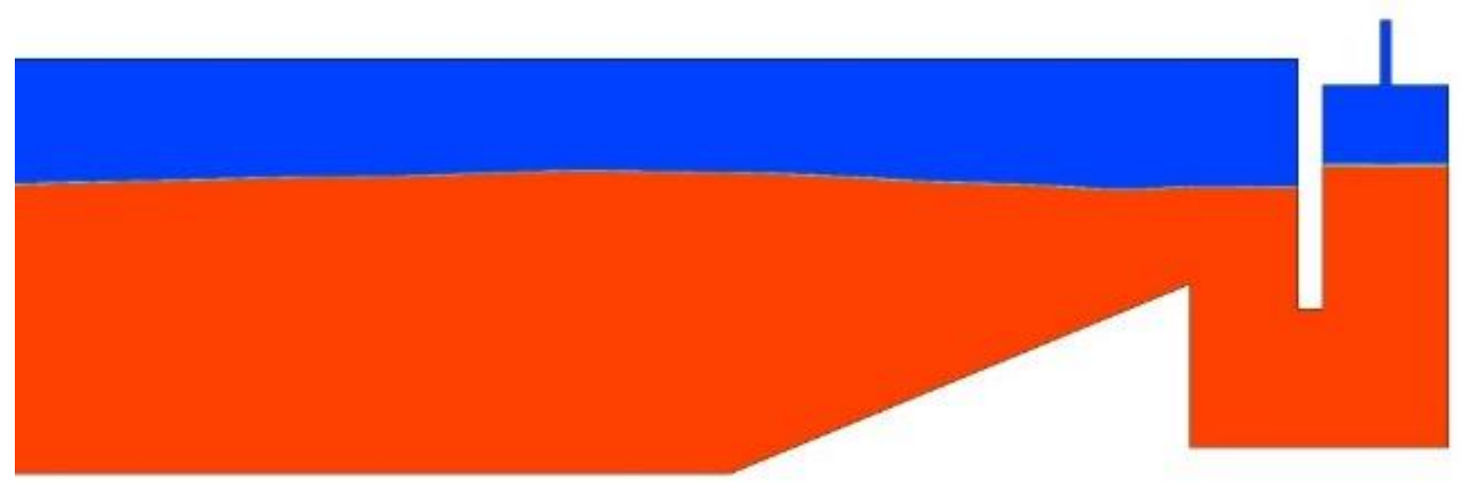


Figure 4. a) Phase contour at t= 15.34 s

Equations (2), (3), and (6) were employed to calculate the efficiency of the wave resonant chamber, which required computing the V_{fs} and ΔP. To determine the OWC ε, it was necessary to quantify the incident wave power utilizing Equation (3). Under the wave conditions studied here, P_{in} was determined to be 0.504 W. Similarly, Equation (6) was employed to compute the pneumatic output power, requiring the numerical determination of ΔP and V_{fs} during a steady time period ranging from 7.61 to 8.7 s, corresponding to a T of 1.09 s. To obtain the area under the curve, numerical methods were used with a Δt of 0.001 s. The resulting P_{out} was 0.337 W, leading to a ε value of 66.8%.

The hydrodynamic performance (ε) of an OWC resonant chamber can be optimized by considering four key factors in the design illustrated in Fig. 5. These include h1/h, b2/h, d/b2, and α, where h represents the depth of the water, h1 is the vertical length of the front wall, b2 is the width of the chamber resonant, d is the width of the air outlet, and α is the angle of inclination of the front wall. By using the response surface methodology (RSM) through a design of experiments, it is possible to achieve the optimal ε for the resonant chamber. By carefully considering these geometric design parameters, the hydrodynamic performance of the OWC can be enhanced, which can lead to a greater energy efficiency and overall system effectiveness.

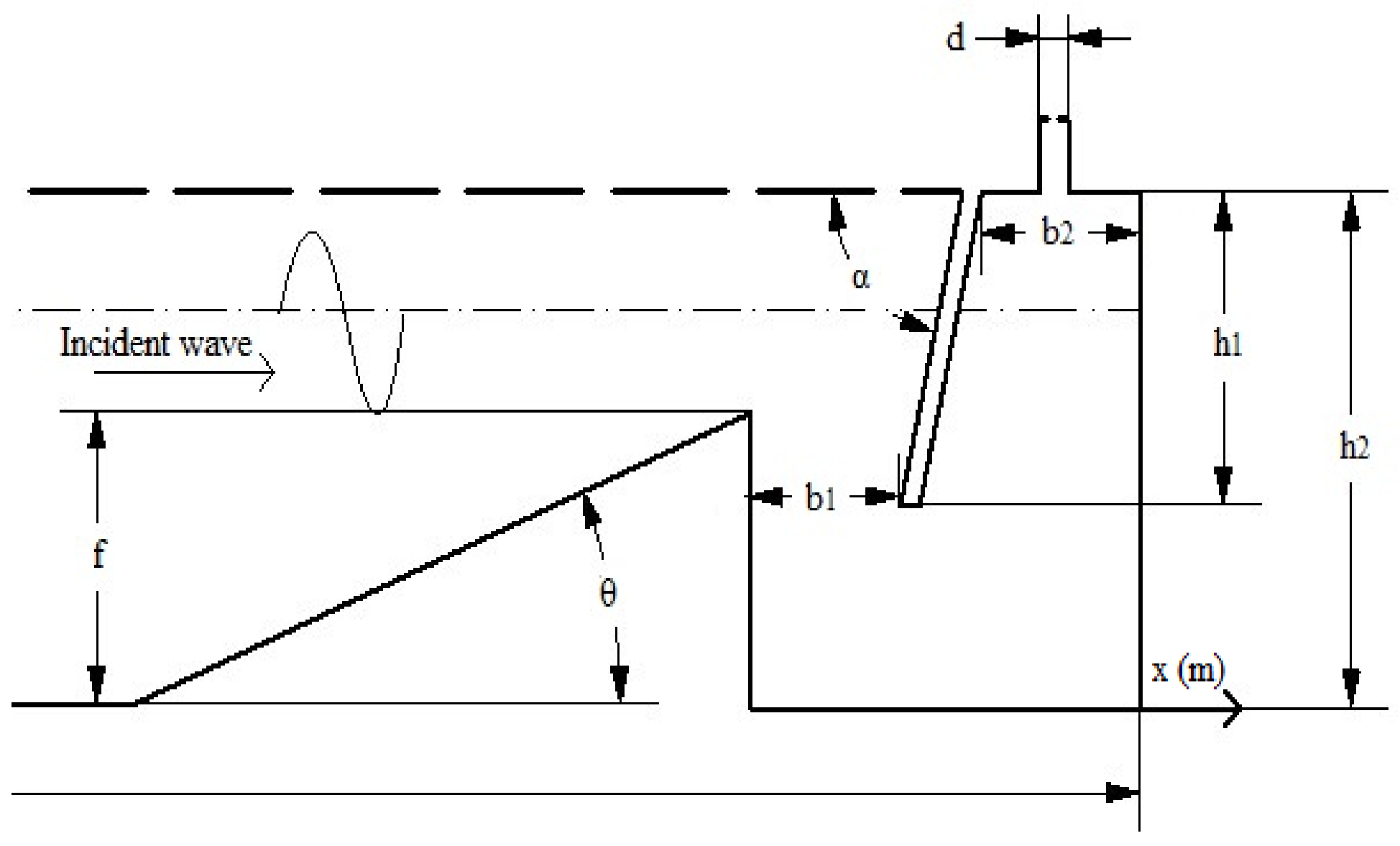


Figure 5. Geometric factors of the resonant chamber of a water column that can be considered for optimization

Conclusion

An analysis of the performance of a resonant wave chamber designed to harness the wave energy in the Pacific Ocean of Colombia was presented. The chamber geometry was based on a U-shaped OWC. The maximum efficiency and the mean velocity of the chamber free surface were found to be 66.8% and 0.17 m/s, respectively. The numerical results for the wave height obtained through simulation were validated by comparing them to analytical expressions reported in the existing literature, and a significant level of agreement was observed. Optimizing the chamber shape parameters for the specific wave characteristics is concluded to be crucial to enhance the operating efficiency of the OWC. To improve this efficiency, an optimization study of the key geometric factors of the resonant chamber is necessary. These factors include the length, inner width, immersion depth, and the angle of inclination of the front wall, as well as the diameter of the air outlet. Understanding the significance of these parameters and their interactions in capturing the energy of a wave front is crucial, and the response surface or surrogate model methodologies could be considered as tools of utmost importance.

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