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CFD analysis of the energy conversion process in a fixed oscillating water column (OWC) device with a Wells turbine

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Abstract

Oscillating Water Column (OWC) devices, both the fixed structures and the floating ones, are an important class of Wave Energy Converter (WEC) devices. In this work, we carried out a numerical investigation aiming to give a deep insight into the fluid dynamic interaction between waves and a U-shaped OWC breakwater, focusing on the energy conversion process. The U-OWC breakwater under consideration, represents the full-scale plant installed in the Civitavecchia (near Rome) harbour. The adopted numerical method is based on the solution of the unsteady Reynolds Averaged Navier-Stokes equations (URANS). The water-air interaction is taken into account by means of the Volume Of Fluid (VOF) model. A two-dimensional domain has been adopted to investigate the unsteady flow outside and inside the OWC device. In order to simulate the action of an air turbine of the Wells type, the air chamber has been connected to the atmosphere by means of a porous medium able to reproduce its linear relationship between pressure drop and flow rate of the air turbine. Several simulations have been carried out considering periodic waves of different amplitudes in order to analyze the performance of the plant and, in particular to analyze the resonance with incoming waves, when the U-OWC is expected to absorb more energy. In order to characterize the plant efficiency, we split the energy conversion process into three main steps, 1) the primary conversion from wave energy to hydraulic energy the water discharge flowing inside the U-duct; 2) the secondary conversion from the OWC inlet to the oscillating pneumatic power made available to the turbine and, finally, 3) the turbine mechanical power output. To this purpose, the simulations of three different cases, varying wave period and height, have been carried out to quantify the energy captured by the plant and the fluid dynamic losses both in the water and in the air.

Keywords: Oscillating Water Column, Volume of Fluid, CDF, eigen period, resonance condition, performance.

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1. Introduction

A U-OWC breakwater consists of a chamber with an opening to the sea below the water line at the end of a vertical duct. Waves enter through this opening with only some small diffraction effects from the front wall (see [1]) and they propagate on the water surface inside the plenum chamber. On the roof of the plenum there is a pipe connecting the atmosphere with the air chamber enclosed between the water surface and the roof. This pipe contains one or more self-rectifying turbines (such as Wells turbine, see [2]). The air inside the chamber, is compressed and expanded alternately. As a consequence, an air flow is produced which drives the turbine in the pipe.

U-OWC plants ([3], [4], [5], [6]) are breakwaters in reinforced concrete embodying an OWC with an additional vertical duct on the front wall. The performance of a U-OWC with a Wells turbine has been investigated through a small-scale field experiment by Filianoti and Camporeale [5].

2. CDF simulations

2.1. Numerical model

The numerical approach is based on a two-dimensional CFD simulation using the commercial code Ansys Fluent 17.0, Academic Version. The water-air interaction is taken into account by means of the Volume Of Fluid (VOF) model. In the VOF model, two or more fluids (or phases) are not interpenetrating and the volume of a phase is computed as volume fraction. The volume fraction in those cells that lie near the interface between two phases is calculated by means of the Geometric Reconstruction scheme, in its explicit formulation in order to avoid excessive numerical dissipation. In this approach, the interface between fluids is represented through a piecewise linear interpolation. Both air and water flow fields are assumed to be unsteady and are computed solving the Reynolds-Averaged Navier-Stokes (RANS) equations. These equations are discretized according to a Finite Volume approach, adopting a pressure-based algorithm in its implicit formulation. In this work, we introduce the k-ω turbulence model only to the computational region inside the U-OWC. The SIMPLE (Semi-Implicit Method for Pressure Linked Equations) scheme has been used for the pressure-velocity coupling. It is a segregated algorithm that uses a relationship between velocity and pressure corrections to enforce mass conservation and to obtain the pressure field. In order to obtain the spatial discretization of the convection terms, we used the Green-Gauss Cell-Based method and the PRESTO! (PREssure STaggering Option) scheme for pressure equation. The other convection-diffusion equations (e.g. momentum or energy equation) were discretised by means of the Second Order Upwind scheme. Regarding the temporal discretization, a time step $\Delta t = T/1000$ has been adopted, T being the wave period. The part of the computational domain indicated by a red rectangle in Figure 3, was set as "porous zone" in order to model the pressure difference between the chamber and the external ambient due to the oscillating flow. This "porous zone" is characterized by viscous (for the Wells turbine) and inertial (continuous) losses, whose parameters have been suitably set to reproduce the actual pressure losses in the air duct.

2.2. Computational domain

The computational domain is a wave-flume, having a piston-type wavemaker placed in the left extremity and a U-OWC breakwater in the right extremity (see Fig. 1a). The 2D domain is 1 kilometer long and 30m high. The length of the flume has been chosen in order to have many wavelengths, at least 10, upstream the U-OWC breakwater, for all the sea states simulated. The U-OWC is a schematic of the plant installed at the Civitavecchia harbour of Rome (Italy) in the Tyrrhenian sea (Arena et al. [7]). More in detail, the width of the plenum chamber is 3.2 m long and the width of the vertical duct is 1.6 m. The still water depth was set at 15 m and the draft of the opening to the sea is 2m. The pipe inside which hosts the Wells turbine has a diameter of 74cm. Considering waves moving perpendicularly to the OWC, two-dimensional CFD simulations are carried out in order to reduce the computational effort and resources with respect to a fully three-dimensional simulation. The spatial discretization of the computational domain (see Fig. 1b) was made by means of the grid generator Pointwise adopting a hybrid mesh, formed by rectangular elements in the overall length of the flume, whereas near the U-OWC device triangular elements were adopted. The total mesh has approximately 300,000 cells.

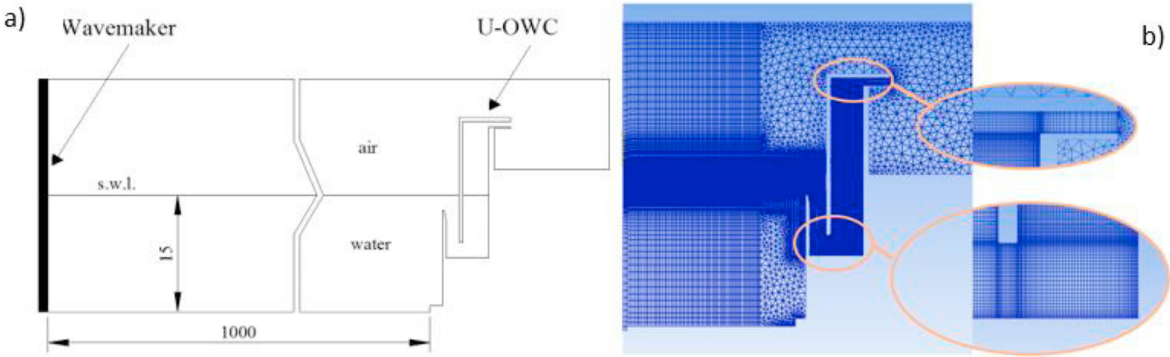

Fig. 1 - a) Sketch of the computational domain (measures are in meter); b) the spatial discretization of the computational domain.

2.3. The wave generation process

A piston-type wavemaker starting from rest and moving sinusoidally for a given time interval Δt, produces in a flume a free surface displacement described analytically by Hughes, 1993 [8]. In this case, a simple harmonic motion was assigned, in order to produce a periodic wave train. In order to simulate the plant working conditions with waves having sizes similar to the actual ones, we generated waves with $H = H_{rms}$ and $T = T_p$, where H_{rms} is the square root of the average of the squares of all wave heights in a sea state, that is approximately equal to H_s divided by 1.4. T_p is the period corresponding to the peak of the energy spectrum, which can be computed as

$$T_p = 8.5\pi\sqrt{\frac{H_s}{4g}} \tag{1}$$

To check the wave generation and propagation in the flume, the free surface displacement obtained from numerical simulation has been compared with the analytical solution. Fig. 2 shows, in dotted line, the instantaneous free surface elevation along the flume, at a fixed time instant after the beginning of the paddle motion for sea state 7, with H_s = 3.5m and T_p = 8s. For comparison, the analytical solution of [8] is shown in continuous lines. As we can see, there is an excellent agreement between them.

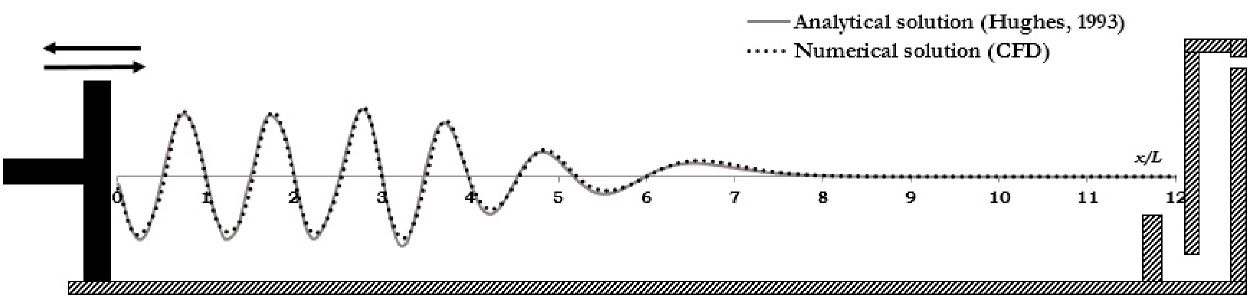

Fig. 2 - Comparison between the analytical solution for transient waves in a flume (Huges,1993) and numerical solution carried out by the preliminary experiment.

3. The results and discussions

3.1. The absorption coefficient

In the present work, the sea states 4, 6 and 7 reported in Arena et al. [7] have been simulated (Table I). The turbine is assumed to act as a linear damper, with a total pressure drop coefficient equal to about 4. It corresponds to a monoplane Wells turbine having 0.74 m of diameter, rotating at about 3200 rpm. For each sea state, the instantaneous wave energy flux Φ_{abs} absorbed by the plant has been evaluated at the horizontal cross section on the opening of the plant as the product of the pressure fluctuation by the volumetric flow rate (Fig. 3).
The ratio between time averaged values of Φ_{abs} and energy flux of incident waves, represents the absorption coefficient, *A*. In Table 1 the summary of this calculation is shown. For instance, for the sea state n.4 (SS4), the mean energy flux of the incoming wave train (i.e. the waves generated by the wavemaker) is approximately equal to 11 kW/m whereas the time average energy flux absorbed by the plant is about 4.2 kW/m, that is about 38% of the incoming wave energy flux. Analogously, for the seas states n.6 and 7 (SS6 and SS7), the absorption coefficients are 38% and 32%, respectively.

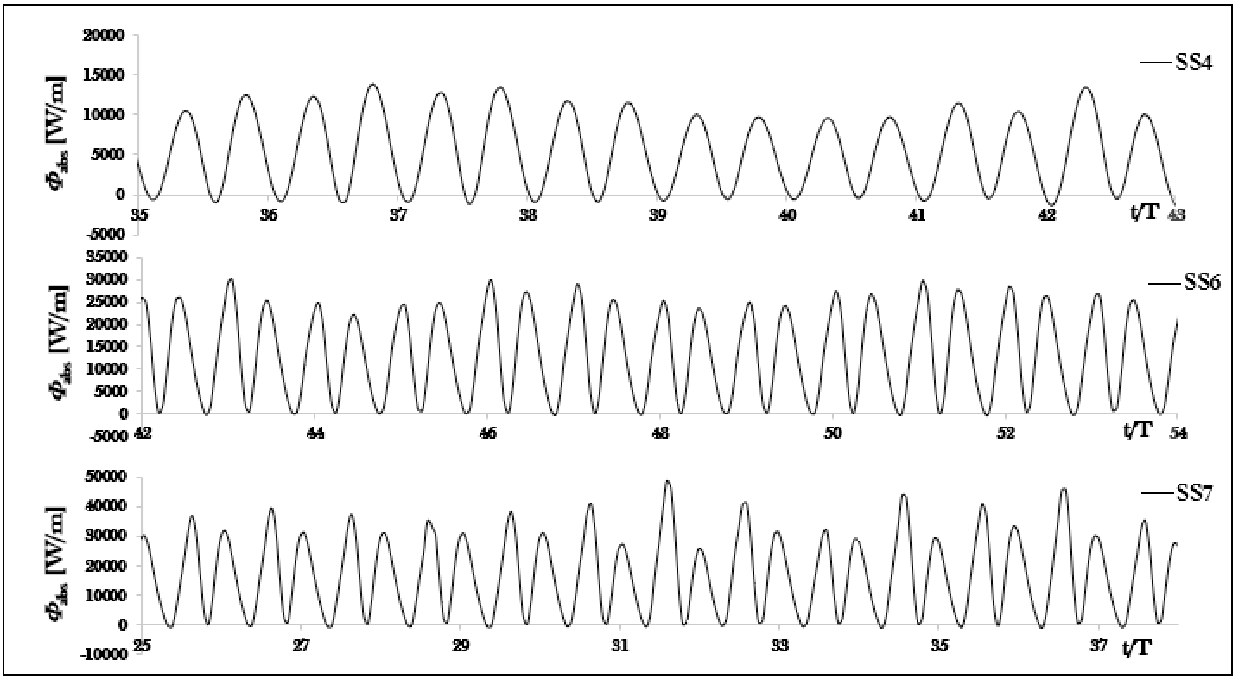

Fig. 3 – Time histories of the energy fluxes absorbed by the plant in the different sea states.

Tab.1 - Summary of simulations.

Sea state	Hs [m]	Tp [s]	Φ_{in} [kW/m]	Φ_{abs} [kW/m]	$A= \Phi_{abs} / \Phi_{in}$ [%]
SS4	2.0	6.0	11.05	5.23	47.3%
SS6	3.0	7.4	30.26	12.57	41.5%
SS7	3.5	8.0	52.10	16.45	31.6%

3.2. The energy losses

The energy flux absorbed at the outer opening of the vertical duct (sect. A-A in Fig. 4a) is partially dissipated in the water flow due to fluid dynamic losses. Almost all the remaining part reaches the air turbine as pneumatic power, apart a small fraction dissipated in the air inside the plenum chamber (from sect. B-B to sect. C-C in Fig. 4a) due to thermodynamic losses caused by the compression-expansion cycle. In order to quantify the energy dissipations, we applied the energy balance to specific control volumes. Focusing on the first control volume, relative to the OWC plant between the cross sections A-A and B-B, the difference between the mean energy flux entering the cross-section A-A and the mean energy flux leaving the cross-section B-B, represents the water energy losses. These losses are produced by large eddies inside the water flow. In the water, they are located in correspondence to abrupt changes of direction of the flow, which occur near the outer opening and in the lower U-turn of the vertical duct. In order to evaluate the energy dissipation inside the air chamber the difference between the energy fluxes computed at cross sections BB and CC have been considered.

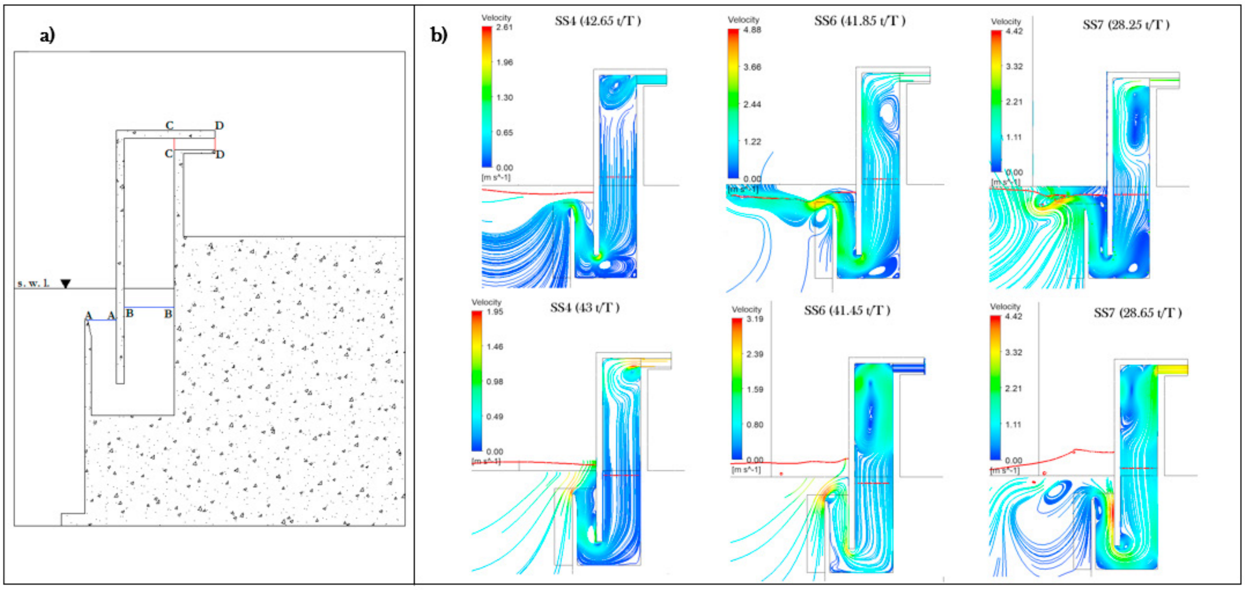

Fig. 4 - a) Reference scheme for the evaluation of the energy flux in sections A-A, B-B. C-C and D-D; b) Streamline of velocity for each of sea states simulated.

Fig.5 shows, for all the simulated sea states, the instantaneous energy flux absorbed by the OWC and measured at the cross-section A-A (continuous line) and the energy flux transmitted to the air mass (dashed line) and computed at the cross section B-B. As we can see, the transmitted energy flux is delayed in time with respect to the instantaneous energy flux absorbed by the plant. Focusing on sea state 4, the energy flowing through section A-A (=5.2 kW/m), is partially used to force the water flow to move the air mass in the chamber reducing its value in section B-B about 23% less (=4.03 kW/m). Similarity, for sea state 6 and 7 we have obtained a reduction of the mean energy flux of 26% and 24%, respectively. This reduction represents the energy losses in water.

Fig.6 shows the same analysis illustrated in Fig. 5, for the control volume included between the cross sections C-C and D-D, chosen to evaluate the pneumatic power absorbed in the porous medium that reproduces the characteristic curve of the Wells turbine. The energy flux across section C-C is evaluated as the product of the pressure fluctuating pressure by the volumetric air flow, neglecting the thermal energy due to the temperature fluctuation. The pneumatic power crossing section C-C is fully absorbed in the porous medium and is zero in section D-D where the pressure is constant and equal to the atmospheric value.

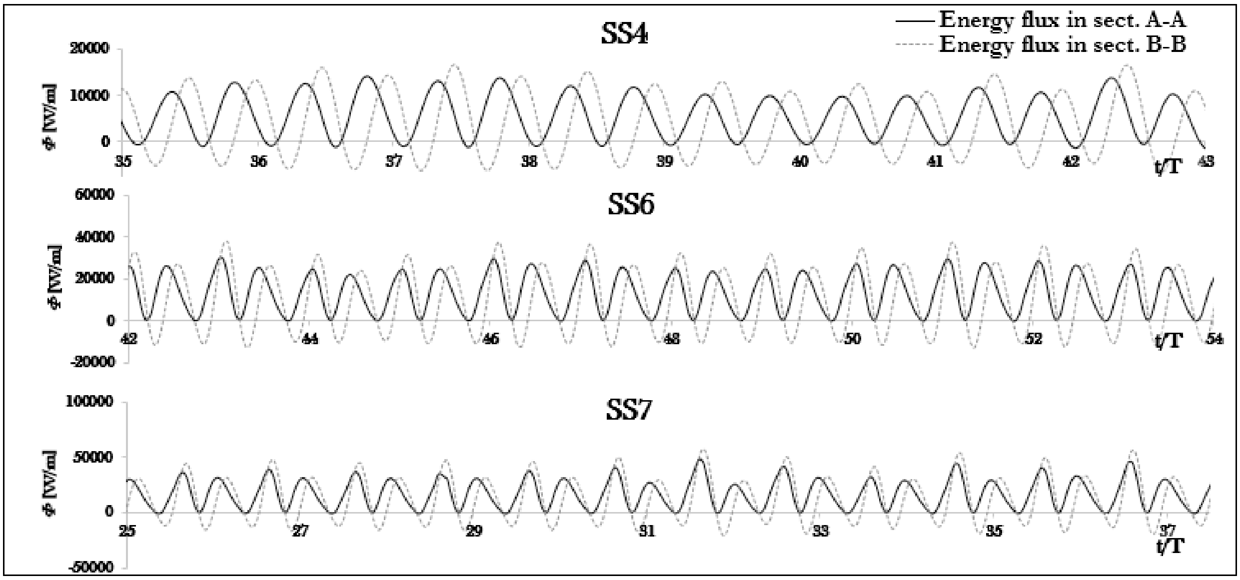

Fig. 5 - Time histories of the energy fluxes in sect. A-A and B-B.

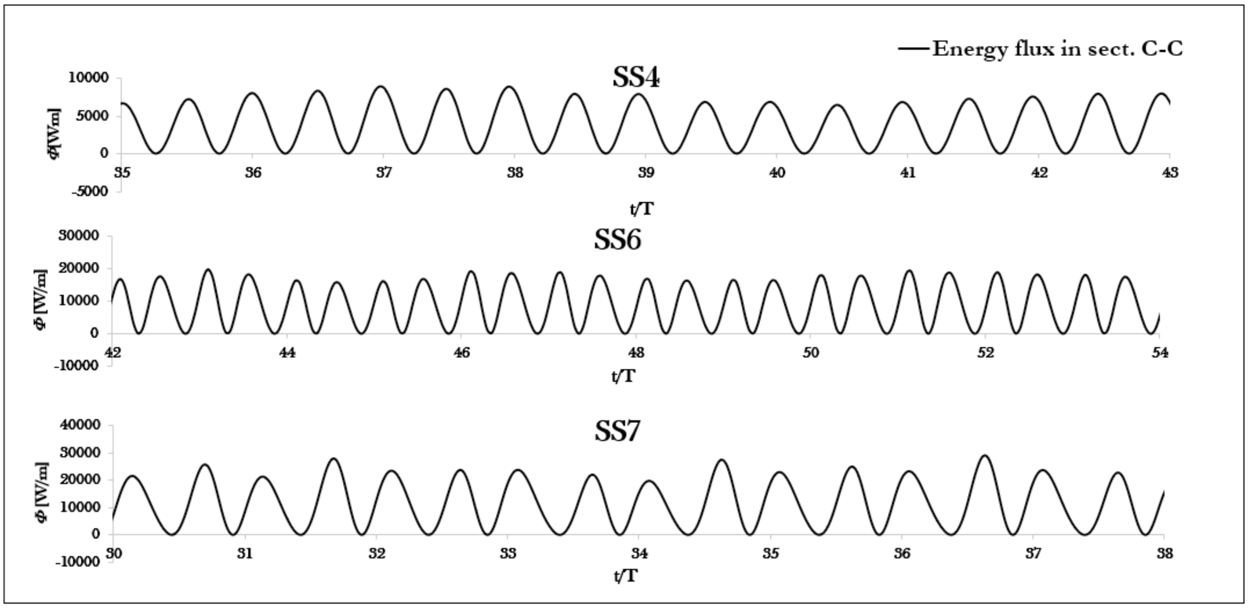

Fig. 6 - Time histories of the pneumatic power absorbed in the porous medium reproducing the air turbine characteristics.

The time average energy fluxes evaluated at the outer opening of the plant (sect. A-A), in the chamber (sect. B-B) and in the inlet section of the conduit of the turbine (sect. C-C). It is reported also the energy losses in water, in air through the turbine and between water and air interface.

Tab.2 Summary of the energy conversion process (time average values).

No. Sea state	Hs [m]	Tp [s]	Φ_{abs} sect.A-A [kW/m]	Mean Energy flux in sect. B-B [kW/m]	Mean Energy flux in sect. C-C [kW/m]	Water energy losses	Energy losses in the air chamber	Pneumatic energy to the Wells turbine
SS4	2.0	6.0	5.23	4.03	3.72	22.9%	5.9%	71,2%
SS6	3.0	7.4	12.57	9.28	8.66	26.2%	6.7%	67.1%
SS7	3.5	8.0	16.45	12.58	11.79	23.5%	6.3%	70.2%

3.3. *Thermo-fluid dynamics inside the plant*

When the incident wave train hits the absorber-breakwater, the water inside the plant starts to oscillate, alternatively compressing and expanding the air mass in the plenum, which moves the air through the turbine conduit. As a consequence, all fluid dynamic quantities fluctuate with the same oscillating period of the incoming waves. Fig. 7 shows the fluctuation of the free surface displacement inside the chamber and the oscillation of the mean temperature inside the plenum. It can be observed that the temperature oscillates of several degrees: this effect combined with the mass exchange with the atmosphere through the air turbine causes the increase of the mean temperature shown in Fig.7 and the energy losses in the air chamber synthesized in Table 2.

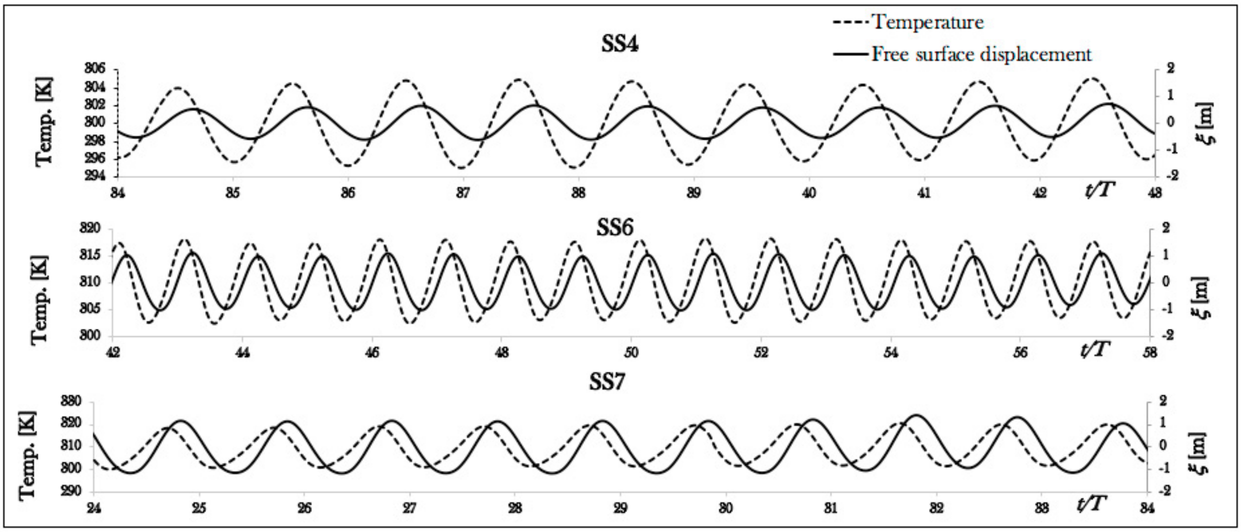

Fig. 7 - Temperature and free surface displacement inside the chamber.

Conclusions

In this work, a numerical experiment to evaluate the amount of energy loss in the energy conversion process that occurs in a U-OWC device was carried out. The interaction between three different incident wave trains and the Civitavecchia harbour U-OWC was simulated numerically. The CFD simulation was carried out by means of the commercial CFD code Ansys Fluent v.17 Academic version, using a Volume of Fluid model to simulate the multiphase flow. First of all, we checked the wave generation process checking the free surface displacement generated numerically and the analytical solution [8]. Secondly, we evaluated the energy flux absorbed by the plant and consequently the absorbed coefficient of the plant, being the latter, the share of the incident wave power captured by the plant. We focused our attention on the amount of energy lost from the plant entrance to the turbine duct. Analysing in depth the energy conversion process, we found that the largest part of energy loss occurs in water because of the presence of large eddies due to the particular shape of the plant. More than the 66% of the absorbed energy is converted into pneumatic power made in the turbine duct. Finally, analysing the streamlines coloured by the velocity magnitude we found that the design a U-OWC with an eigen period close to the wave period is not enough to maximize the power. Likely, the shape of the plant could be optimized in order to reduce the vortexes and consequently to reduce the energy losses in water.

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