CONTRIBUTIONS TO THE STUDY OF HYDRODYNAMIC BEHAVIOUR OF INNOVATIVE ARCHIMEDEAN SCREW TURBINES RECOVERING THE HYDROPOTENTIAL OF WATERCOURSES AND OF COASTAL CURRENTS

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EXTENDED ABSTRACT

This paper presents the results of research carried out within the program ARCHIMEDES III, entitled “Rebirth of Archimedes: contribution to hydraulic mechanics study and Archimedean cochlear waterwheels hydrodynamic behaviour, for recovering the hydraulic potential of natural and technical watercourses, maritime and tidal currents”, concerning series of innovative conventional and unconventional inclined and horizontal axis floating Archimedean screw turbines to be installed in a multitude of very promising sites throughout Greece. These cochlear devices could harness the unexploited Archimedean hydropower potential and kinetic tidal energy potential of Euripos Strait and Cephalonia’s coastal paradox flow. For such innovative Archimedean turbines, an ongoing Ph.D. research has developed a very promising inventory of Greek Archimedean small hydropower potential, series of innovative experimental small-scale models of new cochlear wheels and their hydrodynamic performance prediction methods. The developed Greek Archimedean small hydropower potential inventory estimates that more than 30 TWh could be harnessed and proves that, there are thousands of very promising cochlear potential sites at small waterfalls and many river weirs across the country. Preliminary research efforts proved the useful exploitation of new screw techniques, under the form of innovative Archimedean Inclined Axis Cochlear Turbines (AIACT’s) and innovative Archimedean Water Current Turbines (AWCT’s) with horizontal floating cochlear rotors, harnessing the unexploited flowing hydraulic potential of natural streams, open channels hydraulic works, and coastal and tidal currents as well. These inclined and horizontal axis Archimedean screw rotors have been analyzed from fluid dynamics point of view, by using modern Computational Fluid Dynamics (CFD) techniques, simulating the behavior of flowing water through the rotating Archimedean blades and investigating the hydrodynamic performances of the AIACT’s and AWCT’s. It seems that, under the current Greek economic situation and in Era of Transition, the very promising results obtained could become the future leading green technology, a viable alternative solution for clean hydro electricity generation and sustainable development in Greece.

Keywords: Archimedes III project, Archimedean Turbines, Archimedean screw, Small Hydropower, Clean Energy, Sustainability

1. INTRODUCTION

The inverse use of the Archimedean screw, as a kind of screw pump-turbine, is under discussion, during the last years, within the hydropower scientific community (Müller, 2009), (Nuernbergk and Rorres, 2012). The area of low head hydropower has attracted the attention of many researchers in order to use and develop new and efficient, environmental friendly Archimedean cochlear hydropower plants (Stergiopoulou and Kalkani, 2012). Archimedean small hydropower plants were installed during the last decade in Central Europe by several industrial companies, which are based on the inversion of the energy flow in their pump operation and turning the old screw pumps into new Archimedean turbines (Pelikan and Lashofer, 2012), (Kandert, 2008). Figure 1 gives the commonly used application domain for turbines selection. This leads to the choice of Pelton and Turgo turbines at high heads, crossflow and Francis turbines at mid heads and Kaplan-propeller turbines, waterwheels and Archimedean screw turbines at low heads (Stergiopoulou and Stergiopoulos, 2012a) (ESHA, 1998).

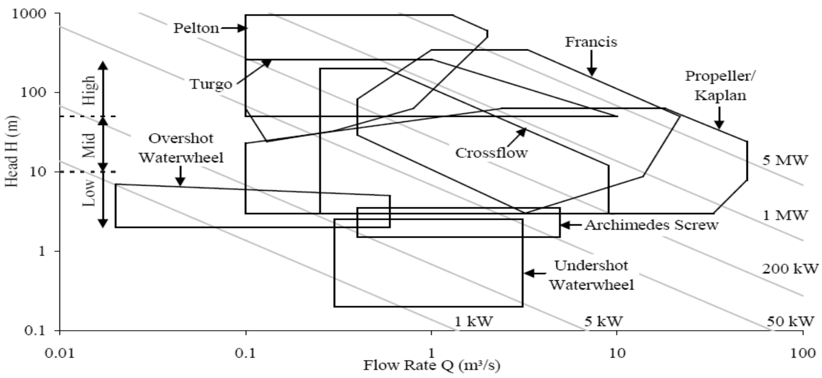

Figure 1: A typical small hydropower turbine application range chart.

The current Greek economic crisis situation and all systematic efforts relative to the hydrodynamic behavior studies of innovative Archimedean screw turbines recovering the hydropotential of watercourses and coastal currents probably should give an increased impetus in low head hydraulic renewable energy sources. According to the present research, within ARCHIMEDES III program, entitled “Rebirth of Archimedes: contribution to hydraulic mechanics study and Archimedean cochlear waterwheels hydrodynamic behavior, for recovering the hydraulic potential of natural and technical watercourses, maritime and tidal currents”, the “Inclined and Horizontal Archimedean Cochlear Screws” could find very promising modern applications, as efficient hydraulic turbomachines.

2. A FIRST GREEK ARCHIMEDEAN HYDROPOWER POTENTIAL INVENTORY

Greece is rich in small and large watercourses having rough terrain, steep slopes and non-uniform precipitation distribution. An area of about 45.915 km^2, corresponding to 35% of total Greek surface 131.913 km^2, was here investigated by using simple quasi-linear formulas, water discharge values and data determined by precipitation, evapotranspiration, infiltration through subsoil porous and karstic media. It is possible to obtain a first theoretical hydropower potential estimation of each Greek watershed, each water basin and district, as a function of mean flow and gross head for the 14 water districts of (1) W. Peloponnese, (2) N. Peloponnese, (3) E. Peloponnese, (4) W.C. Greece, (5) Epirus, (6) Attica, (7) E.C. Greece, (8) Thessaly, (9) W. Macedonia, (10) C. Macedonia, (11) E. Macedonia, (12) Thrace, (13) Crete and (14) Aegean Islands. The theoretical Archimedean hydropower potential is calculated by using the following linear formula, with Q_i(m^3/s), as the representative from the flow duration curve water discharge and ΔH_i (m), as the available constant over the year head in watercourse sites of $E_{i,\ th}$ (KWh) = $9.81\times(Q_i\times\Delta H_i)\times 8{,}760$. The flow discharges were estimated in a basis of collected measurement data, which are sometimes systematic and other times, sporadic and incomplete, or by using simplified theoretical calculations, comparisons and interpolations between neighbouring basins with certain geological and hydrological similarities. Figure 2 gives the percentages of Greek water districts investigated areas and the theoretical Archimedean hydropotential, in GWh, of the Greek Water Districts.

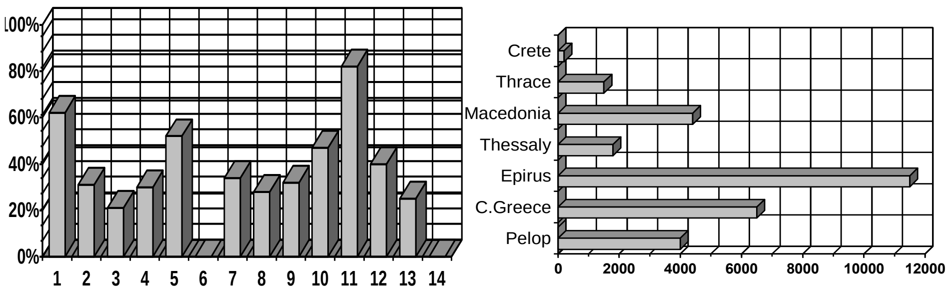

Figure 2: Percentages of the 14 Greek water districts investigated areas and the calculated theoretical Archimedean hydropotential, in GWh

The total theoretical Archimedean hydropower potential of the natural watercourses obtained for the estimated Greek area is around E_{th} = 30 TWh (Stergiopoulou and Stergiopoulos, 2012b). The present calculations correspond to an overall theoretical Archimedean small hydrocapacity of about 3,412 MW. In this inventory is not included the important small hydropower kinetic energy potential of natural watercourses, water supply and irrigation systems neither the very promising coastal and tidal currents potential.

3. INNOVATIVE ARCHIMEDEAN INCLINED AXIS COCHLEAR TURBINES (AIACT's)

Series of innovative small-scale cochlear turbines were designed and developed, by following the similarity methodology of Buckingham's π-theorem (Stergiopoulou *et al.*, 2010), concerning various Archimedean wheel configurations, by using small-scale models. The dimensions of spiral small-scale models are connected with circular ducts data, given by specific parameters relations of spiral lead s, spiral profile thickness g, and cylindrical mandrel diameter d_m to a circular duct diameter d, are presented as s/d, g/d and d_m/d ratio, respectively. Some flow measurements have been made in S3/TILTING FLUME Armfield channel, for two spiral wheels. The dimensionless ratios of these wheels are s/d=0.7(1.4), d_m/d=0.2(0.15), g/d=0.035, with s=5 cm the spiral lead, d=7.2cm the circular duct dimension, d_m the circular mandrel dimension (1.4cm for the first cochlear wheel and 1.1cm for the second). The maximum water depth in the open channel was 31cm. The rotors orientation angle was variable between 20-34º (Stergiopoulou and Stergiopoulos, 2012b). Figure 3 illustrates three representative Archimedean experiences in this open flume channel.

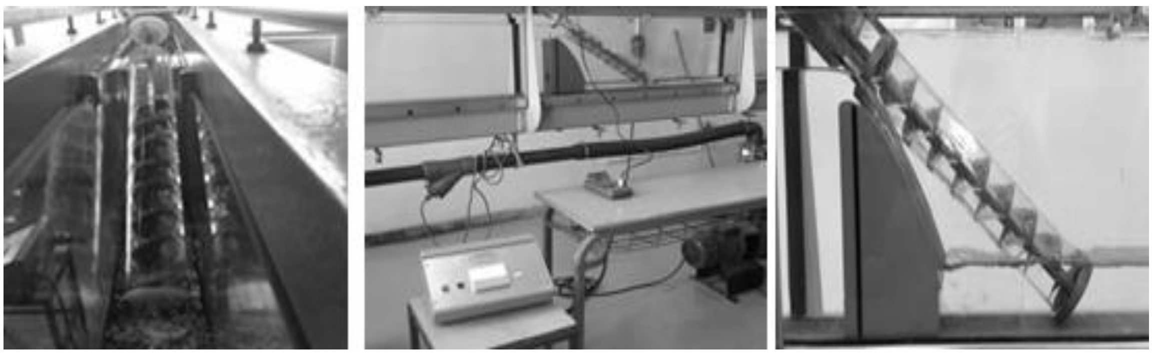

Figure 3: Three representative Archimedean experiences in S3 Armfield channel.

The first calculations and measurements showed the important effect of inflow water level to diameter and seem to give efficiencies between 78 and 83%, making these an interesting alternative for turbines in low head hydropower applications (Stergiopoulou and Stergiopoulos, 2012c; 2012d). Figure 4 shows the geometric definition of used spiral wheels, presents small Archimedean models and an artistic view of a cochlear rotor in the hydraulic channel.

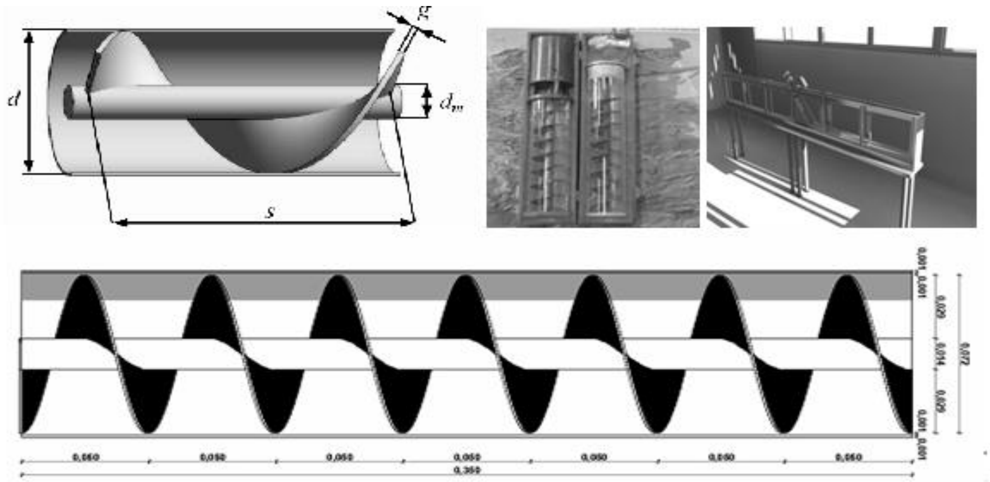

Figure 4: Geometric definition of used spiral wheels, small Archimedean models and an artistic view of a cochlear rotor in the hydraulic channel.

In laboratory measurements an optical tachometer for rotational speed, one tilt sensor for rotor axis inclination and a vernier system for depth flow h assessment (h = L.sin a, with L = 35 cm, the length of the screw rotor) were used. The rotor inner diameter is d_m, d_m = L/20 - L/25, while the outer diameter is d=7.2cm. The water supply Q (m^3/s) was measured with a conventional propeller flow current meter. The efficiency is $\eta = P_{out}/P_{in}$, as a function of geometry and screw rotational speed n and supply Q, calculated by determining the input power P_{in} and output power P_{out}, with P_{in} (W)=P_{th}=ρ.g.Q.H and P_{out} (W) = T.ω = T.2.π.n, where ω is the angular velocity and T(N.m) the growing axis of rotation torque. The following figure shows the first theoretical experimental results of power P_{th}, screw rotational speed n (rev/s) and applied torque T (N.m), as a function of supply Q (l/s) (Stergiopoulou and Stergiopoulos, 2012a; 2012b).

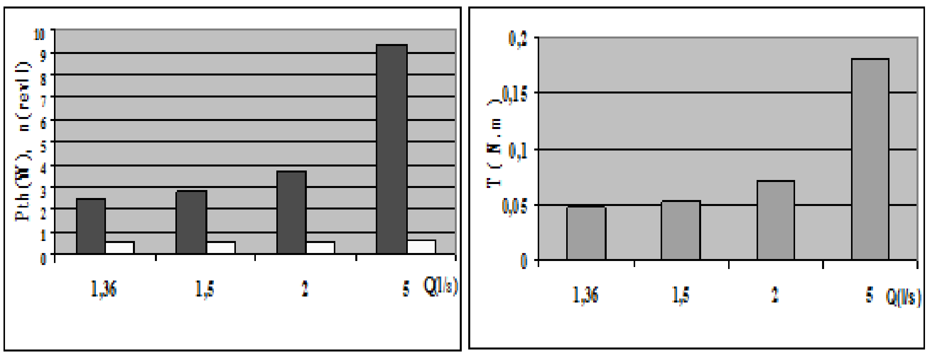

Figure 5: Measured screw power, rotation speed and torque, in function of *Q*.

Figure 6 concerns photorealistic views in "virtual sites" of conventional and unconventional Archimedean Screw Small Hydropower Turbines, with 3-blade and 1-blade rotors, having inclined and horizontal axis, in series and parallel. Also, this figure shows an Archimedean Turbine Park, having 4 inclined and 4 horizontal Archimedean turbines.

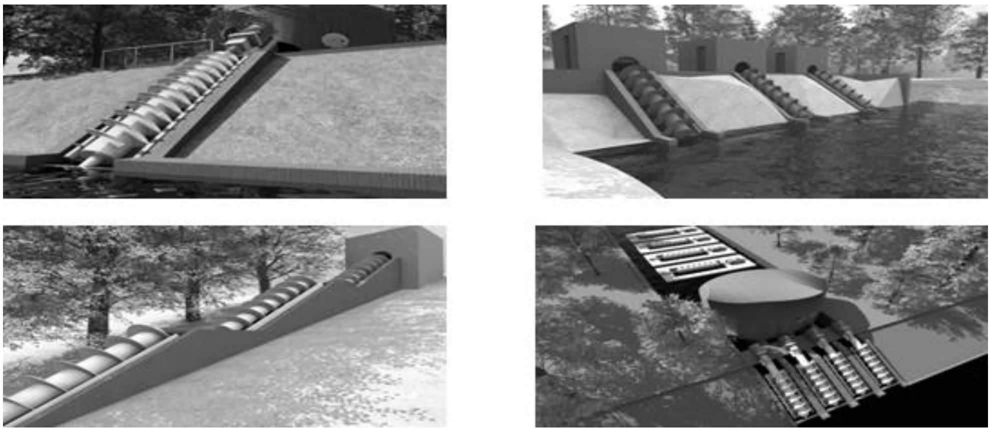

Figure 6: Four artistic photorealistic views for “virtual sites”.

4. INNOVATIVE ARCHIMEDEAN WATER CURRENT TURBINES (AWCT’s)

Recent ARCHIMEDES III research efforts proved, besides the Archimedean Inclined Axis Cochlear Turbines (AIACT’s), the useful exploitation of another Archimedean screw technique, under the form of a second cochlear devices, the form of Archimedean Water Current Turbines (AWCT’s) with horizontal floating cochlear rotors. These devices harness the unexploited flowing kinetic hydraulic potential of natural streams, open channels hydraulic works, coastal and tidal currents as well. A series of floating AWCT’s could be installed for recovering the hydraulic kinetic energy potential of open irrigation and water supply channels. Figure 7 gives photorealistic views of a schematic floating horizontal-axis Archimedean hydro plant and two virtual representations with one AWCT in Evinos River and two rotors in an irrigation channel turning with a flowing speed 1.8-2.1 m/s.

Figure 7: Photorealistic views of a schematic AWCT and two virtual representations of floating rotors in Evinos River and an irrigation channel.

Such AWCT rotors could be tested in the entrance and exit of the natural canal of Cephalonia’s strange sea river current and in Euripus Strait, subject to strong tidal currents, which reverse direction approximately four times a day. The Ionian island of Cephalonia is the site of one of the most astonishing hydrological phenomena in the world, with a seawater massive current flowing continuously into karstic substratum of the island, through sinkholes, near Argostoli’s town. Cephalonia’s coastal paradox constitutes a real world unique mystery (Stergiopoulou and Stergiopoulos, 2012d). The mysterious coastal seawater current reappears, after an underground route of about 15 km long, on the opposite coast of the island at brackish springs, near Sami's town. A recent measurement campaign, from May 2011 to April 2012, in Cephalonia's sea current entrance, demonstrates that mean flow speed is around 1.7-2.0 m/s. It seems that this current flow is sufficiently powerful to drive new well-designed Archimedean spiral power screws and produce valuable electricity. According to the present research a series of floating AWCT's could be installed for recovering the hydraulic kinetic tidal energy potential of Euripus Strait and Cephalonia's coastal paradox flow. Some first floating Archimedean hydro-generators models have been "virtually" examinated giving very promising preliminary results for future ARCHIMEDES III research. Figure 8 presents a general view of Cephalonia, with its coastal paradox, and gives photorealistic views of one AWCT for the energy recovering of Cephalonia's astonishing marine phenomenon (Stergiopoulou and Stergiopoulos, 2012c; 2012d).

Figure 8: Views of Cephalonia with its coastal paradox.

Series of such similar or different floating Archimedean energy screws could be also installed in Chalcis strait, for recovering the hydraulic kinetic energy potential of Euripus tidal channel. Figure 9 gives representative photorealistic views of one, two and three AWCT's in Euripus Strait for harnessing the hydraulic kinetic energy potential of Euripus tidal channel.

Figure 9: Photorealistic views of AWCT's in Euripus Strait.

5. PRELIMARY CFD STUDY OF AIACT's & AWCT's HYDRODYNAMIC BEHAVIOUR

To simulate in the present research the complex 3D flow phenomena through rotating cochlear turbines, modern CFD (Computational Fluid Mechanics) techniques are required. A screw designed by using CAD codes needs a converter program to obtain its STL (stereolithography) form admitted by CFD codes. Then, the introduced STL object to the CFD technique helped to create the mesh grid generation and resolve the Navier-Stokes equations for various inclined axis screws and for 1, 2 or more horizontal screws. CFD codes (e.g. FINE-Turbo, OpenFoam, FLOW-3D etc.) were used having important contributions to the study of hydrodynamic behaviour of Archimedean screw turbines. These codes use interactive grid generation software and computation flow solver modules simulating continuity, Euler and Navier-Stokes equations, in all the cases of the flow regimes.

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}\cdot\left(\rho\vec{V}\right) = 0\ , \quad \rho\frac{D\vec{V}}{Dt} = \rho\left[\left(\vec{V}\cdot\vec{\nabla}\right)\vec{V} + \frac{\partial \vec{V}}{\partial t} + \right] = -\vec{\nabla}p + \rho\vec{F}$$

$$\rho\frac{D\vec{V}}{Dt} = \rho\left[\left(\vec{V}\cdot\vec{\nabla}\right)\cdot\vec{V} + \frac{\partial \vec{V}}{\partial t}\right] = -\vec{\nabla}p + \rho g + \frac{\partial}{\partial x_j}\left[\mu\left\{\frac{\partial V_i}{\partial x_j} + \frac{\partial V_j}{\partial x_j}\right\} + \delta_{ij}\lambda\, div\vec{V}\right]$$

Horizontal screw rotors, with one or more blades, are the same rotors like the inclined screws having the same blade number with a zero inclination angle. Figure 10 shows typical screws in various inclination angles, and one bladed inclined and horizontal STL screw turbines objects imported in the mesh blocks.

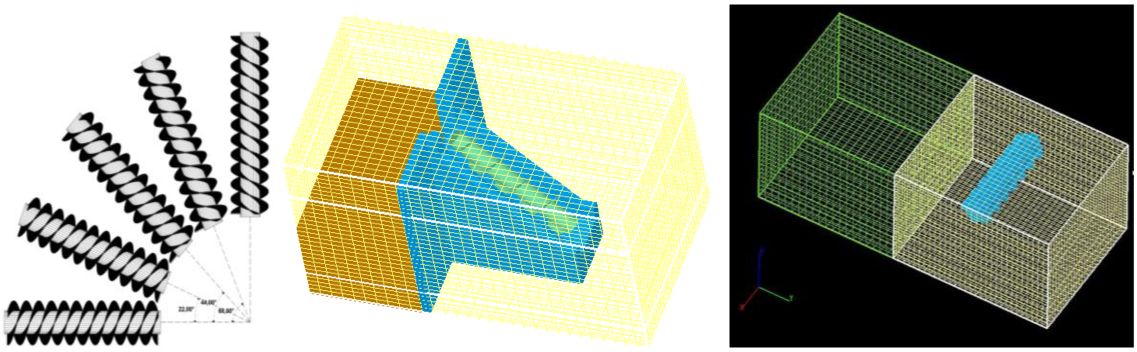

Figure 10: Inclined and horizontal STL turbines objects imported in the mesh blocks.

All CFD screw problems are defined in terms of initial and boundary conditions. It is important that the user specifies these correctly and understands their role in the numerical algorithm. Figure 11 gives the boundary conditions with the symbols V, O, S and G representing the input, the output, symmetry and the grid overlay conditions.

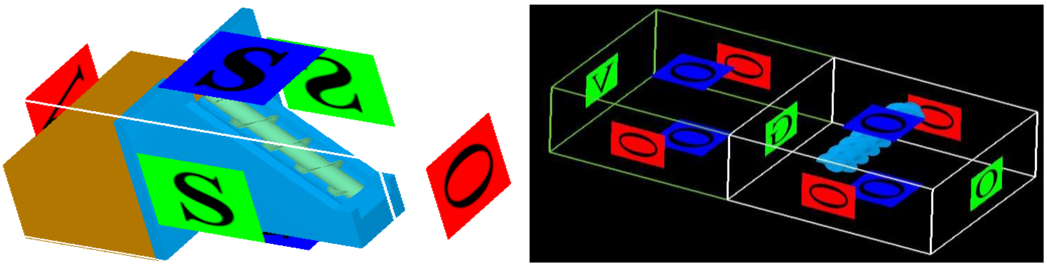

Figure 11: Boundary Conditions.

The hydrodynamic performances of AIACT and AWCT have been analyzed in various values of input flow. The rotation speed, in RPM, was obtained, in function of the external diameter D_o, from the relation of Muskens $N = 51/D_o^{2/3}$. Figure 12 gives two characteristic CFD simulation screens for a AIACT and a AWCT.

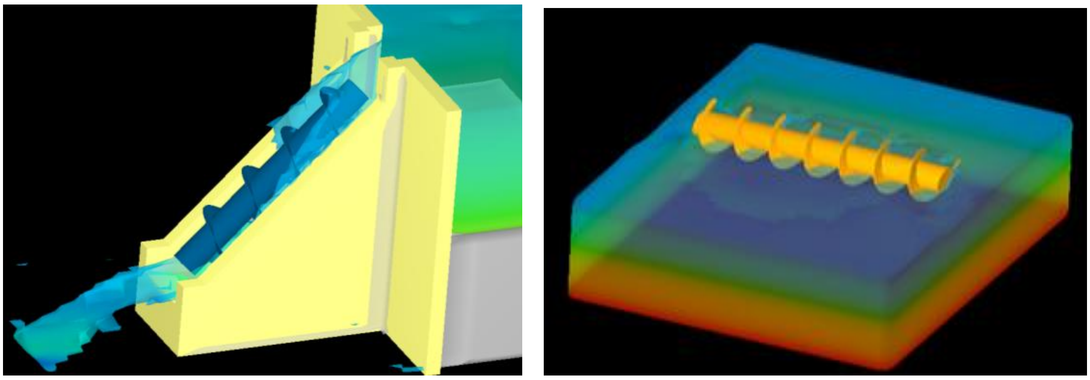

Figure 12: CFD simulation screens for a AIACT and a AWCT.

6. PRELIMINARY CONCLUSIONS

The presented here contributions to the hydrodynamic behavior study of innovative cochlear screw turbines and the preliminary ARCHIMEDES III research efforts proved the very promising and very useful exploitation of two types innovative screw techniques, under the form of Archimedean Inclined Axis Cochlear Turbines (AIACT's) and Archimedean Water Current Turbines (AWCT's), harnessing the important unexploited low-head Greek hydraulic potential of watercourses and recovering the flowing kinetic energy of streams, open channels, coastal and tidal currents as well.

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