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CFD Simulations of Tubular Archimedean Screw Turbines Harnessing the Small Hydropotential of Greek Watercourses

Alkistis Stergiopoulou[1], Vassilios Stergiopoulos[2]

[1] Institut für Wasserwirtschaft, Hydrologie und Konstruktiven Wasserbau, B.O.K.U. University, Muthgasse 18, 1190 Vienna, (actually Senior Process Engineer at the VTU Engineering in Vienna, Zieglergasse 53/1/24, 1070 Vienna, Austria).
[2] School of Pedagogical and Technological Education, Department of Civil Engineering Educators, ASPETE Campus, Eirini Station, 15122 Amarousio, Athens, Greece.

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Abstract

This paper presents a short view of the first Archimedean Screw Turbines CFD modelling results, which were carried out within the recent research entitled "Rebirth of Archimedes in Greece: contribution to the study of hydraulic mechanics and hydrodynamic behavior of Archimedean cochlear waterwheels, for recovering the hydraulic potential of Greek natural and technical watercourses". This CFD analysis, based to the Flow-3D code, concerns typical Tubular Archimedean Screw Turbines (TASTs) and shows some promising performances for such small hydropower systems harnessing the important unexploited hydraulic potential of natural and technical watercourses of Greece, of the order of several TWh / year and of a total installed capacity in the range of thousands MWs.

Keywords: CFD; Flow-3D; TAST; Small Hydro; Renewable Energy; Greek Watercourses.

1. Introduction

It seems that Archimedean hydropower technology has a very long history in the world and in Greece. This technology has attracted recently the attention of many Universities and of several European industrial companies installing a series of screw plants during the last decade [1-4]. The rebirth in Greece of nowadays of the Archimedean screw philosophy, as a modern hydropower tool, could cover various hydropower requirements of hundreds of low-head sites. The installation of a series of such small Tubular Archimedean Screw Turbines (TASTs) in the Greek natural and technical watercourses could be relatively simple, with a good efficiency, similar or higher than that of other small water power stations [1, 4-12]. The following Figure 1 presents a photorealistic view of such a small scale inclined axis TAST plant containing mainly the water inlet, the screw turbine and the outlet.

Such TASTs could be used for small heads, in the range of 1 to 5 m, with various flow rates and should be inclined at an angle, between 22° and 32° from the horizontal [1, 4, 6, 7]. For greater heads, a cascade of two or more similar TASTs could give an efficient hydropower solution. For the case of important water discharges the Archimedean technology imposes two or more TASTs in parallel.

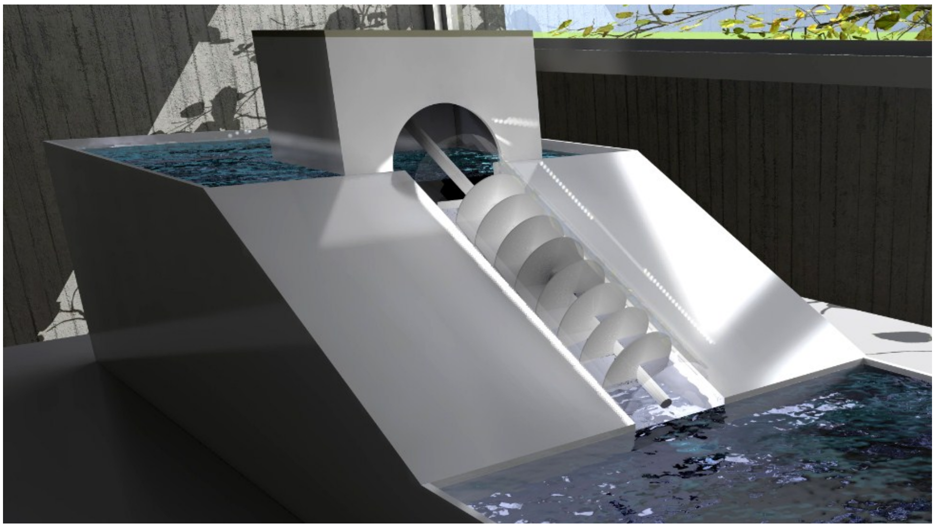


Figure 1. Photorealistic view of an inclined axis TAST (photo A. Stergiopoulou).

A part of about 45.915 km^2 of the total Greek area 131.913 km^2 was investigated recently by adopting a holistic assessment methodology and using simple quasi-linear formulas for the watercourses in order to estimate the theoretical hydropotential E_i (kWh) and the hydropower P_i (kW), mainly as functions of the available river water discharge Q_i and the topographical height ΔH_i, in the framework of a recent Greek Inventory of the Archimedean Hydropower Potential [13]. This inventory gives an overall theoretical Archimedean small hydrocapacity of about 3,500 MW and a total theoretical Archimedean hydropower potential around 30 TWh and proves that pleiades of promising small hydro sites in Greece for TASTs could be installed mainly along the "Two Archimedean Hydro Spears (AHS)" presented in Figure 2. In this double AHS representation, it is obvious the important small hydroelectric role of Pindos mountain range, along the first AHS, from Epirus, Thessaly, Central Greece, Peloponnesus, and the role of the mounts Vermion, Voras, Paikon and Rodope of Northern Greece, Macedonia and Thrace, along the second AHS [13].

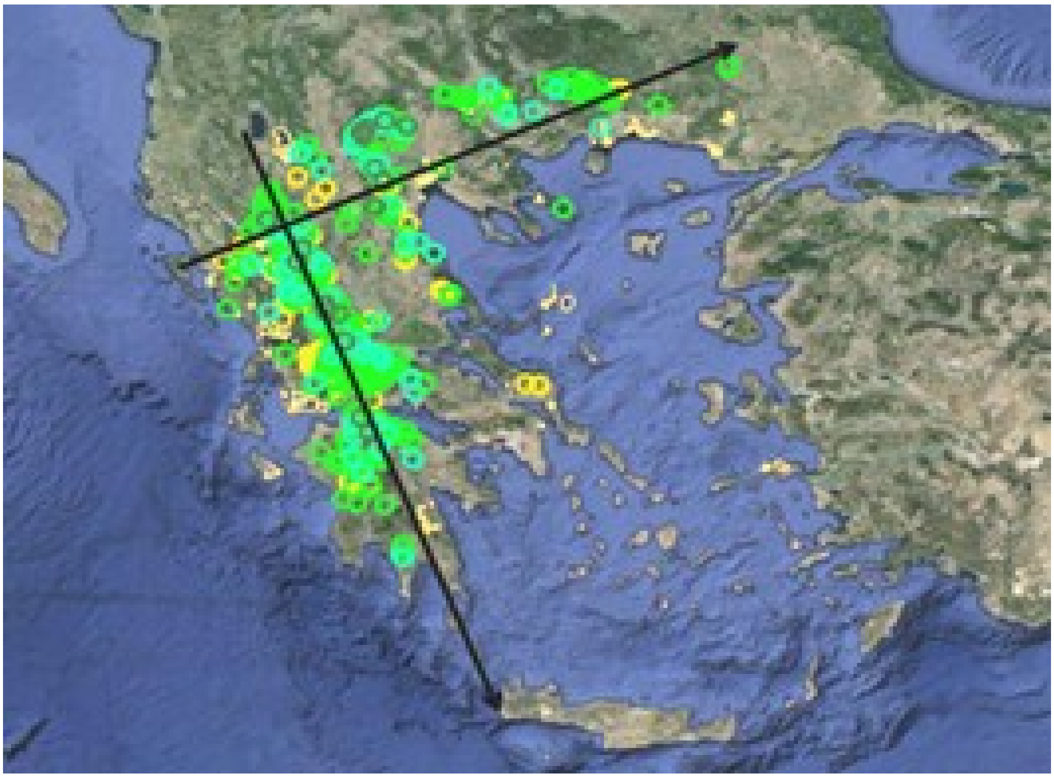


Figure 2. The two Archimedean Hydro Spears of Greece

2. Short View of TAST Design and Meshing Geometry

A short view of the first Tubular Archimedean Screw Turbines CFD modelling results, which were carried out within the recent research entitled “Rebirth of Archimedes: contribution to the study of hydraulic mechanics and hydrodynamic behavior of Archimedean cochlear waterwheels, for recovering the hydraulic potential of natural and technical watercourses” will be presented below. A CFD analysis, based in the Flow-3D program, concerning a typical TAST to be installed with various angles of orientation in promising small hydro sites in Greece for harnessing the important unexploited hydraulic potential of small values of water flows, will be presented for the power performances. In the present work, we study the performances of such TASTs in operation in 3 water discharges (Q = 0.15, 0.30, 0.45 m^3/s) with some inclination axis angles $\theta 1=22^o$, $\theta 2=25^o$, $\theta 3=28^o$, $\theta 4=32^o$, among all the possible inclination axis screw angle cases, θ1, θ2……θn, except the extreme orientation cases, of the horizontal and vertical axis screws, good only for the recuperation of the kinetic hydraulic energy (Figure 3).

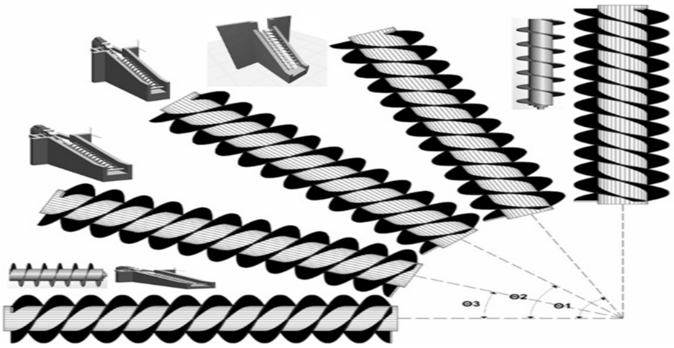
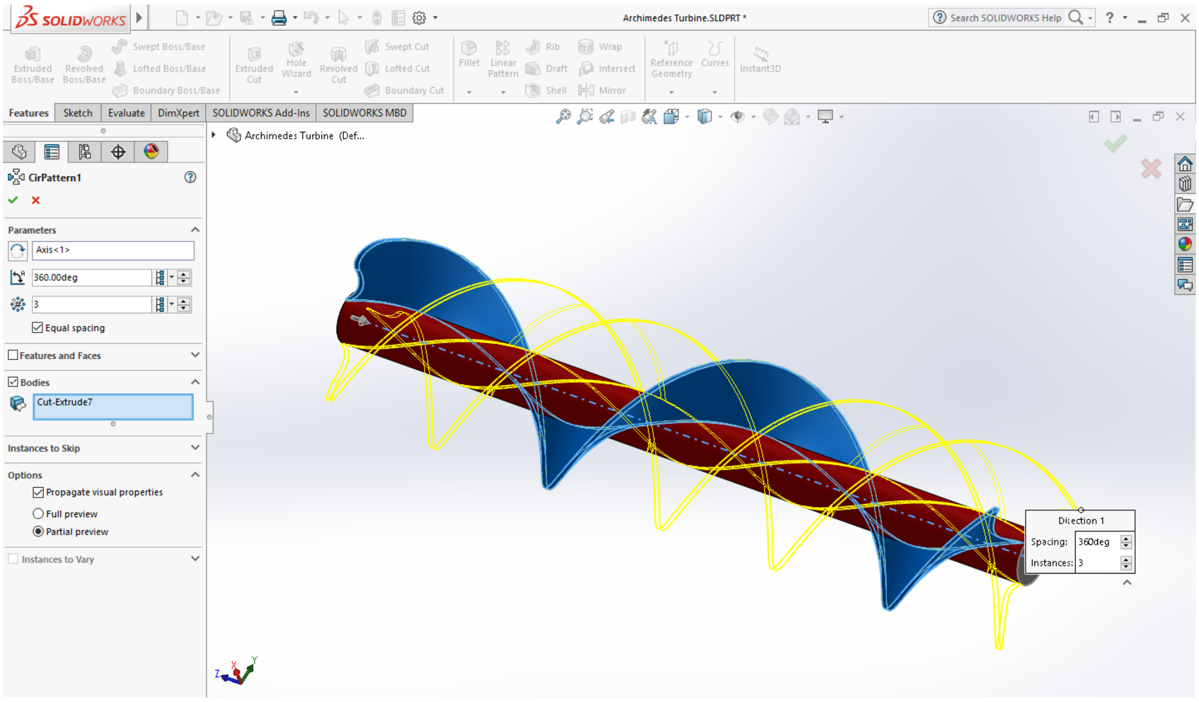


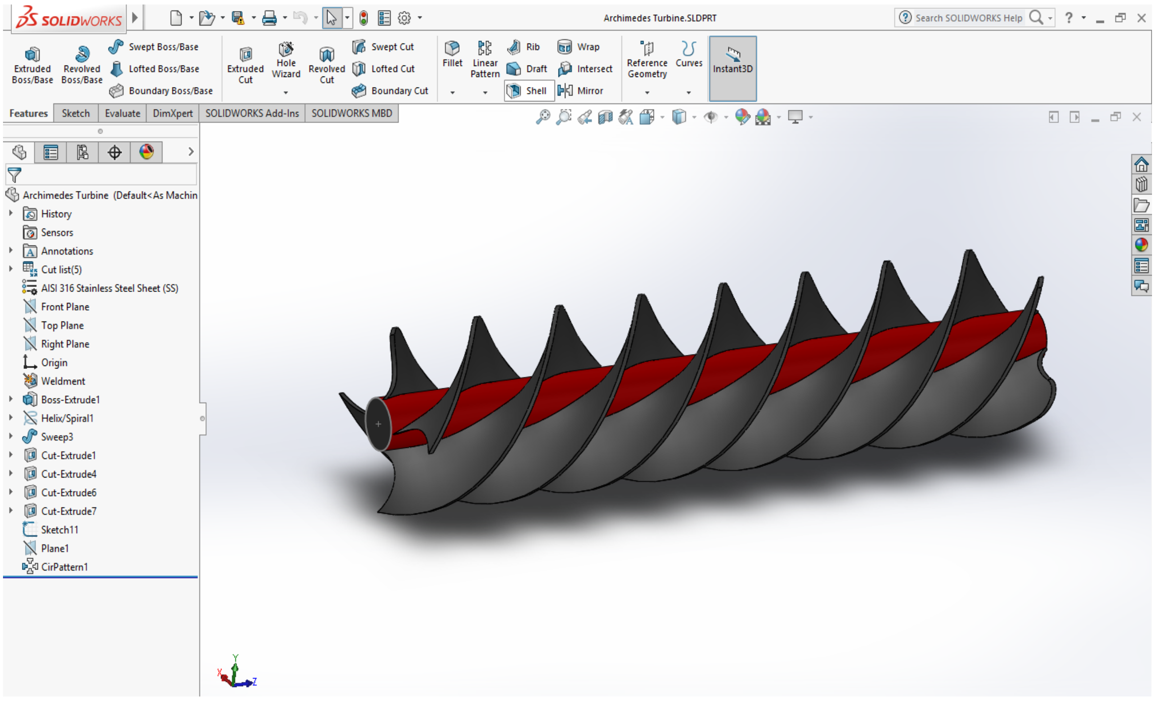
Figure 3. The spectrum of all the screw axis orientation cases.

CFD commercial code Flow-3D (version 11.2) developed by Flow Science, Inc. was selected in the present study, with licenses obtained by ASPETE (School of Pedagogical and Technological Education, Athens, Greece) for the Master courses (Ms Management Technologies of Waters, soft Energy Sources and Environmental Mechanics) and for research needs [14]. The software licenses included also the post-processing tool Flow Sight, designed to deliver sophisticated visualizations of Flow-3D results. Taking into account that the object library of the Flow-3D code did not include Archimedean screws the equivalent of drawing programs was used and a CAD model shown in Figures 4 and 5 was prepared using SolidWorks, for represent one typical TAST, as a quite simple water screw rotor. To configure an inclined axis Archimedean screw a design software (CAD) was used, which is able to perform a two-dimensional design and also a three-dimensional parametric geometry. Furthermore, specific objects were used, namely the cylinder and screw propeller which are some of the basic solids in the CAD program. These objects were changed in order to have the desired dimensions. Initially, a cylinder with fixed length and diameter was constructed. Then the screw blade was designed in such way that the internal radius coincides with the radius of the cylinder and its length is an integer multiple of the cylinder length. Furthermore, the inclined helix was placed on the cylinder and finally, copies of the helix along the length of the cylinder were created. Then the final form of the screw is easy to be shaped of the helix along the length of the cylinder. Moreover, a wide variety of number of helices (2, 3, 4…. n) can be used. Constructing the three helices, placing them on the cylinder and finally making copies of the propellers along the cylinder, give the final form of screw rotor. The object form, that receives the CFD Flow-3D code, is STL (stereolithography). Thus a converter program was used to convert the CAD object into STL object. The typical tubular turbine geometry in the modeling is designed using SolidWorks software with a total length L equal to 2550 mm, an outer diameter equal to 490mm and 3 blades. The creation of this 3bladed Archimedean Screw with SolidWorks is given in Figure 4. Figure 5 presents a photorealistic view of this Archimedean Screw.



Axis<1>
360.00deg
3
☑ Equal spacing
Cut-Extrude7
☑ Propagate visual properties
○ Full preview
● Partial preview
Direction 1
Spacing: 360deg
Instances: 3

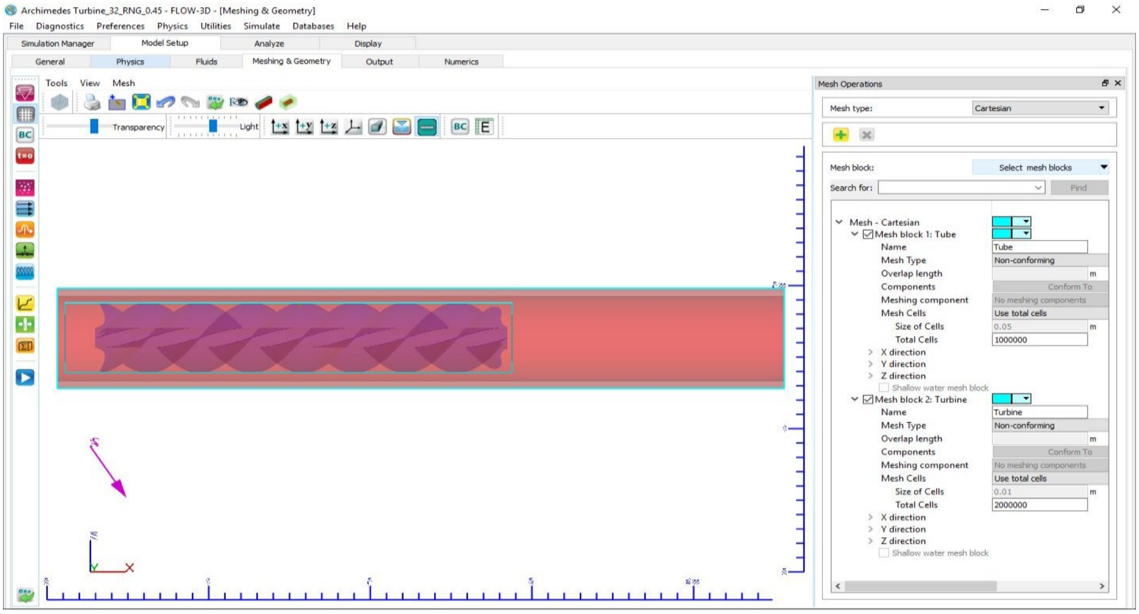
Figure 4. Creation of the 3bladed Archimedean Screw with Solidworks.



Archimedes Turbine (Default<As Machin
History
Sensors
Annotations
Cut list(5)
AISI 316 Stainless Steel Sheet (SS)
Front Plane
Top Plane
Right Plane
Origin
Weldment
Boss-Extrude1
Helix/Spiral1
Sweep3
Cut-Extrude1
Cut-Extrude4
Cut-Extrude6
Cut-Extrude7
Sketch11
Plane1
CirPattern1

Figure 5. A photorealistic view of the 3bladed Archimedean Screw Turbine

The computational domain is constructed using the utility provided by the Mesh block of the CFD program Flow-3D. It contains the water inlet, the screw and the outlet as it is already indicated in the TAST of Figure 1. In order to decrease the computational time, the screw and the supporting mechanism were designed, with the SolidWorks program, avoiding complicated constructive details**.** At the "Meshing & Geometry" tab of the Flow-3D program a tubular cylinder having the same diameter with the outer screw rotor diameter was created. The geometry of the screw rotor designed by SolidWorks was imported into the program as STL file. The STL object introduced to the CFD Flow-3D helped to the mesh grid generation. A mesh was created just for the total length of screw rotor with 2 000 000 cells (nested mesh) and another mesh covering the whole geometry (tube and screw rotor) with 1 000 000 cells (Figure 6).



Mesh type: Cartesian

Mesh block: Select mesh blocks

Search for:

- Mesh - Cartesian
  - ☑ Mesh block 1: Tube
    - Name: Tube
    - Mesh Type: Non-conforming
    - Overlap length: m
    - Components: Conform To
    - Meshing component: No meshing components
    - Mesh Cells: Use total cells
      - Size of Cells: 0.05 m
      - Total Cells: 1000000
    - X direction
    - Y direction
    - Z direction
    - ☐ Shallow water mesh block
  - ☑ Mesh block 2: Turbine
    - Name: Turbine
    - Mesh Type: Non-conforming
    - Overlap length: m
    - Components: Conform To
    - Meshing component: No meshing components
    - Mesh Cells: Use total cells
      - Size of Cells: 0.01 m
      - Total Cells: 2000000
    - X direction
    - Y direction
    - Z direction
    - ☐ Shallow water mesh block

Figure 6. “Meshing & Geometry” tab Operations (Flow 3-D).

3. Flow-3D Simulations and Hydropower Performances of TAST’s

Flow-3D code uses finite volume approach, interactive grid generation software and computation flow solver modules, to solve continuity, Euler and the Reynolds-averaged Navier-Stoke’s (RANS) equations, in all the cases of the flow regimes over the screw turbine computational domain.

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}\cdot\left(\rho\vec{V}\right) = 0 \tag{1}$$

$$\rho\frac{D\vec{V}}{Dt} = \rho\left[\left(\vec{V}\cdot\vec{\nabla}\right)\vec{V} + \frac{\partial\vec{V}}{\partial t} + \right] = -\vec{\nabla}p + \rho\vec{F} \tag{2}$$

The computational domain is subdivided into several mesh blocks containing rectangular grid cells (structured mesh). With each cell there are associated local average values of all dependent variables. For each cell values variables are solved at discrete times using a staggered grid technique [14-16]. The numerical model involves the variables of velocities (u, v, w) and fractional areas (A) at the centers of cell-faces, pressures (P), fluid fractions (F), fractional volumes (VF), densities (ρ), internal energy (I), turbulence quantities for energy (q), dissipation (D) and viscosity (μ) located at cell centers. The staggered grid places all dependent variables at the center of each cell except velocities and fractional areas, which are located at the center of the cell faces normal to the corresponding direction. Fluid velocities and pressures are located at staggered mesh locations. Free surface of the flow is tracked using the Volume of Fluid (VOF) method developed by [6]. Solid body is defined as an obstacle by the implementation of the Fractional Area/Volume Obstacle Representation (FAVOR) method where obstacles are embedded in a fixed grid by allowing them to block portions of grid cell faces and cell volumes. The geometry is therefore conveniently represented within the grid cells [14-16]. The FAVOR method is a porosity technique to define obstacles. The grid porosity value is 0 within the obstacle and one for cells without the obstacle. Cells only partially filled with an obstacle have a value between 0 and one [17-20]. The RNG model was used for the turbulence modelling. A systematic CFD uncertainty evaluation process known as Grid Convergence Index (GCI) described in [1, 20] is used for evaluating the uncertainties in the numerical model. The equations of fluid dynamics are solved numerically using the Flow-3D software for various flow conditions and for different geometric screw variations (e.g. change the orientation angle of the rotation axis), adopting the Navier-Stokes equations for incompressible fluid and RNG model (k-e) for simulating the turbulence of the flow field. Towards this direction, from the tab “Model Setup → Physics” the following options were activated: a) Gravity and non-inertial reference frame (activation of gravity on the axis z= -9,81 m/s^2), b) Moving and simple deforming objects (activation of the GMO model k-ε with explicit moving object selection), c) Viscosity and turbulence (activating the RNG model with dynamically computed option). From the tab "Model Setup→ Fluids", the water is selected as the working fluid, whereas the density at 20 °C is 1000 kg/m^3 and the dynamic viscosity is 0.001 N.s/m^2. The other fluid physical data follows the fluid properties in the existing literature. As Initial Conditions (initial input conditions) the uniform Hydrostatic Pressure distribution is chosen, whilst defining as Initial Fluid elevation, the water level upstream of the screw. There is an obvious need to set the boundary conditions in each of the three mesh blocks created, thus the following table lists them.

Table 1. Boundary conditions for each mesh block.

Boundaries	Block 1 (located the screw)	Block 2 (inlet)	Block 3 (outlet)
X min	Symmetry	Symmetry	Symmetry
X max	Symmetry	Symmetry	Symmetry
Y min	Symmetry	Symmetry	Symmetry
Y max	Symmetry	Symmetry	Specified Pressure
Z min	Wall	Specified Velocity	Wall
Z max	Specified Pressure	Outflow	Specified Pressure

The rotation speed of the screw is necessary to be specified as it deals with each different corresponding water flow. Thereupon, it is essential that the screw, in terms of computational fluid dynamics, can be correctly rotated by choosing type of moving object the prescribed motion. From the tab "Moving object Set up→edit→Motion constraints→6 degrees of freedom→Initial/Prescribed Velocities→Angular velocity components (in body system)" the ω_x, ω_y, ω_z are set. The prime objective of the present CFD Flow-3D simulations is to evaluate the hydrodynamic performances and yield of the typical Tubular Archimedean Screw Turbines (TASTs) to be installed in various low-head sites in Greece for various flow discharges and with various angles of the rotation axis orientation. The simulations lead to the identification of the torque results, for that is activated the sequence of tabs "Component Properties → output→Pressure and Shear force output" and tabs "Analyze→ Probe→ General History→ Component 1 GMO residual x- torque about fixed axis in body system (Integrate)→Text/ Graphical→ Render" [1, 20].

We present below some CFD Flow-3D simulation information concerning the hydropower performances of one typical Tubular Archimedean Screw Turbine operating in various flow discharges conditions and various orientation angles of the rotation axis. It seems that the finish simulation running time of 5 **s** was enough for most of the present hydrodynamic performances through Flow-3D simulations of the TAST to reach the convergence. The variation of the quantities has shown a reducing oscillations until reaching a statistically stationary value, with some very small and regular variations about the mean value. In the following Figures 9, 10 and 11 it is possible to visualize the water flow free surface present in the typical TAST in the second 5 of simulation.

Figure 7 gives comparisons of Archimedean screw power performances P(W) for flow rates Q equal to 0.15 m^3/s and 0.30 m^3/s and for angles of orientation 22° & 32°.

Figures 8 gives comparisons of Archimedean Screw Turbine Power Performances P(W) for various water discharge values equal to 0.15, 0.30, 0.45 m^3/s and for angles of orientation $\theta = 22^o$ and 32°.

Figures 9 and 10 present various hydrodynamic performances of the Archimedean Screw (e.g. MKE/Mean Kinetic Energy, Torque, Turbulent Kinetic Energy, Turbulent Dissipation) for flow discharge Q = 0.15 m^3/s and for orientation angles of the rotation axis $\theta = 22^o$ and 32°.

Figures 11 and 12 present various performances of the Archimedean Screw (MKE/Mean Kinetic Energy, Torque, Turbulent Kinetic Energy, Turbulent Dissipation) for flow discharge Q = 0.45 m^3/s and angles of orientation, $\theta = 22^o$ and 32°.

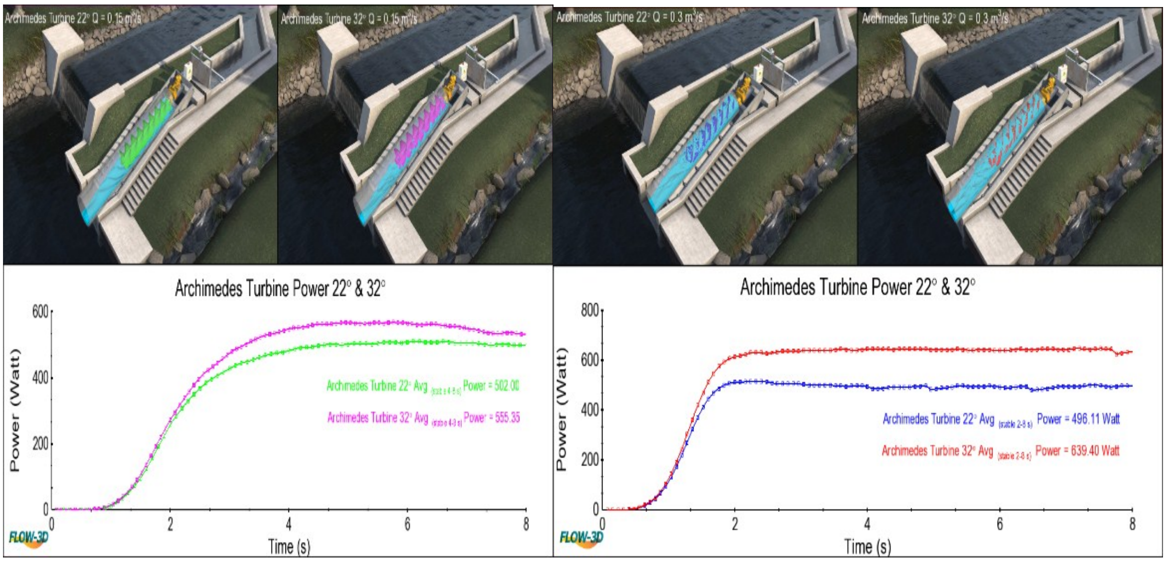


Figure 7. Comparison of Archimedean screw power performances P(W) for Q = 0.15 m^3/s and 0.30m^3/s and angles of orientation 22° & 32°.

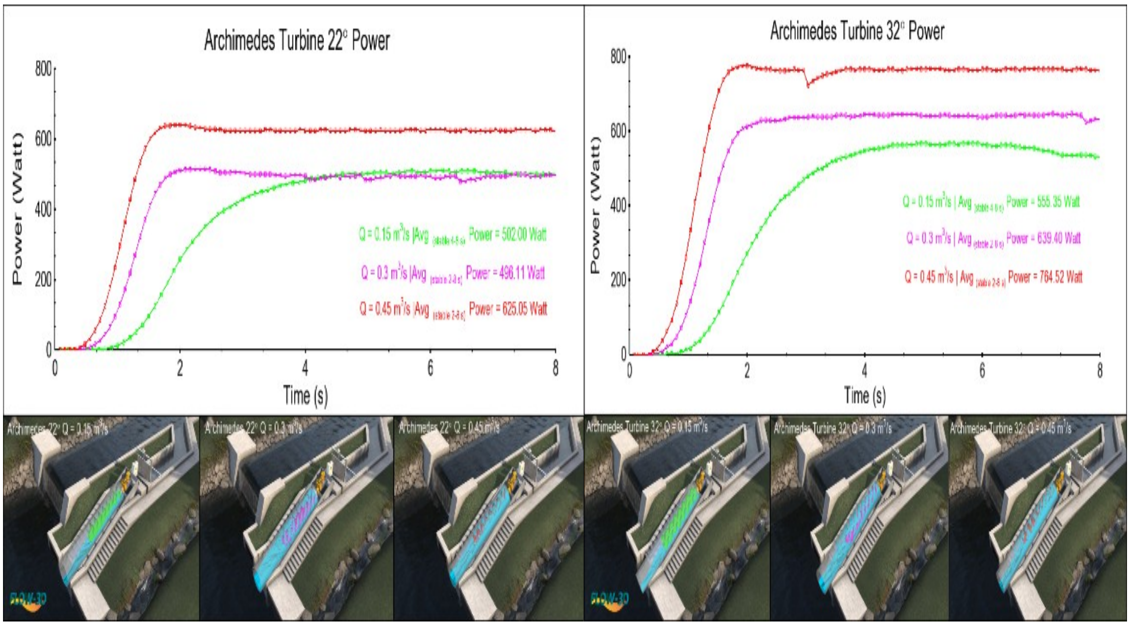


Figure 8. Comparison of Archimedean Screw Turbine power performances P(W) for angle of orientation θ = 22° and 32° and for various water discharge values Q = 0.15, 0.30, 0.45 m^3/s.

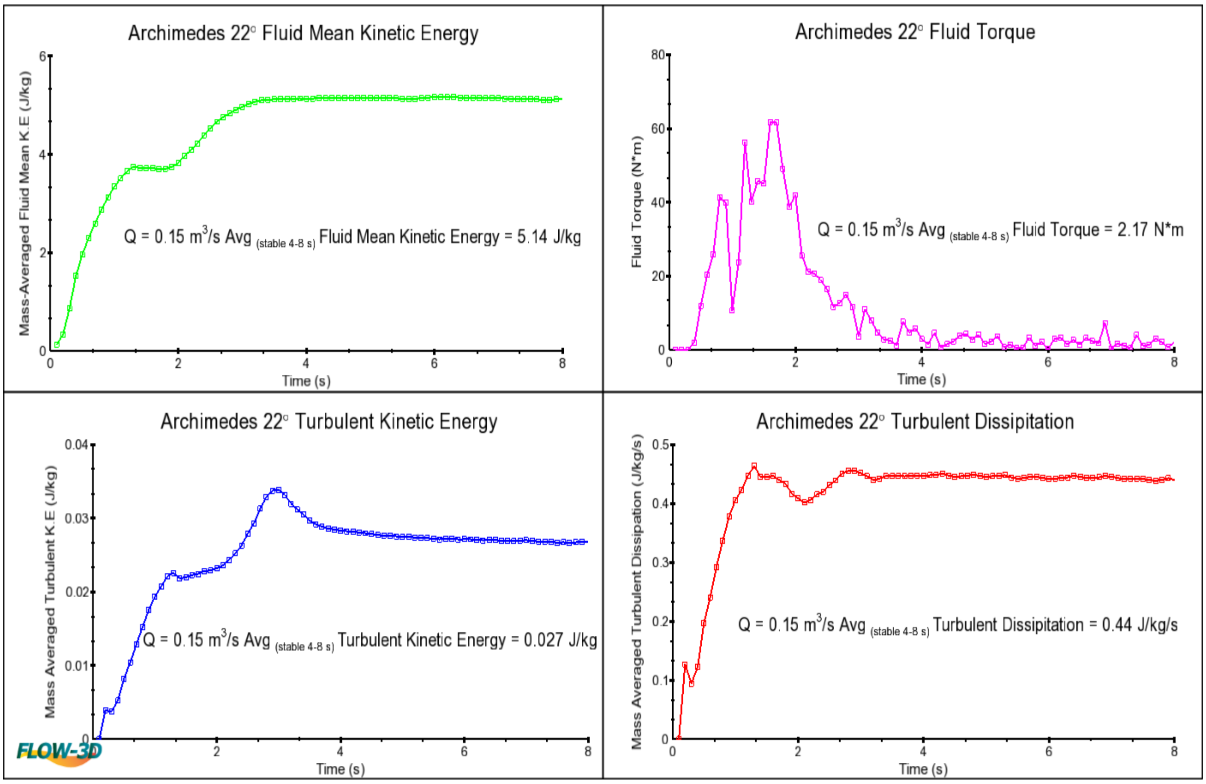


Figure 9. Various performances of the Archimedean Screw (MKE/Mean Kinetic Energy, Torque, Turbulent Kinetic Energy, Turbulent Dissipation) for flow discharge Q = 0.15 m^3/s and an angle of orientation θ = 22°.

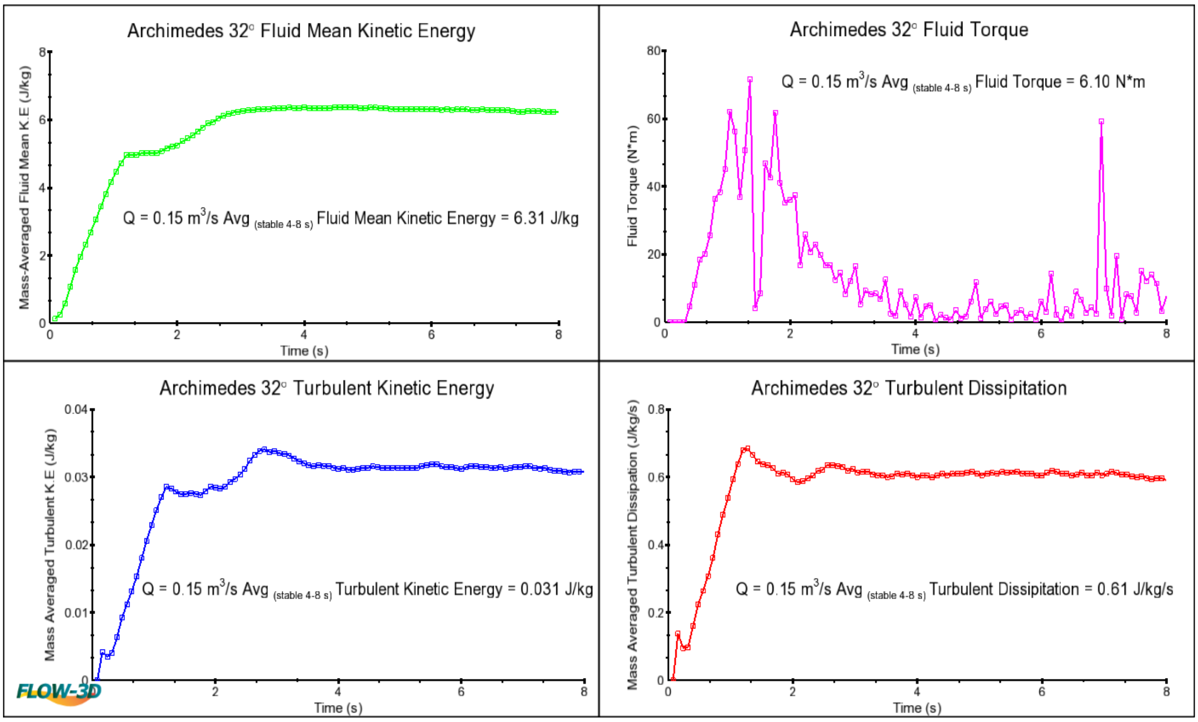


Figure 10. Various performances of the Archimedean Screw (MKE/Mean Kinetic Energy, Torque, Turbulent Kinetic Energy, Turbulent Dissipation) for flow discharge Q = 0.15 m^3/s and an angle of orientation θ = 32°.

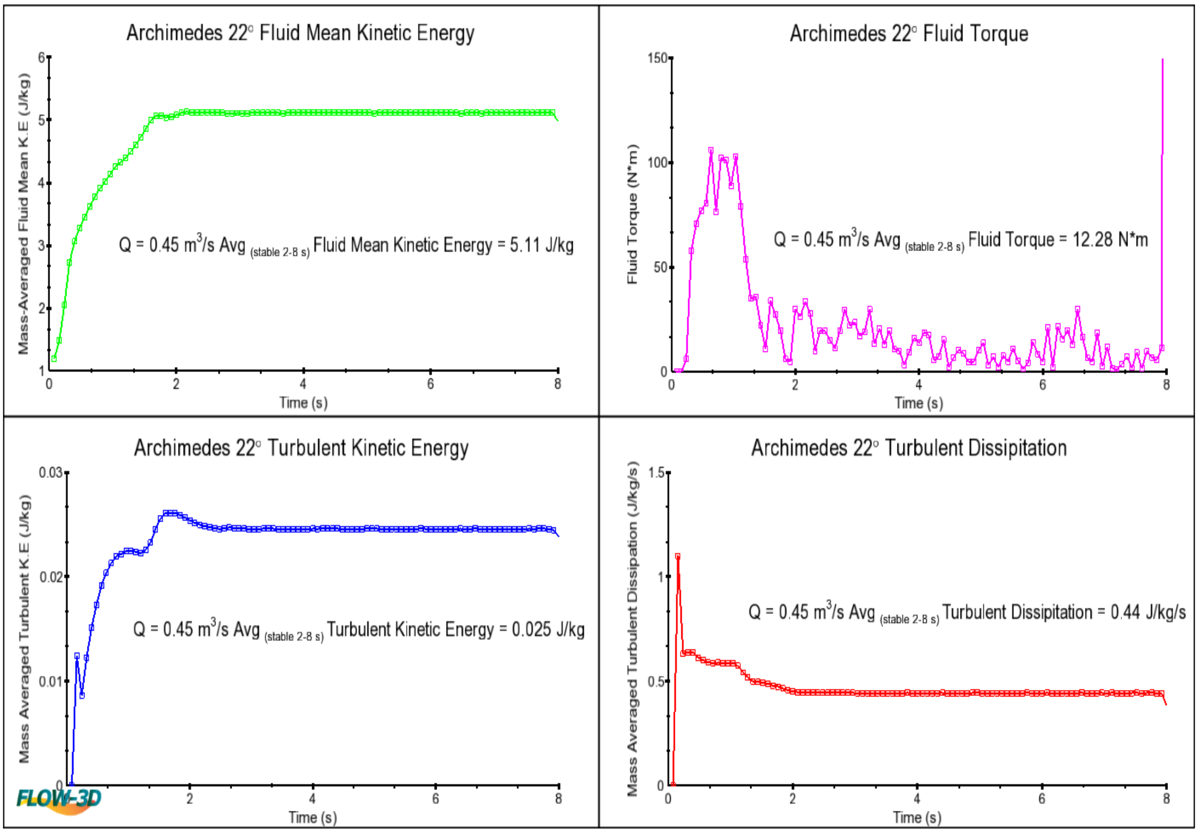


Figure 11. Various performances of the Archimedean Screw (MKE/Mean Kinetic Energy, Torque, Turbulent Kinetic Energy, Turbulent Dissipation) for flow discharge Q = 0.45 m^3/s and an angle of orientation $\theta = 22^o$.

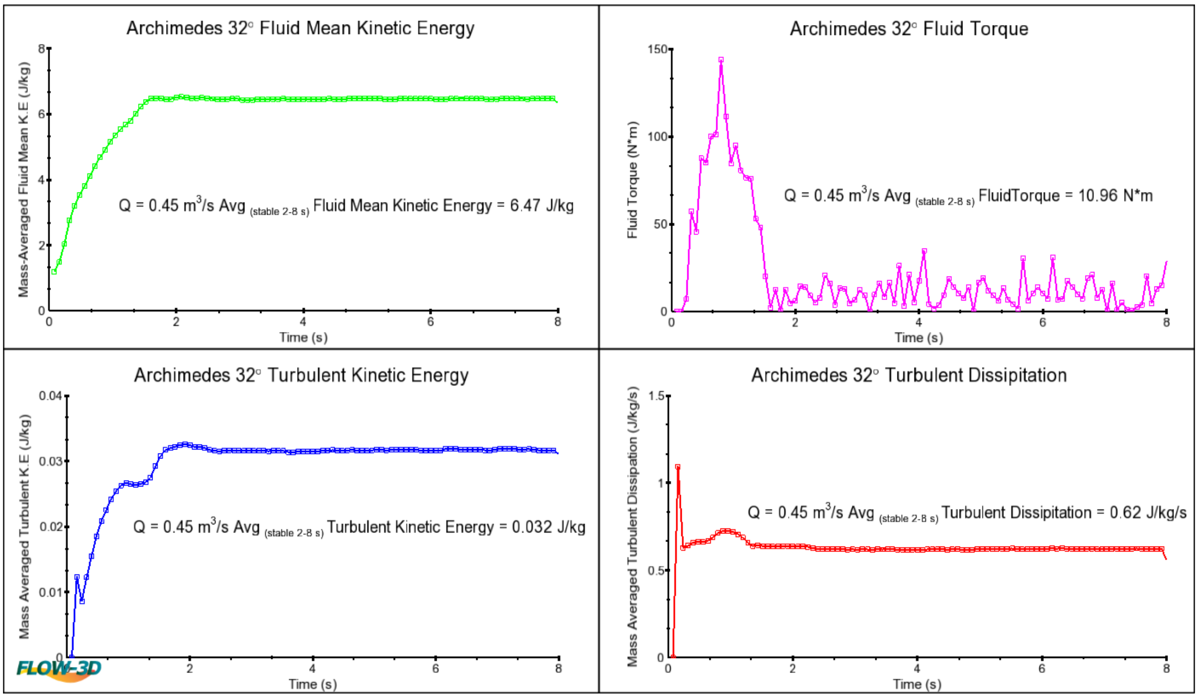


Figure 12. Various performances of the Archimedean Screw (MKE/Mean Kinetic Energy, Torque, Turbulent Kinetic Energy, Turbulent Dissipation) for flow discharge Q = 0.45 m^3/s and an angle of orientation $\theta = 32^o$.

4. Some First TASTs Flow-3D Conclusions

The prime objective of the present CFD Flow-3D simulations was to evaluate the hydrodynamic performances and yield of typical Tubular Archimedean Screw Turbines (TASTs) to be installed in a series of low-head sites in Greece. The presented here preliminary Flow-3D simulation results for such TASTs operating in various water discharges and various orientation angles of the rotation axis used in low-head sites for harnessing the important unexploited Greek small hydropower potential are very promising. It seems that the preliminary optimal TAST operation conditions correspond to the orientation angle $\theta = 32^o$ and to the flow discharge value $Q=0.45$ m^3/s.

A typical TAST, designed by using CAD codes, needs a converter program to obtain its STL form admitted by CFD. Flow-3D code. Then, the introduced STL object to the Flow-3D technique helped to create the mesh grid generation and resolve the Navier-Stokes equations for various inclined axis TASTs. Flow-3D code using interactive grid generation software and computation flow solver modules simulating continuity, Euler and Navier-Stokes equations, in all the cases of the flow regimes, seems to have important contribution to the study of hydrodynamic behavior of Tubular Archimedean Screw Turbines. In the present paper the hydrodynamic performances of 3bladed TASTs, have been analyzed in various values of input flow and inglination angles.

The Flow-3D is a powerful CFD tool for investigation of TASTs hydrodynamic performances and to simulate 3D through flow phenomena. The three dimensional water flow, through the blade channels of the rotating screw turbine, is one of the most complex hydraulic situations. Even more when this phenomenon is to be simulated, it introduces a special complexity, with difficulty in searching and finding satisfactory solutions for areas with interfaces. Further research investigations should be done for a large panel of TAST geometries, screw inclinations and flow conditions. Further TAST Flow-3D steps to follow are, the reconsideration of the boundary conditions, the refinement of the mesh blocks, the idea of changing the axis gravity in order to reduce the computing time by rotating the screw and the mesh blocks.

Dedication

The present paper is dedicated to the memory of our wonderful son and brother George Stergiopoulos, Biosystem Engineer and M.Sc. in Waste Treatment, who recently passed away.

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Alkistis Stergiopoulou is Doctor of Philosophy (Ph.D.) of the National Technical University of Athens, Master of Science in Water Resourses & Technology (Civil Engineering School, National Technical University of Athens, 2008), Master in Total Quality Management (Open University of Greece, 2012), BSc in Natural Resources Management & Engineering (Agricultural University of Athens, 2007). She was Researcher of the BOKU University of Natural Resources and Life Sciences (Vienna, Austria, 2014-2017) and Basic Scientific Member of the National Research Project ARCHIMEDES III. Her main research interests are, Archimedean Screw Turbines, Small Hydropower, Renewable Energy Sources, C.F.D., Applied Hydraulics, Fluid Mechanics, Optimization and Special Water Processes. She is the co-founder of the FISCHCOM company. She was Process Engineer in the M+W Group. Actually she is Senior Process Engineer at VTU Engineering in Vienna, Austria.

E-mail adress: alkisti_ster@yahoo.gr

Vassilios Stergiopoulos is Professor of Hydraulics and Hydropower at the Civil Engineering Educators Department of the School of Pedagogical and Technological Education (ASPETE, Athens, Greece), Docteur d'Etat ès Sciences Mathématiques (University of Aix-Marseille II, France) Docteur-Ingenieur and D.E.A. in Fluid Mechanics (University of Aix-Marseille). His main research interest are Archimedean Screw Turbines and Plants, Small Hydropower and Hydraulic Turbomachines, Renewable Energy Sources, Environmental Hydraulics and Fluid Mechanics, C.F.D.
E-mail adress: bstergiopoulos@aspete.gr