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Experimental and theoretical research of zero head innovative horizontal axis archimedean screw turbines

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Abstract
The first aim of this paper is to present data concerning the design, construction, installation and operation of the first in the world Horizontal Axis Archimedean Screw Turbine (H.A.A.S.T.), having a length L=1m, diameters (output and input) D_o=200mm and D_i=100mm, a pitch S=200mm and a number of blades n=3. This horizontal screw could rotated horizontally and change direction ($\Delta\theta = 100^o$), forming an upstream angle of 50 ^{o} with its initial position and a downstream angle of 50 ^{o} with its initial position. The second aim of the paper is to present experimental results of the operation in a big hydraulic channel under various controlled conditions, simulating the operation of the physical conditions of rivers, open channels, etc**.** The third aim of the paper is to present a series of theoretical performance prediction results based on various S1/S2 algorithms and Linear Actuator Disk simulations.

Keywords: Archimedean turbines; Horizontal screw; Renewable energy systems; Kinetic energy.

1. Introduction

All hydropower turbines convert hydraulic energy into rotational mechanical energy, which is subsequently converted in electric energy [1]. There are three types of turbines, the reaction, the impulse and the Archimedean screw turbines, the difference being mainly the manner of water head conversion. In the last centuries many turbines, which work on the basis of the three types, have been invented. This doesn't mean that there can't be new inventions in this field [2-4]. The paper presents theoretical and experimental research of an innovative Horizontal Axis Archimedean Screw Turbines (H.A.A.S.T.) harnessing the kinetic energy of rivers, currents and open channels works, newly developed under the present ARCHIMEDES III research.

The possibility of exploiting kinetic hydraulic energy of irrigation and drainage hydraulic networks, and currents of technical and natural watercourses, represents a large renewable energy resource. Pleiades of zero head sites in small and big watercourses, open water channels, as well as important sea and tidal currents, could be used for recovering zero head hydraulic energy and marine power for electricity generation. Little attention has been given towards this exploitation, despite the fact that such zero head sites and currents represent a large renewable energy resource that could be exploited by modern horizontal axis Archimedean hydropower technologies to provide impressive levels of electric power.

2. Towards the first in the world horizontal axis Archimedean turbine

The first in the world Horizontal Archimedean Screw Turbine, recently proposed by A. Stergiopoulou [5, 6], is installed and experimented in the hydraulic channel of the Institute for Water Management, Hydrology and Hydraulic Engineering/Department für Wasser-Atmosphäre-Umwelt/Institut für Wasserwirtschaft, Hydrologie und konstruktiven Wasserbau (IWHW), in Vienna, with the main geometrical characteristics $L_{channel}$= 4.17m, $b_{channel}$= 1.4m, $h_{channel}$ (depth)=1m. Four characteristic views of experimental tests in this hydraulic channel before the installation of the Horizontal Axis Archimedean Screw Turbine are given in Figure 1.

Figure 1. Four characteristic views of experimental tests in the hydraulic channel before the installation of the Archimedean Screw (photos A. Stergiopoulou, [5])

The length L, the diameters (output and input), the pitch S, and the number of blades of the new screw rotor are: L= 1m, D_o = 200mm, D_i= 100mm, S/Do = 1, S=200 mm, n= 3 (number of blades) (Figure 2).

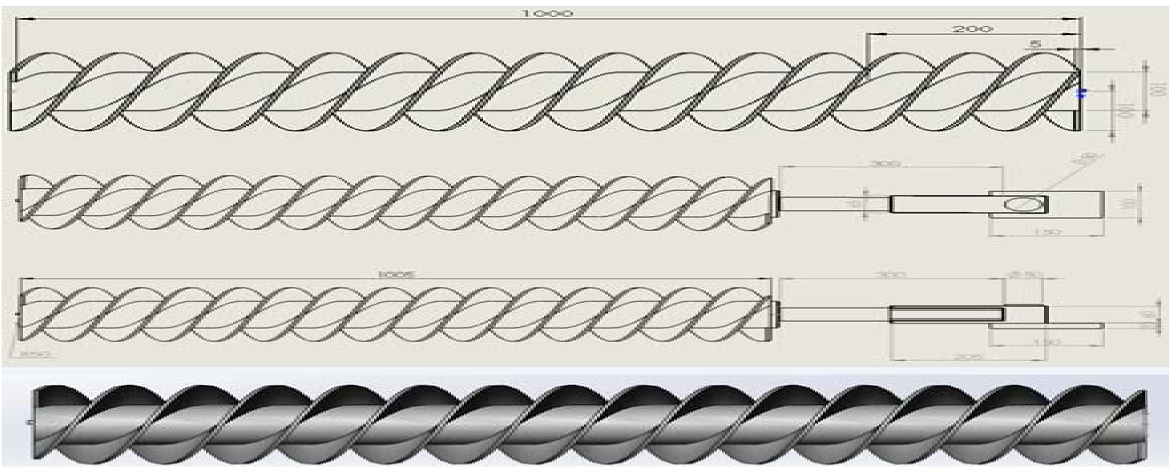

Figure 2. Design of the horizontal screw rotor (A. Stergiopoulou, [5])

This screw rotor could rotated horizontally and change direction ($\Delta\theta = 100^o$), forming an upstream angle of 50^o with its initial position and a downstream angle of 50^o with its initial position (Figure 3).

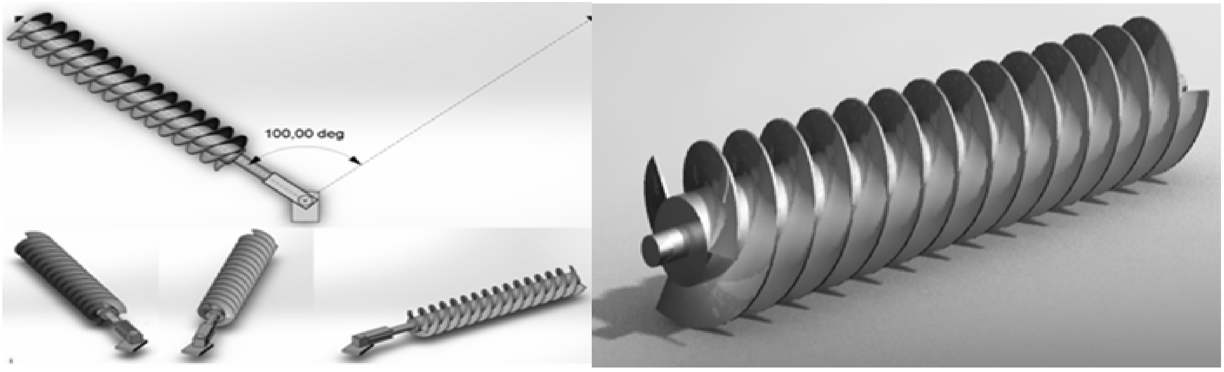

Figure 3. The horizontal screw rotor could change horizontally direction ($\Delta\theta = 100^o$) (photos A. Stergiopoulou, [5])

Some information concerning two possibilities for the rotation of the horizontal screw is given in Figure 4 below. According to the 1st possibility the screw rotor stays horizontal and is based on a "guide" at his right edge. The rotor could be moved along its "guide" towards "above" and "below" (inside the hydraulic channel of a depth 1m). According to the second possibility the horizontal screw rotor could be rotated horizontally ($\theta 1$, $\theta 2$, $\theta 3$….) with the help of the "right guide", which could also be rotated.

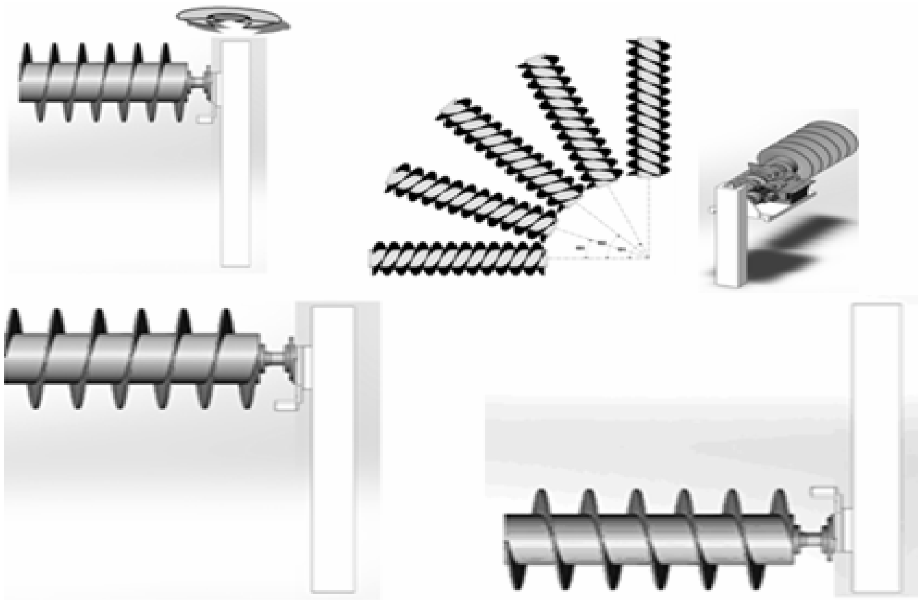

Figure 4. Rotation possibilities of the horizontal screw (A. Stergiopoulou [5])

3. Experimental investigations of the first H.A.A.S.T.

To configure the horizontal Archimedean screw, from a design and experimental point of view, were used the design software (CAD) which is able to perform a two-dimensional design and also a three-dimensional parametric geometry. Furthermore, were used specific objects, namely the cylinder and blades of the rotor. These objects were changed in order to have the desired dimensions, as described follows. Initially, was constructed the cylinder with fixed length and diameter. Then the screw blade constructed so that the internal radius coincides with the radius of the cylinder and its length is an integer multiple of the cylinder length. Then all the parts of the helix were placed on the cylinder along its length. Furthermore we use 2 and 3 helices, as shown below for the case of three blades. Then it is easy the final form of the 3-bladed screw. Constructing of three blades and then placing the blades along the cylinder. Figure 5 gives some perspective representations of the characteristic similarities between the design and the real construction of the first in the world Horizontal Archimedean Screw Turbine.

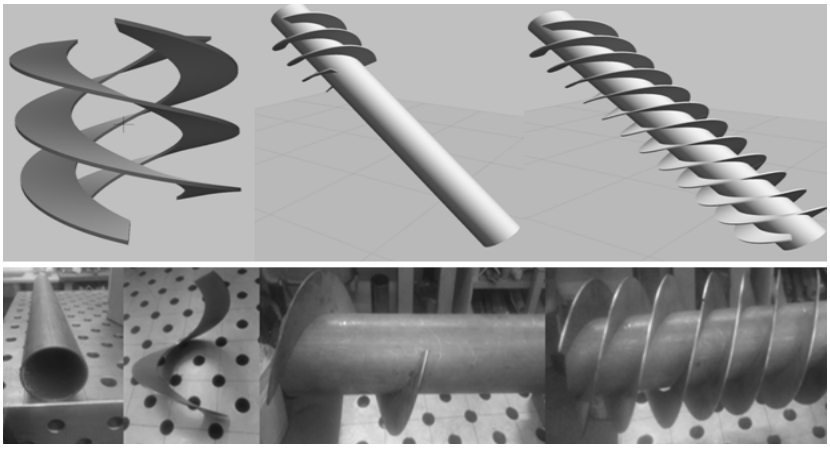

Figure 5. Perspective representations of the characteristic similarities between the design and the real construction of the first in the world horizontal archimedean screw turbine (photos A. Stergiopoulou [5])

Some views of the initial steps of the 3-bladed horizontal axis Archimedean screw rotor are given in Figure 6.

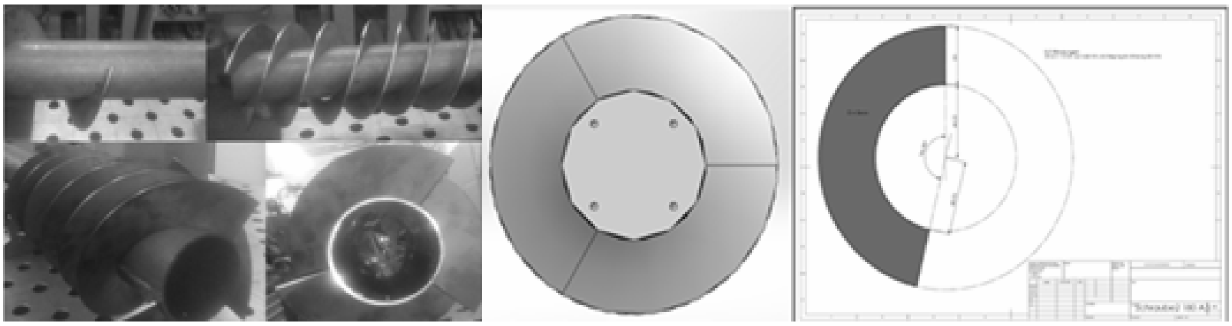

Figure 6. Views of the new 3-bladed horizontal axis Archimedean screw rotor

Figure 7 gives three rrepresentative views of the final H.A.A.S.T. steps before installing it in the experimental channel of the Institute for Water Management, Hydrology and Hydraulic Engineering (IWHW) of Vienna.

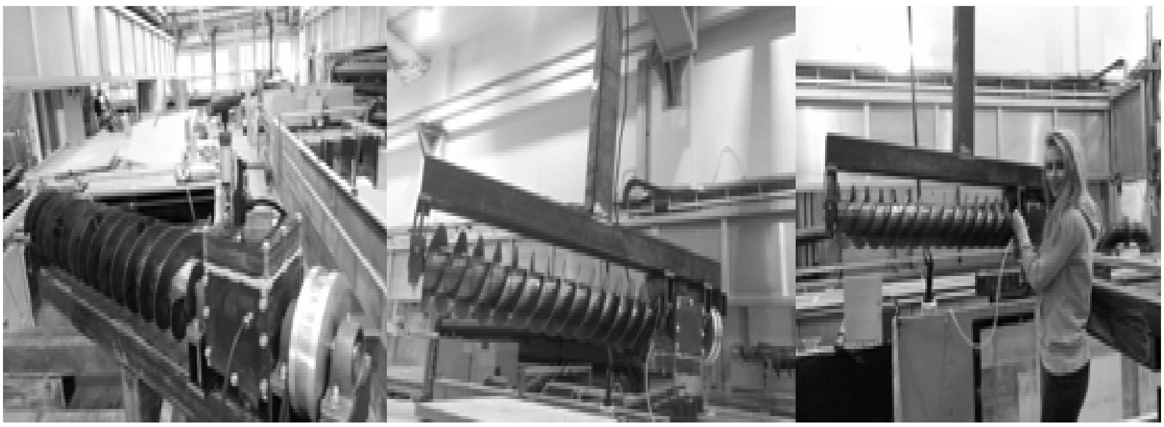

Figure 7. Steps towards the installation of the Archimedean Screw (photos A. Stergiopoulou [5])

Figure 8 gives seven characteristic views of the first in the world developed horizontal axis 3-bladed Horizontal Axis Archimedean Turbine in experimental operation in the hydraulic channel of the Institute for Water Management, Hydrology and Hydraulic Engineering/Department für Wasser-Atmosphäre-Umwelt / Institut für Wasserwirtschaft, Hydrologie und konstruktiven Wasserbau (IWHW), in Vienna.

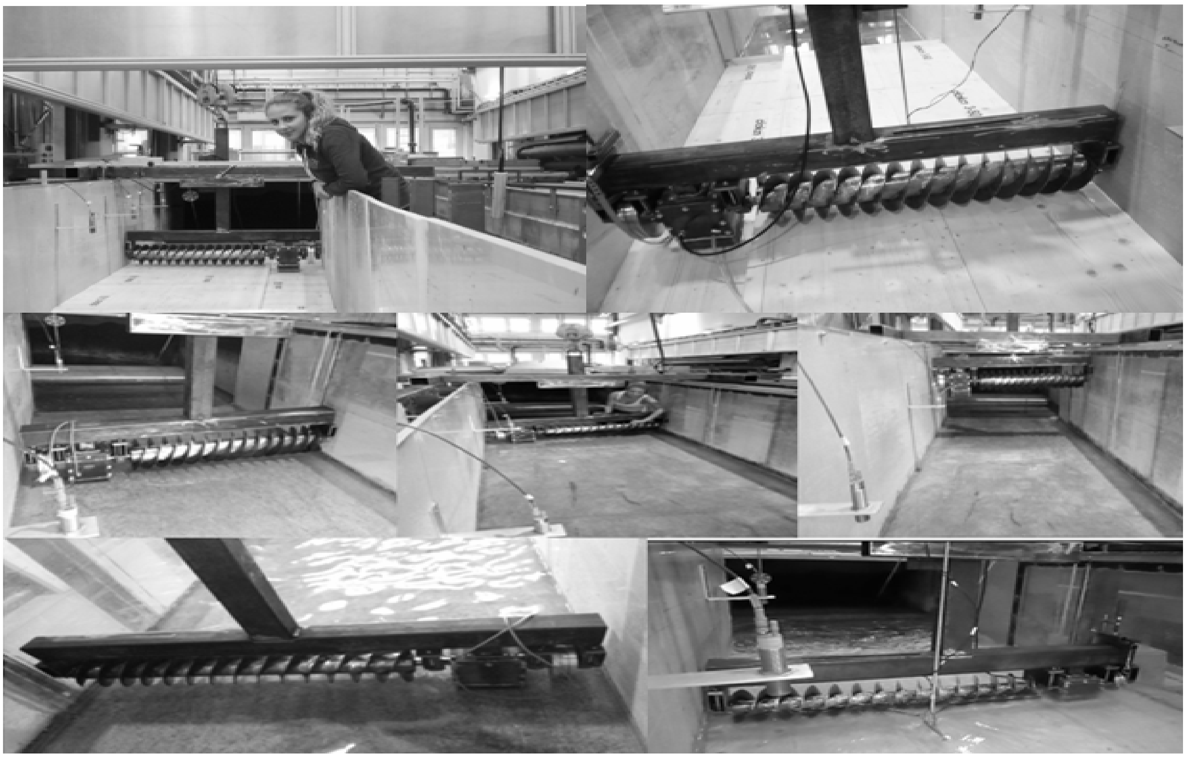

Figure 8. Seven characteristic views of the first in the world developed horizontal axis 3-bladed horizontal axis archimedean turbine in experimental operation in the channel (photos A. Stergiopoulou [5])

The experimental results of the efficiency performances of the Horizontal Axis Archimeden Screw Turbine, for different values of the flow discharge Q = 40 l/s - 120 l/s, for different values of the orientation angle, θ = 0 ^{o} - 30 ^{o} , are presented in the 3D - diagram of Figure 9.

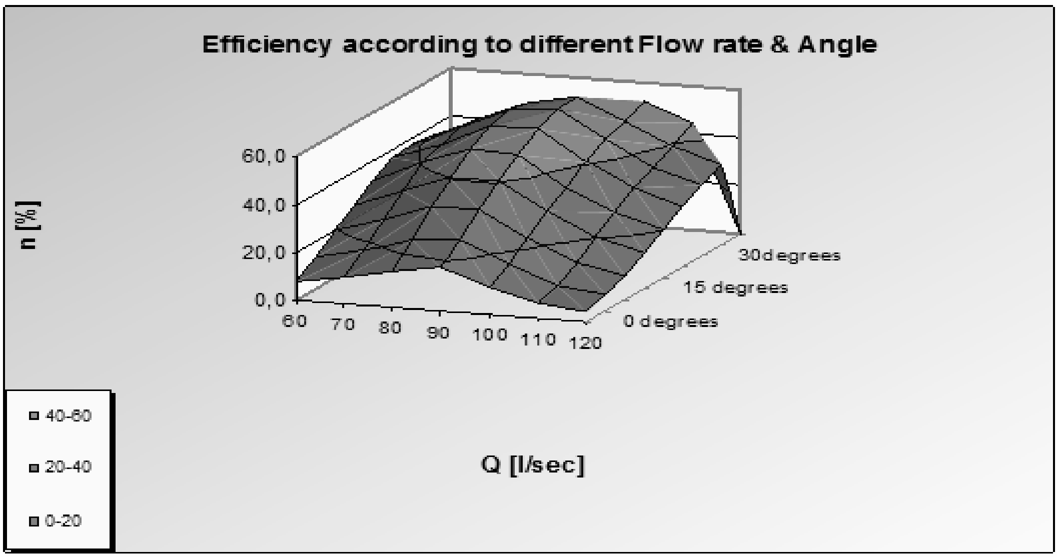

Figure 9. Efficiency experimental results of the Horizontal Axis Archimeden Screw Turbine operating in the Channel (A. Stergiopoulou [5])

4. Preliminary theoretical investigation of the first H.A.A.S.T.

To illustrate a quite simple basic theory of horizontal screw machine based on the drag principle or in the S1/S2 Black-Box flow theory [5], the undershot screw waterwheel could be considered as a first example. Consider the screw waterwheel, having an effective radius R, a blade area A_b and an angular velocity ω rotating in a stream flow of velocity $V=V_c$ (see Figure 10).

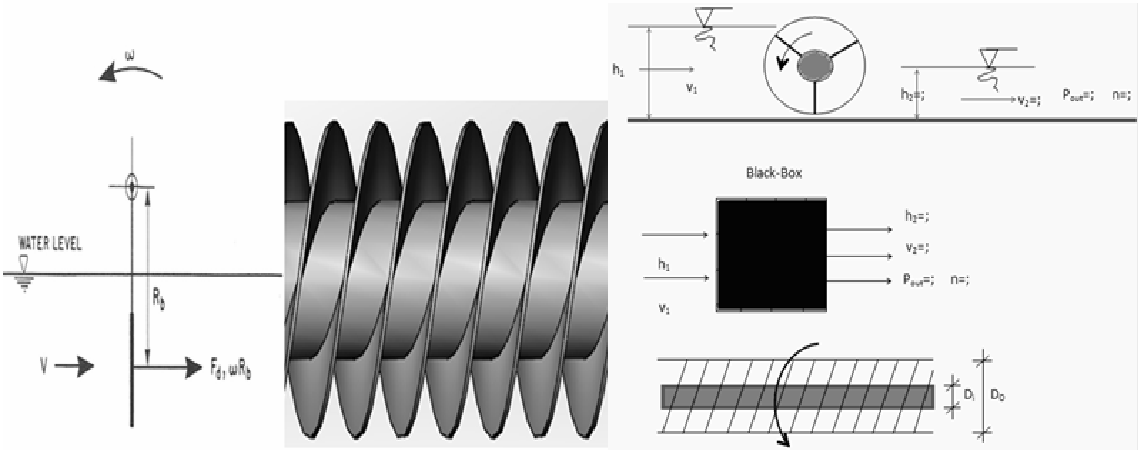

Figure 10. Approximations of the screw waterwheel rotating in stream flows (left) and the principle of S1/S2 Black-Box flow theory (right)

The force exerted on the flat blade, simulating one screw blade, is given by the relation, $F_d = 0.5.\ \rho\ .\ A_b\ .\ C_d\ .V_r^2$, where ρ represent the fluid density, C_d is the blade coefficient of drag and V_r is the difference (V_c-V_b) between stream flow velocity V_c and blade velocity V_b=ω.R. The relative velocity V_r decreases as ω/R approaches V_c and the force F_d decreases toward zero. The power produced by the blade can be calculated with $P_T = F_d.\ V_b = 0.5\ .\ \rho\ .\ A_b\ .\ C_d\ .\ \omega\ .\ R\ .\ (V_c - V_b) = 0.5\ .\ \rho\ .\ A_b\ .\ C_d\ .\ \omega\ .\ R\ .\ (1 - \lambda)^2\ .\ V_c^3$, where λ is the tip-speed ratio. By using $Cp = C_d\ .\ \lambda\ .\ (1 - \lambda)^2$ the power relation reduces to $P_T = 0.5\ .\ \rho\ .\ A_b.\ C_p\ .\ V_c^3$. The derived function for Cp gives a value of zero for λ = 0 and λ = 1 and a maximum value of 0.148 for λ =1/3. The power for constant-speed operation is proportional to (C_p/λ^3) but as the stream velocity increases the power continues to increase. The flow and the geometrical data are V_c = 1.76 m/s [6].

For these preliminary calculations, the following characteristic values are used: F_d=51.62N, ω=7.882 r/s, T= F_d.R=3.8175N.m, $V_b=V_c/3$=0.5866 m/s. The power produced by the horizontal screw wheel is P_T= ω.T = 2.π.n.T, **w**here *ω* is the angular velocity of the runner, T is the torque acting on the turbine shaft, and *N* is the rotational speed of the runner. The hydraulic efficiency of the screw turbine is defined as the ratio between the mechanical power developed by the turbine to the available theoretical water power, $\eta_{hyd} = P_t/P_{th}$. For the developed by A. Stergiopoulou new experimental 3-bladed horizontal Archimedean screw rotor, the minimum blade wet area is A_b= L_b . (R_o-R_i) =1 (m) x0 .05(m) = 0.05 m^2, and the maximum blade wet area A_b= L_b . 2.R_o=1x 0.20 = 0.20 m^2 , with L_b = length of the blade, R_o and R_i are the outlet and the inlet of the blade.

Then, the theoretical power of the input current of the Cephalonia Sea River, in the open channel, could be P_{th}=(1/2).ρ.A_b .C_d.V_c^3= 136,29 W [7-9]. In the Sami's exit Cephalonia Sea River there is for the developed machine P_{th}=(1/2).ρ.A_b .C_d.V_c^3=0.5. 1025.0.20.1. 1.62^3 = 435.78 W. In the Argostoli's input there is for the same machine P_{th}=(1/2).ρ.A_b .C_d.V_c^3= 0.5. 1025.0.20.1. 0.52^3 = 14.41 W.

If the machine could cover the whole wet section then the power performances will be 108.1 W in the input and 2178.91 W at the exit section. However a series of Archimedes screws, as Archimedean Screw Farms, in the Argostoli input and in the Sami's exit, could give more interesting power performances. If the wet section of one bigger horizontal screw turbine, having a blade height equal to the depth of the input or output channel of Cephalonia, is the whole channel section, A_b= L_b. 2.R_o=2m x 0.5m =1m^2, then the theoretical kinetic potential for a current speed 1.62 m/s is around of 2178.91 W. A rough estimation of the maximum installed power capacity for such a turbine should be 1.62 KW. A farm with a series of 1000 similar turbines will give a total installed capacity of 1.62 MW.

With the known tidal graphs of North and South Port of Chalkis, on the Euripus Strait, installed by the Hydrographical Department of War Navy, the mean velocity Nord-South tidal current is 2.01 m/s and the mean South-Nord tidal current is 2.29 m/s [7-9]. The maximum velocity developed, in the overall section of the Strait is in average 2m/sec.

The mean current velocity, undependably from the direction is around of 1.27 m/s. In the area of the Euripus the mean per m^2 kinetic power potential, undependably from the current direction, is about P/A =1.05 KW/m^2. The power density of the North-South current is P/A = 4.16 KW/m^2. The South-North power density is P/A = 6.15KW/m^2. For the whole cross section of the Euripus Straits the values of the theoretical kinetic power of the North-South and South-North currents are P_{NS-th} =1331.8 KW and P_{SN-th} =1969.5 KW. The theoretical kinetic power undependably from the current direction P_{th}=335.9 KW. Taking into account the limit of Lanchester-Betz (16/27=0.593) the corresponding Lanchester-Betz kinetic power values are $P_{L-Betz(NS)}$= 789.2 KW, $P_{L-Betz(SN)}$=1167.1 KW and P_{L-Betz}=335.9 KW. A rough estimation of the Euripus Straits yearly kinetic energy potential gives $E_{Betz(NS)}$ = 3457 MWh and $E_{Betz(SN)}$ = 5112 MWh. For one Horizontal Axis Archimedean Screw Turbine (HAAST) having a diameter D_e = 2,0 m and length B = 2 m, with a wet section A = B · (D_e/2) = 2 · 1,0 = 2 m^2, the maximum installed power capacity will be P=3.647 W. For the same section a series of 20 similar HAAST devices will give P_{20} = 72.943 W. Thirty similar series will have one installed power capacity $P_{30,20}$=2.188.290W=2.188, 3KW=2.19 MW. The two possibilities to install Parks of Horizontal Axis Archimedean Screw Turbines in the southern harbor of Chalcis are presented in the Figure 11. A similar scenario could be considered also for the northern harbor of Chalcis. It is obvious that the total installed power capacity for such HAAST hydrokinetic farms in the areas of the Euripus Straits could be more than 4 MW. The corresponding yearly energy produced could be around 32.000 MWh.

5. Conclusions for further research efforts

This paper has explored the performance characteristics of a very promising new small hydropower system, an innovative horizontal Archimedean hydropower screw turbine. Pleiades of zero head sites, in small and big watercourses, open water channels, as well as important sea and tidal currents, could be harnessed by such and horizontal screws for recovering hydraulic energy.

A series of experimental studies continues in the Institute for Water Management, Hydrology and Hydraulic Engineering/Department für Wasser-Atmosphäre-Umwelt / Institut für Wasserwirtschaft, Hydrologie und konstruktiven Wasserbau (IWHW), in Vienna, with another new version of the first in the world Horizontal Axis Archimedean Screw Turbine, having the torquemeter, in another new position, outside of the water (Figure 11).

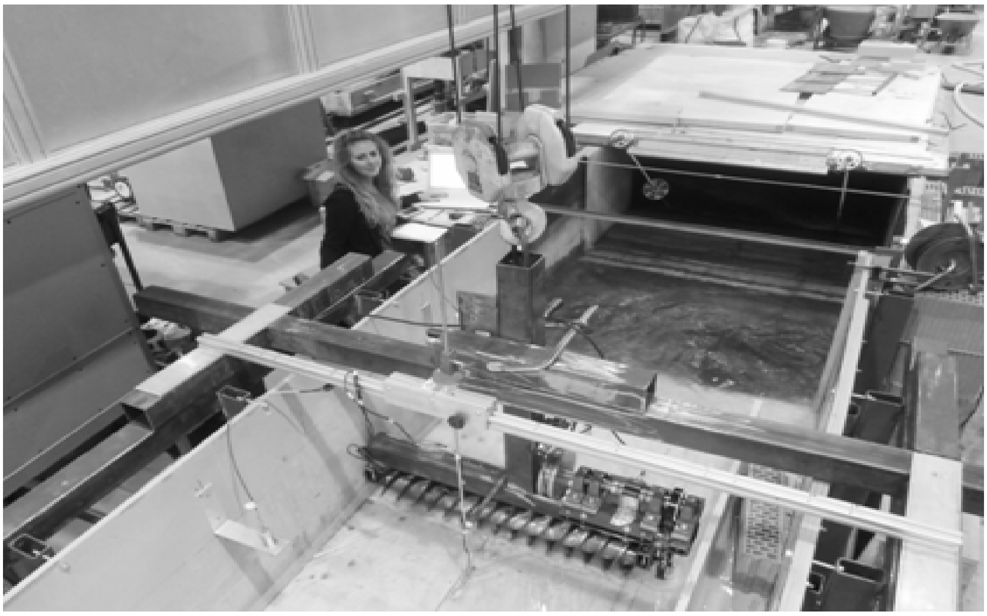

Figure 11. A panoramic view of the new version of the whole innovative Horizontal Axis Archimedean Screw Turbine, in operation in the hydraulic channel of IWHW, in Vienna (photo A.Stergiopoulou [5])

The S1/S2 Black-Box flow theory will be used in order to predict the performances of the Horizontal Axis Archimedean Turbine and to compare with all the collected and the new experimental results. However, the diagrams obtained for the radial impulse turbine show that the highest efficiency of such a turbine prototype could not be measured, so it is hard to analyses the turbine performance. It seems that to determine the maximum efficiency and the turbine performance of this prototype further measurements with more operation points are necessary. Due to optimisations, for example of the jet nozzle, the rotor, the air gap and so on, the efficiency could be increased. Therefore more measurements of different prototypes, mathematic calculations or simulation are needed.

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