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A first CFD study of small hydro energy recovery from the attica water supply network

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Abstract
The present paper proves that the vast water supply infrastructure of Athens and the region of Attica could produce useful hydropower. The first aim of this paper is to present the unconventional small hydro philosophy of recovering the hydraulic energy wasted in the existing break pressure devices and energy dissipating structures of the Water Supply Network of Athens, the capital of Greece and of the whole Attica region. The paper discusses themes concerning the replacement, in this large drinking water infrastructure, of all the existing break pressure devices, by a series of small hydro plants and also the efficient ways by which such small unconventional hydro schemes could be realized. The second aim of the paper is to highlight some important CFD simulation features which however needs further investigations and to present preliminary some Flow-3D results concerning the hydrodynamic performances of this series of small hydro plants harnessing the important wasted hydraulic energy of the Attica Water Supply Network.

Keywords: CFD; FLOW-3D; AWSN; Renewable Energy; Small Hydro; Water Supply Networks.

1. Introduction
Water is brought to Athens, the capital of Greece and to the whole region of Attica, via two main aqueduct systems, the Evinos – Mornos aqueduct, the largest Greek urban water supply system, and the Yliki-Paralimni aqueduct. These primary aqueducts are interconnected with each other, as well as, connected to groundwater wells, through series of secondary and auxiliary aqueducts. A global view of the Attica Water Supply Network (AWSN) is given in Figure 1. AWSN is a gravity free flow system with a design capacity of more than 2.000.000 m^3/day and a maximum flow capacity of about 23m^3/s [1-4]. It is comprised of 16 tunnels with a total length of about 100km, 12 inverted siphons with a total length of 7.2km, and 15 open canals of varying sections, with a total length of 111.7km [4, 5]. It also has 18 flow regulating structures and eight major energy dissipation works. AWSN is characterized by its complexity, the vast geographic distribution of water resources and aqueducts, the great distance between water sources and demand centers.

Figure 1. A general view of the Attica Water Supply Network, the largest Greek urban water system.

We consider in the present paper firstly that water and energy are two associated realities and that the flowing water along a gravity water system is a simultaneous mass and energy transport phenomenon and that all the pressure breakers and energy destruction structures could be replaced by with well designed suitable small hydropower plants, playing exactly the same energy destructor role, the role of new hydro productive energy destructors and dissipators.

At such gravity water supply system using open channels and closed conduits, the excessive pressure head is always considered as a major danger. In order to resolve the overpressure major problem different means of reducing this accumulated pressure and a series of energy dissipation devices, energy destructors and pressure breakers are widely used. Given the length of the aqueducts, the complex morphology and topography of the terrain along these, the large-scale Attica Water Supply Network of the previous Figure 1 was designed with a series of break pressure constructions and energy destructors. The dissipated energy is often regarded as detrimental to the water distribution system and it could be considered as a wasted source of free flowing energy.

2. Energy Destructors and Small Hydropower Plants in the AWSN

Small hydropower plants could be used to recover the excess energy from hydraulic systems and these applications have important potential in renewable energy production. The present work describes the efficient application of this unconventional multipurpose small hydropower philosophy for recovering the wasted hydraulic energy in all the existing break pressure devices and energy dissipating structures of Attica Water Supply Network, giving a first priority to the Kirfi’s, Cithaeron’s, Helicon’s and Mandra’s type energy recovery

By following such a quite simple unconventional water management philosophy it is found, that for AWSN, with a maximum water transfer of $23 m^3/s$, it is efficient to install the following five small hydroelectric plants Evinos SHP, Kirfi SHP, Helicon SHP, Kithairon SHP and Mandra SHP [1-4].

Four of these five plants (Kirfi, Helicon, Kithairon, Mandra) are multipurpose urban unconventional plants harnessing the power dissipated in the hydraulic jumps and energy dissipation devices. Figure 2 gives a general view of the whole AWSP with the mentioned five Small Hydropower Plants four of these recovering the wasted hydraulic energy.

The Kirfi Small Hydroelectric Plant is one representative example of an efficient application of the “Productive Destruction Principle” recovering the wasted hydraulic energy and playing the same exact role with the break pressure mechanisms, shown in the next Figure 3, with details concerning the input tunnel, the spillway, the surge tower, the operation building, the dissipation basin, the by-pass and the exit Mornos Attica channel etc.

A general view of the Kirfi’s site and the Small Hydropower Plant is given in the following Figure 4.

The power produced P(KW) in function of the flow discharge $Q(m^3/s)$ is given in the following Figure 5.

Figure 2. Five Small Hydroelectric Plants in the Water Suplly Network of Attica.

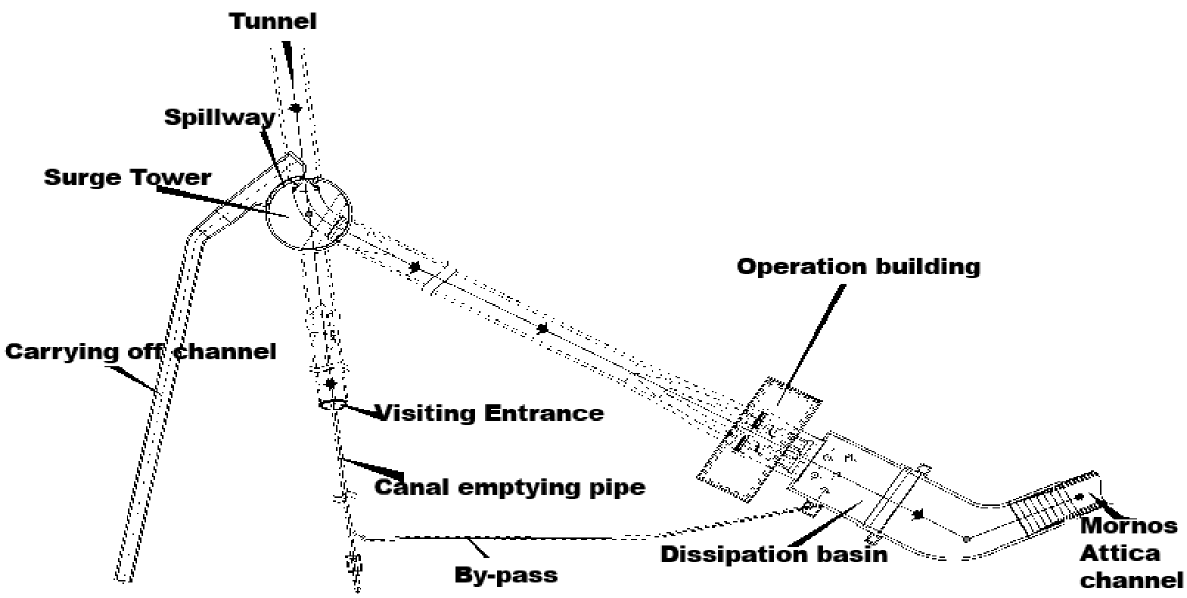

Figure 3. Representative Energy Dissipation Structures in Kirfi (photo A. Stergiopoulou).

Figure 4. General view of the Kirfi's Small Hydrower Plant (photo A. Stergiopoulou).

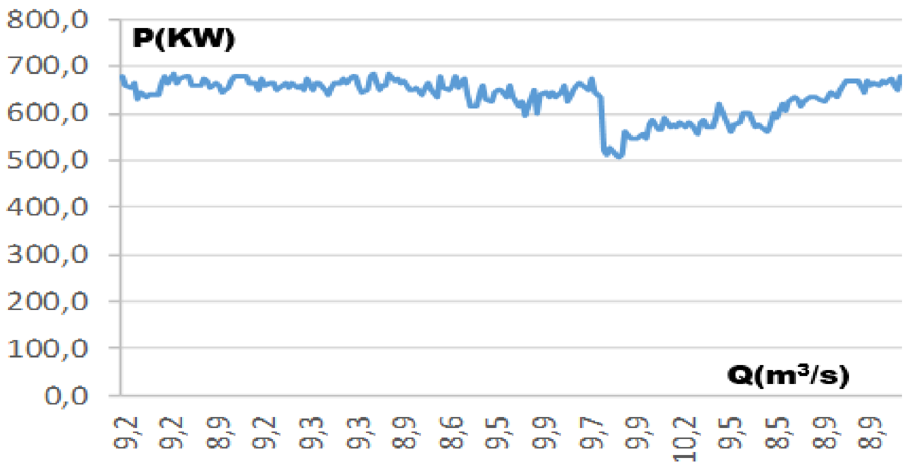

Figure 5. Power produced P(KW) in function of the flow discharge Q(m^3/s) of Kirfi Hydropower Plant.

The installed capacities P (MW) and the yearly produced energy E(GWh) of these plants in function of the available values of water flow discharge Q and net head H and the type of turbines are:
1. Evinos SHP (Q=1,3 m^3/s, H= 70m, P=0.82MW, E= 4 GWh, 1 turbine Francis)
2. Kirfi SHP (Q=11m^3/s, H=8.03m, P=0.76 MW, E= 5.86 GWh, 1 turbine Kaplan)
3. Helicon SHP (Q=11m^3/s, H=6,84 m, P=0.65MW, E= 5.03 GWh, 1 turbine Kaplan)
4. Kithairon SHP (Q=10.5m^3/s, H=16,44m, P=1.20MW, E= 9.50 GWh, 2 Turbines Kaplan)
5. Mandra SHP (Q=10 m^3/s, H=8.25m, P=0.63, 0.65 MW, E= 4.9 GWh, 1 turbine Kaplan)
These five in cascade small hydroelectric plants could have a total installed capacity of about 4.06MW, which could give a total produced electricity of about 29,3 GWh/year,

It seems that the bigger among these hydropower plants concerns the Kithairon's break pressure site. Despite the fact that variation of the water discharge is from 5 to 17 m^3/s and the available net head is variable from 17.8m to 13m, the design point could be described by the nominal conditions of Q = 10.5 m^3/s, H = 11m, P=1.20 MW. In this case, the replacement of the break pressure device by a small hydro plant will harness a total hydraulic energy of about 9.5 GWh/ year. Some details of the Kithairon small hydroelectric plant, concerning one of the wo existing similar Kaplan turbine, are shown in the following Figure 6.

Figure 6. Small Hydropower Scheme with one S-Kaplan turbine recovering the wasted energy applying the P.D.P. in the Kithairon site of the Athenian aqueduct.

3. FLOW-3D and Energy Recovery in the Attica Water Supply Network

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 research needs [5]. Flow-3D uses finite volume approach to solve the Reynolds-averaged Navier-Stoke's (RANS) equations over the computational domain. The computational domain is divided into a grid of cells. 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 [5]. 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. 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 [6-8]. 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 [6, 9]. The RNG model was used for the turbulence modelling. A systematic CFD uncertainty evaluation process known as Grid Convergence Index (GCI) described in [6, 10, 11] is used for evaluating the uncertainties in the numerical model.

Some data about the geometry, the mesh, the initial and final conditions of the Flow-3D simulation for the Evinos's hydropower plant case are presented below in Figure 7.

A first view of the preliminary simulation results tab in Flow-3D application for the Evinos case is given in Figure 8 for a given time, including the variations of pressure.

A simple CAD model shown in Figure 9 was prepared using Solidworks Premium 2017 for represent one typical small hydropower turbine, as a quite simple water wheel. This water wheel simulating a small hydropower turbine has in the whole CFD simulation a purple color. This simple CAD model was imported as a .stl file to be read and interpreted by Flow-3D. Taking the available computational resources and time into consideration, only the symmetrical half of the model was simulated.

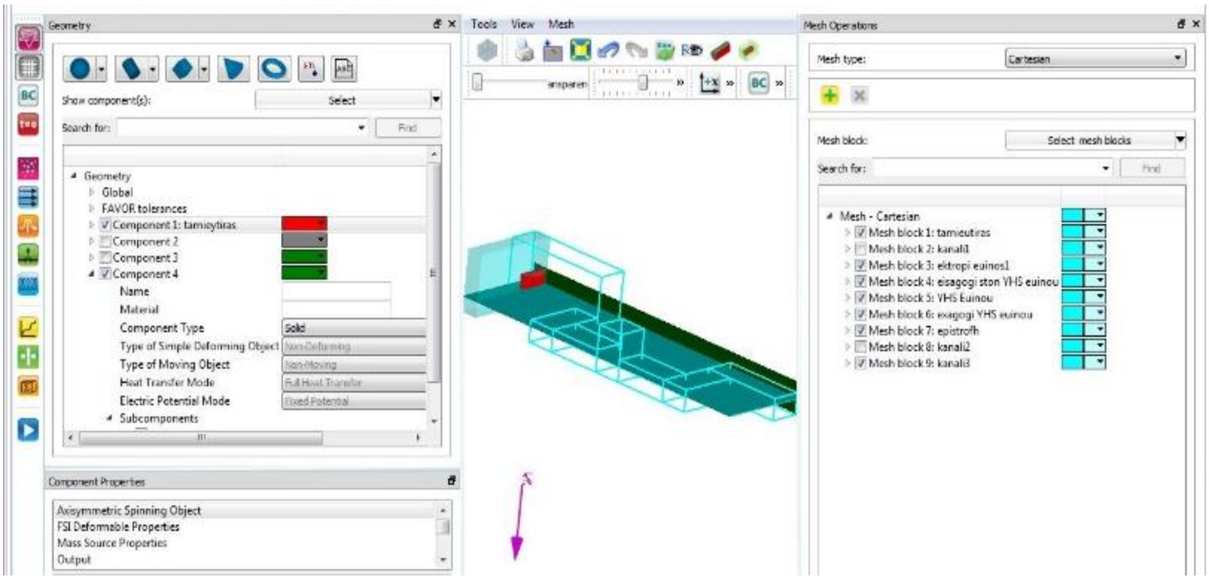

Figure 7. Adjustment tab for simulation geometry of the Evinos's hydropower plant case.

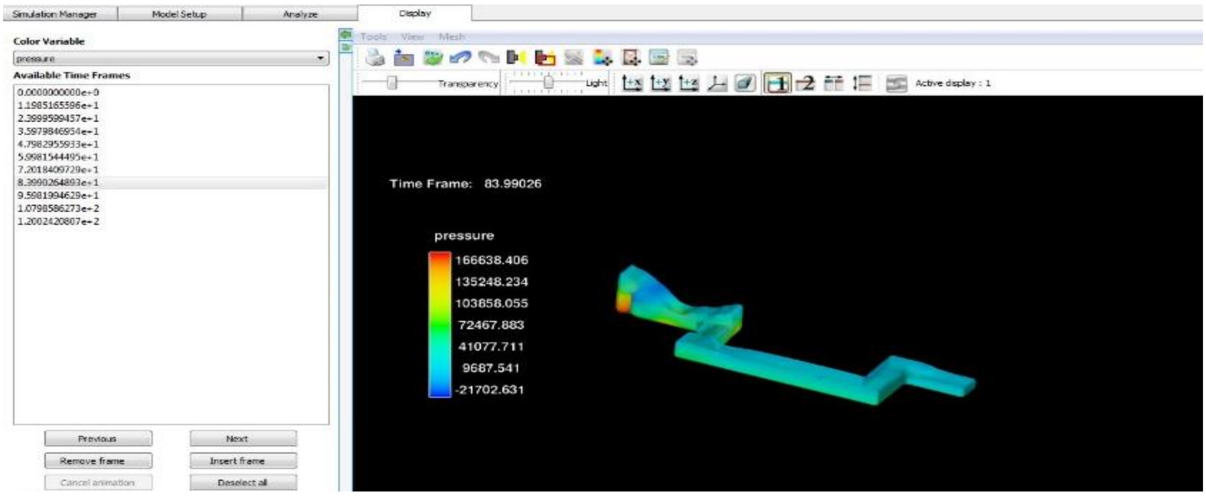

Figure 8. Preliminary Flow-3D simulation results tab for the Evinos case.

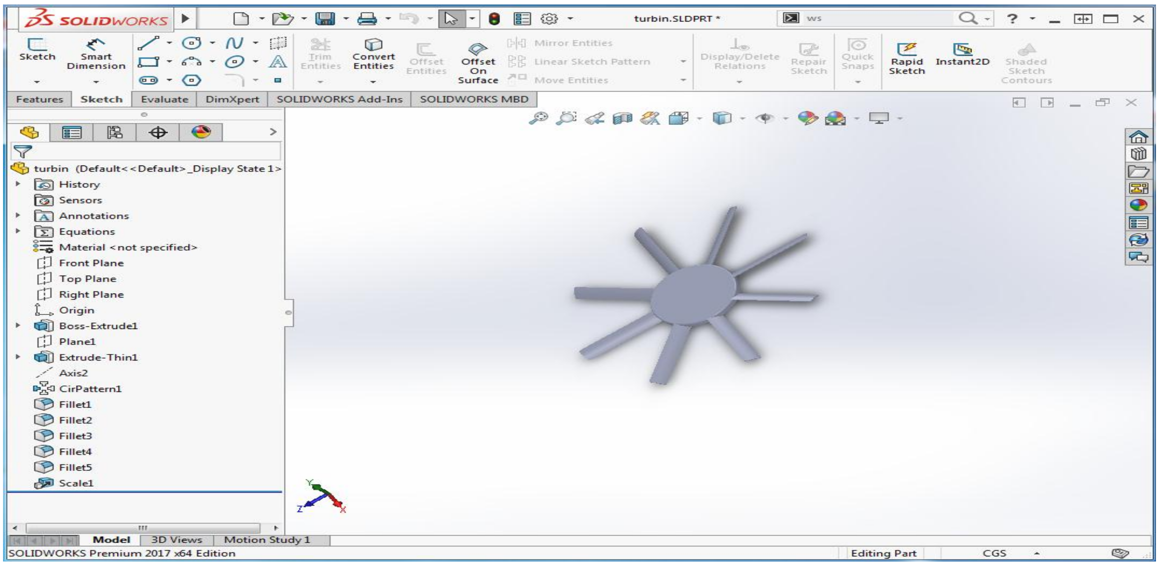

Figure 9. Using Solidworks for one hydropower turbine, as a quite simple water wheel.

Then, the STL object introduced to the CFD technique helped to create the mesh grid generation. FLOW-3D code uses interactive grid generation software and computation flow solver modules simulating continuity, Euler and Navier-Stokes equations, in all the cases of the flow regimes.

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

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

The input data used is taken based on design while the fluid physical data follows the fluid properties in the existing literature. The fluid was defined as water at 20° C with a density of 1000 Kg/m^3 and a dynamic viscosity of 0.001 $N.s/m^2$. Uniform pressure distribution and fluid initialization with fluid elevation were used as initial conditions for the model.

We present some CFD simulation information concerning one of the small hydroplants in cascade of the whole Mornos Attica channel, the case of the small hydropower plant of Kirfi. The preliminary FLOW-3D CFD simulation was running during a time of 120 sec for the case of Kirfi. The diagrams of the mean velocity, volumes and pressures for some indicative values of time t=14.40sec, 23.99sec and t=116.39sec, with the turbine in the by-pass channel of the Kirfi S.H.P.P, are obtained by using the advanced postprocessing and visualization tool Flow Sight of the FLOW-3D code and presented below in Figures 10, 11 and 12 for these values of time.

The first CFD simulation results of the entire Attica Water Supply Network, open channel, from the Mornos lake to the Mandra's small hydropower plant, having four small hydropower plants in cascade, by using the postprocessing and visualization tool Flow Sight of the FLOW-3D code, are presented bellow in Figures 13, 14, 15, 16 and 17, for the representative time values 0, 48, 144, 192 and 384 sec.

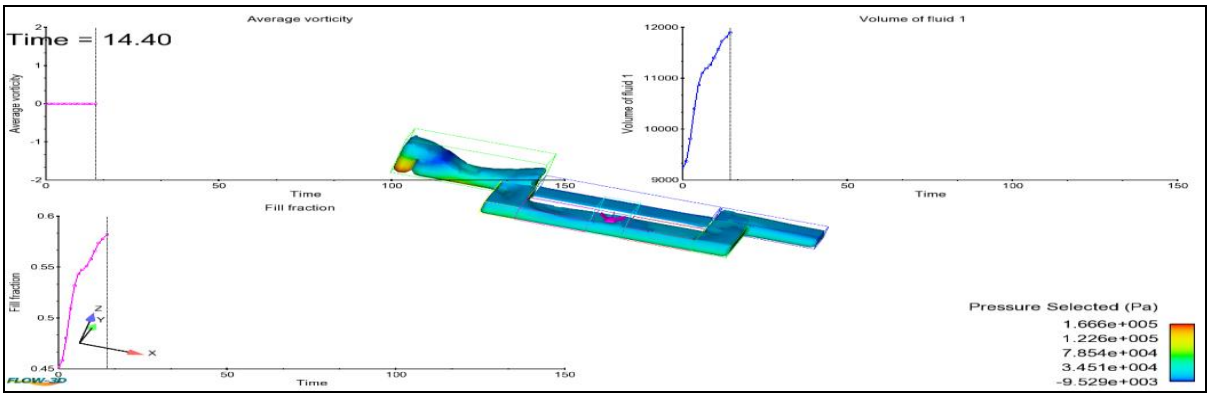

Figure 10. Flow-3D simulations and Flow Sight visualizations at the time 14,40 sec for the Kirfi SHP.

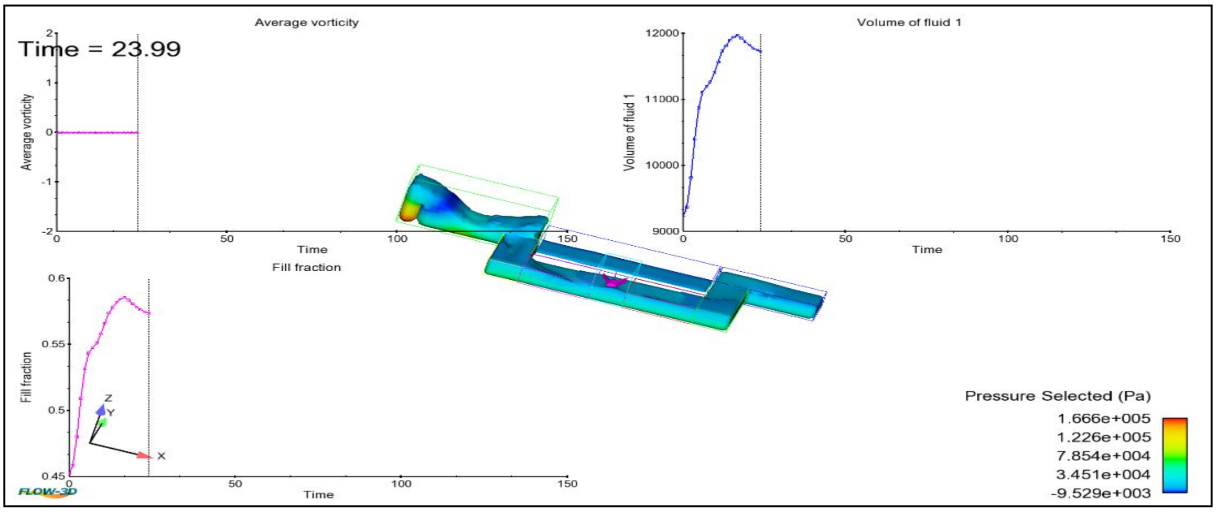

Figure 11. Flow-3D simulations and Flow Sight visualizations at the time 24sec for the Kirfi SHP.

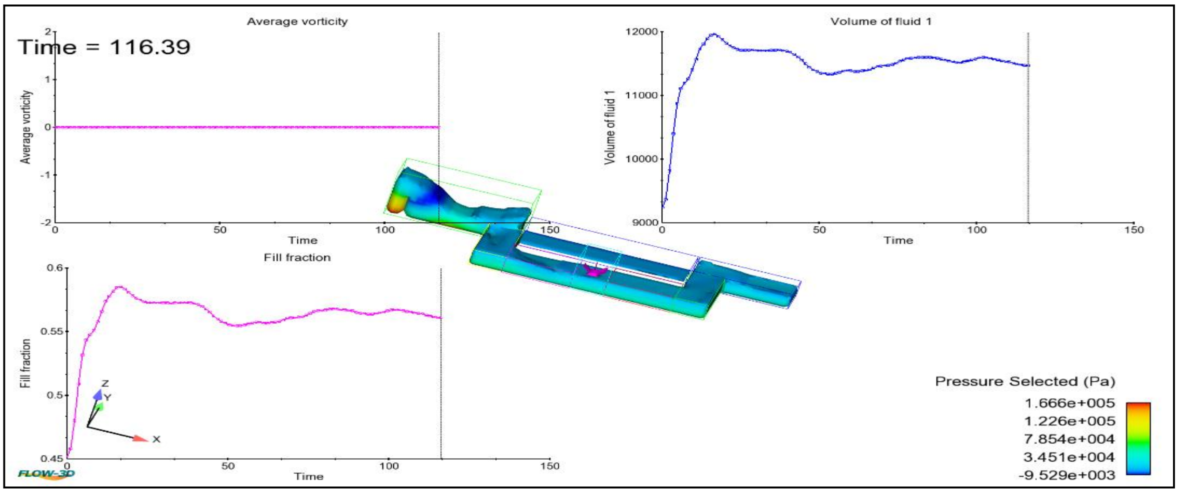

Figure12. Flow-3D simulations and Flow Sight visualizations at the time 116,39 sec for the Kirfi SHP

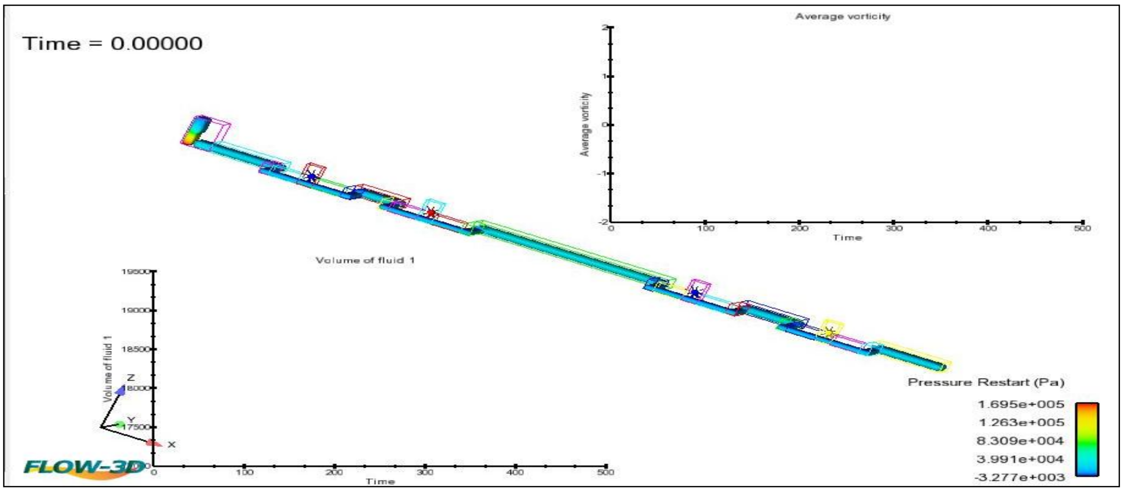

Figure 13. AWSN Flow Simulation - Time 0 sec and diagrammatic illustration in Flow Sight application.

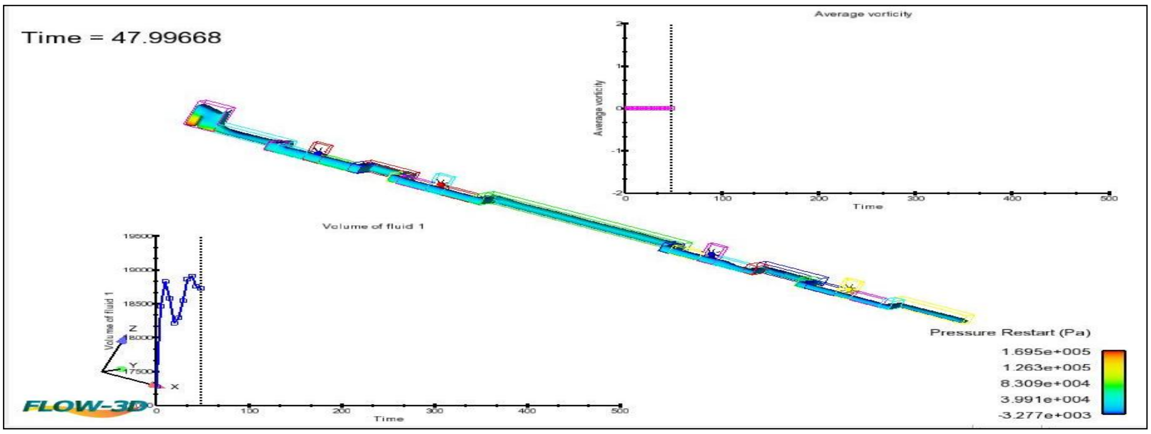

Figure 14. AWSN Flow Simulation - Time 48 sec and diagrammatic illustration in Flow Sight application.

The presented here preliminary Flow-3D simulation CFD results for the cascade Small Hydropower Plants harnessing the wasted hydraulic energy in the dissipation structures of the Attica Water Supply Network are very promising and need further important investigations in order to obtain the optimization of the hydropower performances of the whole AWSN.

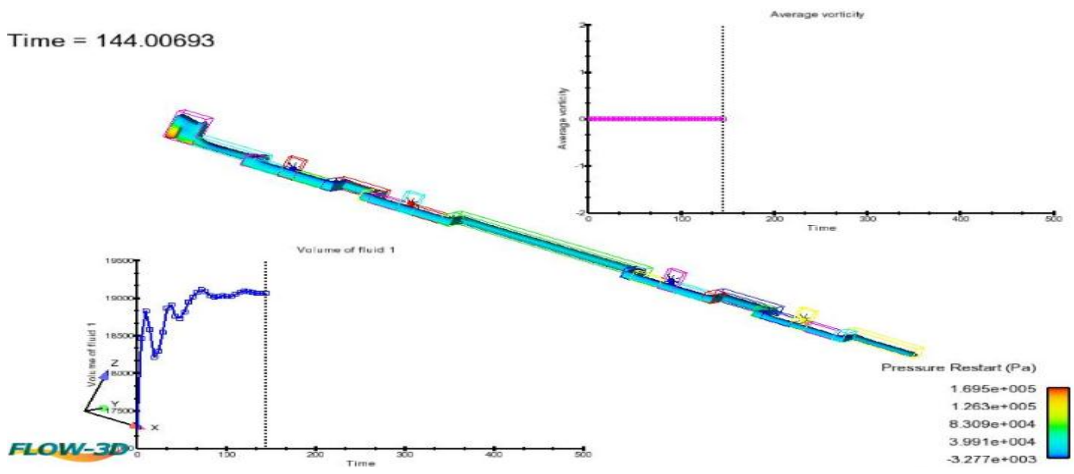

Figure 15. AWSN Flow Simulation - Time 144 sec and diagrammatic illustration in Flow Sight application.

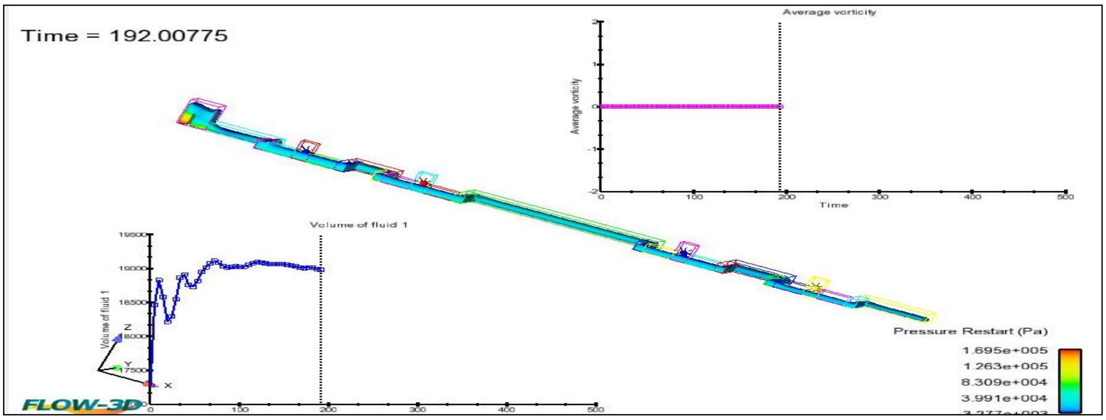

Figure 16. AWSN Flow Simulation - Time 192 sec and diagrammatic illustration in Flow Sight application.

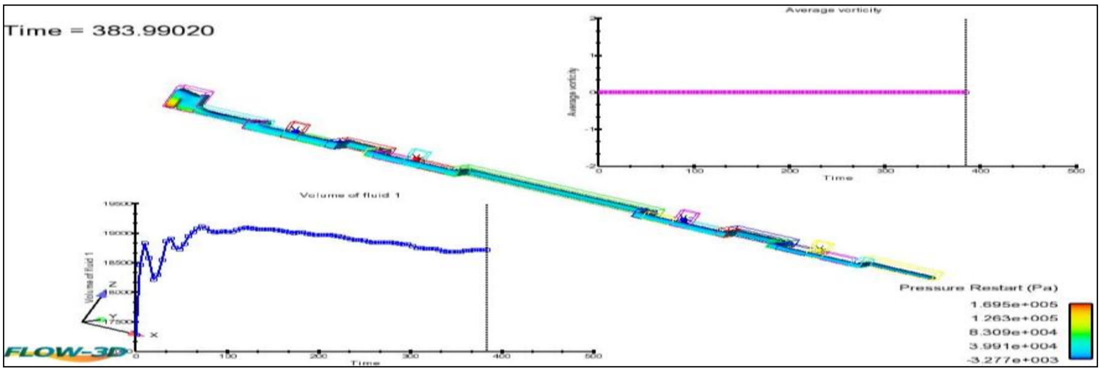

Figure 17. AWSN Flow Simulation - Time 384 sec and diagrammatic illustration in Flow Sight application.

4. Conclusions

The present paper considers that besides the conventional hydropower plants in natural watercourses, there is also a considerable hydropower potential in existing water drinking systems and that in such networks, the excess pressure is dissipated in pressure reduction and energy destruction devices. The paper insists that the excess pressure and the wasted energy could be removed from the system by installing hydro-turbines and it can be converted into useful energy. The present paper proves that Athens and Attica's vast water supply infrastructure could produce important hydropower. In the first part of the present work has been analyzed the utilization of the existing hydropower potential in the Attica Water Supply Network (AWSN). The proposed facilities have numerous advantages compared to river-type hydropower plants.

For the AWSN study, the energy recovery has been investigated in a detailed manner. Despite the fact that there are 12 hydraulic dissipation devices as promising potential sites for energy recovery there is a series of 5 in cascade small hydropower plants installed, four of them are plants harnessing the power dissipated by hydraulic jumps and energy dissipation devices**.** These five in cascade small hydroelectric plants have a total installed capacity of about 4.06MW. In the course of the second part of the paper has been presented some important CFD simulation features and to some preliminary Flow-3D results concerning the hydrodynamic performances of this series of small hydro plants harnessing the important wasted hydraulic energy of the Attica Water Supply Network. These preliminary Flow-3D simulations need further investigations for further optimization of the cascade small hydropower plants recovering energy from the Attica Water Supply Network.

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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