EFFICIENCY EVALUATION OF AN ARCHIMEDEAN-TYPE HYDROKINETIC TURBINE IN A STEADY CURRENT

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ABSTRACT: The efficiency of an Archimedean-Type Hydrokinetic Turbine is studied numerically in order to evaluate its potential for energy production through sustainable consumption of natural resources. The shape of the Archimedean-Type Hydrokinetic Turbine is very similar to the well known Archimedean Screw, used in several small hydropower plants. However, while the classical Archimedean Screw exploits the difference in potential energy between two water reservoirs, the Archimedean-Type Hydrokinetic Turbine exploits the kinetic energy of a flow, for example an open channel flow. The hydrodynamics of the Archimedean-Type Hydrokinetic Turbine are simulated using a three dimensional numerical model that implements the Reynolds Averaged Navier-Stokes equations for incompressible water, closed with an SST k-ω turbulence model. The numerical model reproduces a two stride helical turbine and its simple support system. Some preliminary results are provided on the turbine functioning and efficiency.

1. INTRODUCTION

Exploitation of renewable energies is becoming a fundamental societal issue, because of the increasing need to manage a sustainable development [1]. We propose the use of hydrokinetic turbines as a promising tool to extract energy from steady or slowly-varying water flows. Hydrokinetic turbines may have different shapes [2, 3, 4], but they are useful to extract energy from river flows or tidal currents.

The working principle of hydrokinetic turbines is based on their immersion in an hydraulic flow, which impinges the turbine generating a rotation, the latter to be exploited by an electric generator. In comparison with classical hydroelectric turbines, hydrokinetic turbines are activated by a flow with a negligible potential energy, i.e. the energy exploited is only the kinetic energy of the flow. This characteristic reduces the number of structures required by the turbine, minimizing their environmental impact not only in terms of pollutant (like other hydroelectric turbines), but also in terms of infrastructures. In addition, these turbines are of reduced dimensions, easy to install and manage, this enabling the use of these machines in underdeveloped and remote areas [5, 6, 7, 8], ensuring the access to affordable, reliable, sustainable and modern energy for everybody.

In the family of small hydroelectric turbines, the Archimedes turbine does borrow from wind turbine concepts. Such turbine has been used since the ancient age to extract energy from

river flows, exploiting a water head jump, i.e. the potential energy of the water. However, the shape of the Archimedes turbine (a screw where the blades are continuously attached to the turbine axis) confers the turbine a more robust shape and suggests to use it as an hydrokinetic turbine, being less vulnerable to damages. Since the Archimedes turbine has never been used as an hydrokinetic turbine since now, a study of its efficiency is needed.
The development of an Archimedean-Type Hydrokinetic Turbine comes from an idea of *Soc. Neferti Srl*, which designed and realized several prototypes of this kind of Archimedean-Type Hydrokinetic Turbine. Field tests showed interesting responses and suggested a rigorous study of the turbine by means of numerical simulations. The study, carried out by the Hydraulic Laboratory of the Polytechnic University of Marche, aimed to evaluate the performance of the machine and to optimize the fundamental design parameters.
The idea of an effective Archimedean-Type Hydrokinetic Turbine aims at producing a device that: 1) is simple and cheap, therefore it can be used in remote areas and developing countries, 2) minimizes all environmental impacts, 3) does not require the construction of civil infrastructures (intake and discharge reservoirs, by-pass channels, etc.), 4) works also in channels and rivers with small water depths and 5) maximizes the flow energy exploitation.
In this paper some preliminary numerical results on the performance of the Archimedean-Type Hydrokinetic Turbine are reported. Section 2 illustrates the theoretical model used to evaluate the performance coefficient, while sections 3 and 4 reports the numerical model used to simulate two different flow configuration and the related results. Finally, section 5 discuss the performace of the Archimedean-Type Hydrokinetic Turbine and close the paper.

2. THEORETICAL MODEL

Hydrokinetic turbine theory comes from wind turbines theory, and several types of turbines have been borrowed from wind turbine applications. The types most used in river flows or tidal currents are the horizontal axis rotor turbines [9, 10, 11] and Savonius turbines [12, 13, 14, 15, 16]. The shape of these turbines maximizes the efficiency of the machine, but their slender profiles can be easily damaged, if hit by debris transported by the river flow. To avoid damages and to increase the efficiency, hydrokinetic turbines are always equipped with protection devices and duct, these structures increasing the environmental impact, especially on river fishes [17, 18, 19, 20, 21].
The power production P_t and the performance coefficient C_p of an Archimedean-Type Hydrokinetic Turbine is investigated in this paper, by means of numerical simulations, varying the operative condition of greatest interest. Following wind and hydrokinetic turbine theory, based on Betz one-dimensional model [22], the performance coefficient C_p, which measures the efficiency of the turbine, is:

$$C_p=P_t/P_f \tag{1}$$

where P_f is the power available from the fluid flow and P_t is the power generated by the screw turbine. The theory is based on a simplified geometrical model, where the turbine is assumed a 2D circular rotor, crossed by a perpendicular flow. The power generated by the screw turbine can be evaluated as

$$P_t=M_t \cdot \omega \tag{2}$$

where M_t is the torque generated by the fluid on the turbine (that can be transferred to an electric generator) and ω is the turbine rotation velocity. From Betz's theory, the power available from the fluid flow is:

$$P_f = ½\rho A v^3 \quad (3)$$

where ρ and v are the fluid density and stream flow velocity, respectively, while A is the projection of the surface that fronts the flow on a plane perpendicular to the flow. In view of that, for an Archimedean-Type Hydrokinetic Turbine the inclination of the turbine axis with the flow could have an important influence on the machine's performances. Representing the Archimedean-Type Hydrokinetic Turbine with a circular cylinder that envelops the turbine (see Fig. 1), the area A depends on the angle θ between the turbine axis and the stream flow direction (i.e. the pitch angle) as given by the following geometrical relation:

$$A = R^2 \pi cos(\theta) + 2RLsin(\theta) \quad (4)$$

where R and L are the cylinder radius and length, respectively.
The performance coefficient C_p is dimensionless and for hydrokinetic turbines it is conventionally represented as function of the Tip Speed Ratio (TSR), which is the dimensionless form of the rotation velocity:

$$\text{TSR} = \omega R / v \quad (5)$$

Analyzing Eq.s from (1) to (5), if the geometry of the turbine is assigned, the performance coefficient depends on the TSR and on the pitch angle θ. Therefore, the Archimedean-Type Hydrokinetic Turbine performance is studied, varying not only the TSR, as commonly done for other hydrokinetic turbines, but also the pitch angle θ. The following section illustrates the physical and numerical models used to evaluate the power production and the performance coefficient of the turbine.

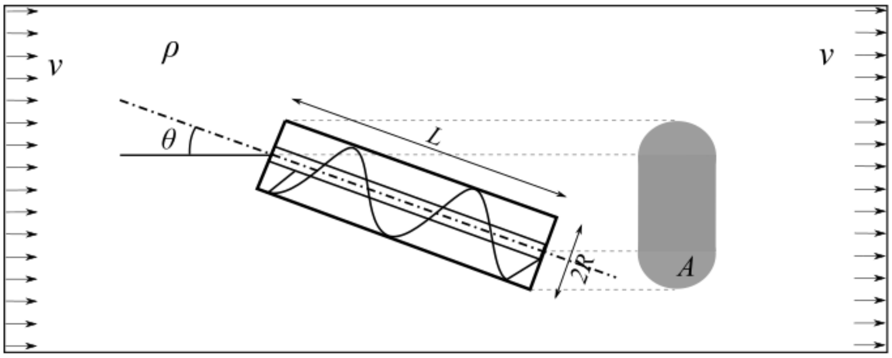

Figure 1- Sketch of the physical model. The projection of the surface that fronts the flow is reported in grey.

3. NUMERICAL EXPERIMENTS

The performances of the Archimedean-Type Hydrokinetic Turbine have been evaluated using numerical simulations, performed with the commercial software Academic Ansys Fluent. The physical model was composed by an Archimedes screw turbine immersed in a water flume where a flow was imposed, while the angular velocity and the pitch angle were varied.
Being the experiments of numerical nature and since we wanted to evaluate the efficiency of the turbine alone, the geometry of the screw turbine was reproduced without any support

system or duct. To reduce the effects of the walls and possible blockage effects, the fluid volume was that of a parallelepiped 2 m long in the streamwise direction, 1 m wide and 0.6 m high. The flow in the domain was generated using inflow-outflow boundary conditions, assigning the velocity v=0,2 m/s at opposite upstream/downstream boundaries. Free slip wall boundary conditions were assigned at the other four boundaries.
The turbine was located at the center of the crossflow section, at a distance of 4R from the inflow boundary and of 30R from the outflow boundary, to minimize boundary effects [23]. The screw model was composed by an axle with diameter 20 mm and a two stride blade 5 mm thick, with external radius R=50 mm. Each stride was long p=160 mm. The blade was not perpendicular to the axle, but inclined of 70°.Two different pitch angles have been studied: θ=0° and θ=10°. The two different configurations, whose horizontal plane of the domain for a general angle θ is sketched in Fig. 2, are referred as "aligned configuration" (for θ=0°) and "inclined configuration" (for θ=10°).

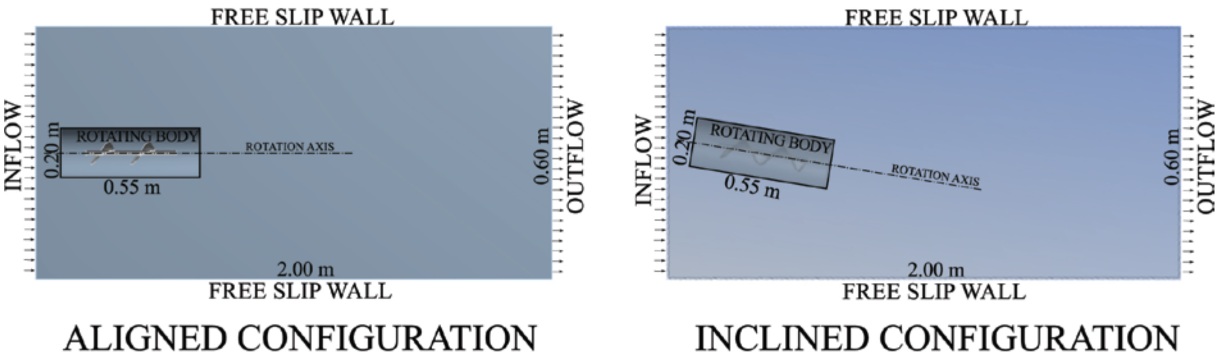

Figure 2- Sketch of the horizontal plane of the domain used in the numerical simulations.

To solve the hydrodynamics due to the flow and to the turbine rotation, the multiple reference frame method was used [24]. The domain was divided into two parts: 1) a rotating body, which is a cylindrical volume with radius twice the turbine diameter and length 0.55 m, which contained the turbine and 2) the complementary to the parallelepiped fluid domain. The mesh was generated separately in the two parts and the rotating body was rotated at each time step with an assigned angular velocity ω. The solutions of the two domains were calculated in the different reference frames for each part and the boundary conditions for the inner rotating body were evaluated by interpolation on the contact surface.
The domains were discretized in linear tetrahedral cells, with maximum size of $3\cdot10^{-2}$ m, with mesh refinement on the surface of the screw, where the mesh size was $3\cdot10^{-3}$ m. Perpendicular to the turbine wall an inflation of twelve layers was assigned, with first layer thickness equal to $1\cdot10^{-4}$ m and growth rate of 1.4. A representation of the refinement is reported in Fig. 3. This generated a mesh of about 157.111 nodes and 529.599 cells for the "aligned configuration" and 141.946 nodes and 527.710 cells for the "inclined configuration".

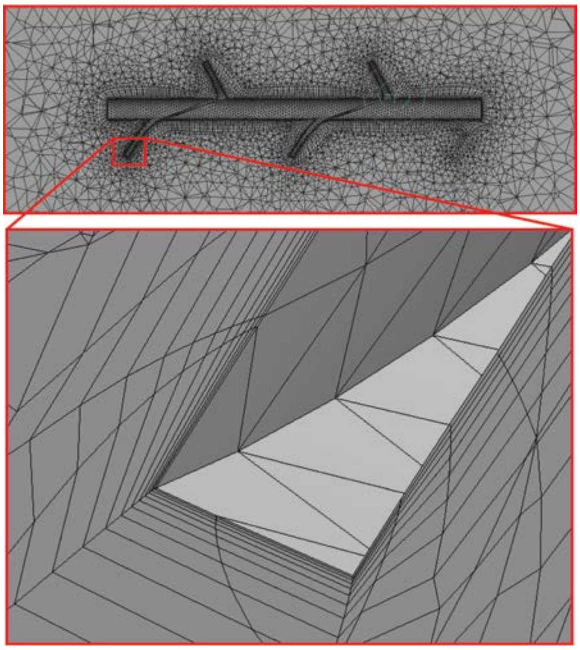

Figure 3- Zoom of the mesh refinement in the proximity of the turbine (top panel) and of the inflation along the turbine surface (bottom panel).

The solution was calculated with a pressure-based model, which solved the discretized form of the Reynolds Averaged Navier Stokes Equation. The turbulence model used to close the equations was the Menter's k-ω Shear Stress Transport (k-ω SST) model, which works well with adverse pressure gradients and separating flow [25, 26, 27].
For each configuration, the angular velocity of the turbine was varied from ω=0.5 rad/s to ω=6 rad/s with steps of 0.5 rad/s. A summary of the conditions for the different numerical simulations is reported in the first four columns of Tab 1.
A transient simulation was run for each configuration and flow condition, for a time of at least 10 s, with time steps of 0.2 s. Convergence iterations at each time step were run up to a relative error of 10^{-3} for mass conservation and 10^{-4} for the velocities, with a maximum number of 50 iterations for each time step. Results of the numerical experiments are reported in Section 3.

4. RESULTS

The power P_t generated and the performance coefficient C_p were evaluated as follows. The torque M_t was calculated from the numerical solution as the time-averaged value of the torque resultant from pressures and shear stresses of the fluid on the turbine surface, neglecting the initial stage peak value (between 3 and 5 s), which corresponded to the transient for the development of the quasi-steady state. Then, the power P_t has been evaluated with Eq. (2). Using P_t and the power of the flow P_f (defined in Eq. (3) and reported in Tab. 1), the performance coefficients C_p was evaluated with Eq. (1). The values of the time averaged torque M_t, the generated power P_t and the performance coefficient C_p for each simulation are reported in the last three columns of Tab. 1.

ID (θ – ω) (adim – rad/s)	*v* m/s	*TSR* adim	P_f mW	M_t Nm	P_t mW	C_p %
0 - 0.5	0.2	0.125	31.416	0.004943	2.471	8%
0 - 1	0.2	0.25	31.416	0.004461	4.461	14%
0 - 1.5	0.2	0.375	31.416	0.003725	5.587	18%
0 - 2	0.2	0.5	31.416	0.003209	6.418	20%
0 - 2.5	0.2	0.625	31.416	0.002902	7.256	23%
0 - 3	0.2	0.75	31.416	0.002489	7.468	24%
0 - 3.5	0.2	0.875	31.416	0.002066	7.242	23%
0 - 4	0.2	1	31.416	0.001689	6.756	22%
0 - 4.5	0.2	1.125	31.416	0.001309	5.891	19%
0 - 5	0.2	1.25	31.416	0.000965	4.825	15%
0 - 5.5	0.2	1.375	31.416	0.000623	3.425	11%
0 - 6	0.2	1.5	31.416	0.000294	1.765	6%
10 - 0.5	0.2	0.125	53.166	0.004739	2.370	4%
10 - 1	0.2	0.25	53.166	0.004456	4.456	8%
10 - 1.5	0.2	0.375	53.166	0.003949	5.924	11%
10 - 2	0.2	0.5	53.166	0.003434	6.869	13%
10 - 2.5	0.2	0.625	53.166	0.002954	7.384	14%
10 - 3	0.2	0.75	53.166	0.002544	7.631	14%
10 - 3.5	0.2	0.875	53.166	0.002191	7.668	14%
10 - 4	0.2	1	53.166	0.001847	7.390	14%
10 - 4.5	0.2	1.125	53.166	0.001494	6.724	13%
10 - 5	0.2	1.25	53.166	0.001131	5.657	11%
10 - 5.5	0.2	1.375	53.166	0.00078	4.289	8%
10 - 6	0.2	1.5	53.166	0.000437	2.623	5%

Table 1- Summary of the conditions varied in the numerical simulations and related results.

5. DISCUSSION AND CONCLUSIONS

The power production and performance coefficient of an Archimedean-Type Hydrokinetic Turbine have been evaluated through dedicated numerical experiments, focussed on the machine efficiency while avoiding frictional losses.

The generated power P_t, reported in Fig. 4, as function of the corresponding TSR, shows a parabolic dependence on the TSR for both “aligned” and “inclined” configurations. The curves of for such configurations are very similar, covering a TSR range between TSR=0 and TSR=1.75, with maximum values of P_t= 7.468 mW for the inclined configuration and P_t=7.668 mW for the inclined configuration. Comparing these maximum values and the two curves in Fig. 4, we notice that the inclined configuration provides a power slightly greater than the “aligned” configuration for TSR>0.75. This suggests that the inclination affects the power production only for the highest angular velocity of the turbine.

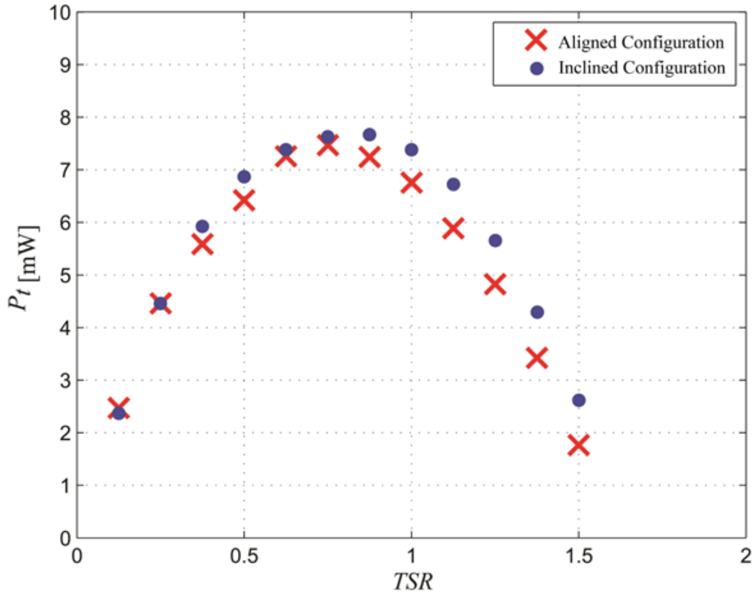

Figure 4- Generated power from numerical simulations, as function of the corresponding Tip Speed Ratio.

The performance coefficients of the two configurations are represented as function of the TSR in Fig. 5, together with the theoretical maximum performance coefficient defined with Betz's theory and the Savonius performance curve [28].

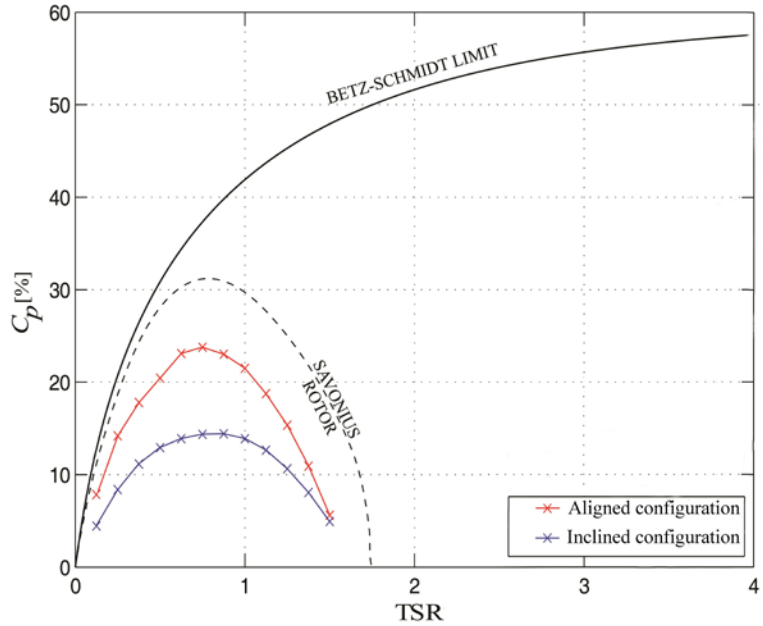

Figure 5- Power coefficient C_p as function of the TSR, evaluated from the numerical experiments. The theoretical limit of Betz's theory and the Savonius rotor performance curve are also reported.

The efficiency of the "inclined" configuration is smaller than that of the "aligned" configuration: the performance curve reaches the peak of C_p=23.8% for the "aligned" configuration (red curve in Fig. 5) and C_p=14.4% for the "inclined" configuration (blue curve in Fig. 5). The performance is lower in the "inclined" configuration, because such

configuration exploits a greater flow power (P_f=53.17 mW for the “inclined” configuration, while it is P_f=31.42 mW for the “aligned” configuration), but the generated power is almost the same, as said before.
Comparing the performance curve of the Archimedean-Type Hydrokinetic Turbine with that of the Savonius turbine we find that they display the same operative range (0<TSR<1.75) and the same maximum performance TSR=0.75. However, the Archimedean-Type Hydrokinetic Turbine shows a lower efficiency, especially for the “inclined” configuration. For example, the “aligned” configuration provides about 2/3 of the power generated by a Savonius turbine in the same flow condition. Although, the comparison in terms of efficiency is adverse for the Archimedean-Type Hydrokinetic Turbine, we observe that the proposed novel way of using the Archimedean-Type turbine leads to performance comparable with the more innovative hydrokinetic turbines. Moreover, the performance curve is located in the low-velocity regime, which is compatible with deployment in riverine ecosystems, since it minimizes both negative impacts on fish stocks and interactions with debris transported by the river stream, hence increasing the lifetime of the turbine.

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