18th International Conference on Renewable Energies and Power Quality (ICREPQ'20)
Granada (Spain), 1st to 2nd April 2020
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.18, June 2020

Numerical analysis of the inlet channel and basin geometries for vortex generation in a gravitational water vortex power plant

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Abstract

Recently, the utilization of low-head hydroelectric technologies has received a great attention for the expansion of distributed power systems into isolated regions that are difficult to be connected to the electrical grid, especially in developing countries. The use of gravitational vortex hydropower systems can be a renewable and suitable option to expand electricity access and promote development in these remote regions, which are concomitantly rich in hydric resources, due to this system can operate with low head without the need of a large reservoir and installation area.

In this study, the performance of the inlet channel and basin of a gravitational water vortex turbine was investigated. Two inlet channels and two basin geometries were numerically analysed in Ansys Fluent software. The velocity and vortex height were calculated and compared for each setting. It was found that the inlet channel with conical basin tended to produce more symmetric vortex in comparisons with that generated by the cylindrical geometry. Additionally, the conical basin maximized the flow velocity on the water surface area.

Key words. Gravitational vortex, low-head hydropower, CFD, cylindrical and conical basin

1. Introduction

Nowadays, one of the main objectives for developing countries is to achieve the diversification of the energy mix and the enhancement of the energy security due to the demand for electricity has been rapidly increasing and it is expected to further rise in the coming years because of population and economic growth [1, 2]. Additionally, the sources of power generation of greater current use, especially the energy obtained from fossil fuels, generate detrimental environmental problems. Therefore, the global trend is focused on the de-carbonization and the use of renewable energy, such as solar and wind energy, small hydropower and hydrokinetic system, and ocean, geothermal and biomass power plant, among others, for the production of electricity [1-3]. Indeed, hydroelectric power remains one of the most cost-efficient sources of renewable energy production. The generation cost depends on the efficiency of the technology used [1-5].

In especial, small hydro-energy is more predictable; typically, it has short construction schedules and is easily built when compared to other renewable forms of energy [3-6]. Around the world, a significant source of green energy could be provided by low head hydropower plants using several types of water turbines; however, for ultra-low head, the gravitational water vortex turbine (GWVT) should be used [6-9].

GWVT is a low hydraulic head turbine that extracts energy from an artificially induced gravitational water vortex in the basin of cylindrical or conical configuration. The main advantage of this type of system is the generation of electricity from ultra-low hydraulic pressure, along with it is environmental friendly due to larger dams are not necessary and the manufacturing costs are relatively reduced because of its simpler construction and the use of locally available materials. Additionally, when the water passing through the turbine, it is aerated [6-9].

In a GWVT, the potential energy of water is converted into kinetic energy by using a basin or rotation tank that has a circular orifice at its base [7-9]. River water is channelled at the bank of the river and conveyed to basin using an inlet open channel, which is responsible to tangentially direct the water flow into the basin. The water is released through a hole central at the bottom of the tank and is returned to the river. In the basin, a gravitational vortex is generated and the kinetic energy of water is extracted by a vertical-axis turbine in the centre of the vortex, with rotates coaxially with it to harness the kinetic energy. The system can be installed in a serial or parallel configuration along the river to increase power production [10-15].

The turbine power output ranges from 3.3 to 20 kW for an average plant capacity of 7.5 kW with an efficiency between 42% and 66% [12]. This efficiency is lower compared to the efficiency of the Kaplan turbine and that of the Archimedes turbine (efficiency in the range from 76% to 84% and from 83% to 92%, respectively) [16]. However, the system yields a higher efficiency in comparison with a traditional undershot or overshot waterwheels, which exhibit an efficiency in the range from 35 to 40% [17].

In the literature, a limited number of studies focused on the design (component physical geometry) and manufacture of the vortex turbine. Furthermore, to the authors' knowledge, no researches based on the assessment of the influence of the wrap-around inlet on the mentioned turbine geometrical configuration have been reported. Under this scenario, this work is aiming at determining an optimal inlet channel and basin for vortex generation using Computational Fluid Dynamics (CFD) numerical models developed in Ansys Fluent software.

2. Channel and basin configuration

For GWVT, the inlet water flow rates used for the energy generation are conducted by a channel connected to the basin that contains the generation unit. The basin could have a cylindrical or conical geometrical configuration. Therefore, four geometrical configurations that result of the combination of two inlet channel types and two basin types were investigated in order to define the model with the best performance for the generation of vortex. In this regard, several models were modelled using CAD Solidworks software. The first model used a cylindrical basin with a tangential inlet channel; in turn, the second model was based on a cylindrical basin with a wrap-around inlet channel; the third model used a conical basin with a tangential inlet channel; and, finally, the latter one used a conical basin with a wrap-around inlet channel. The inlet channel had a square cross-section and was located at the upper part of the basin, uncovered at the top. The geometrical configurations and dimensions are shown in Fig. 1.

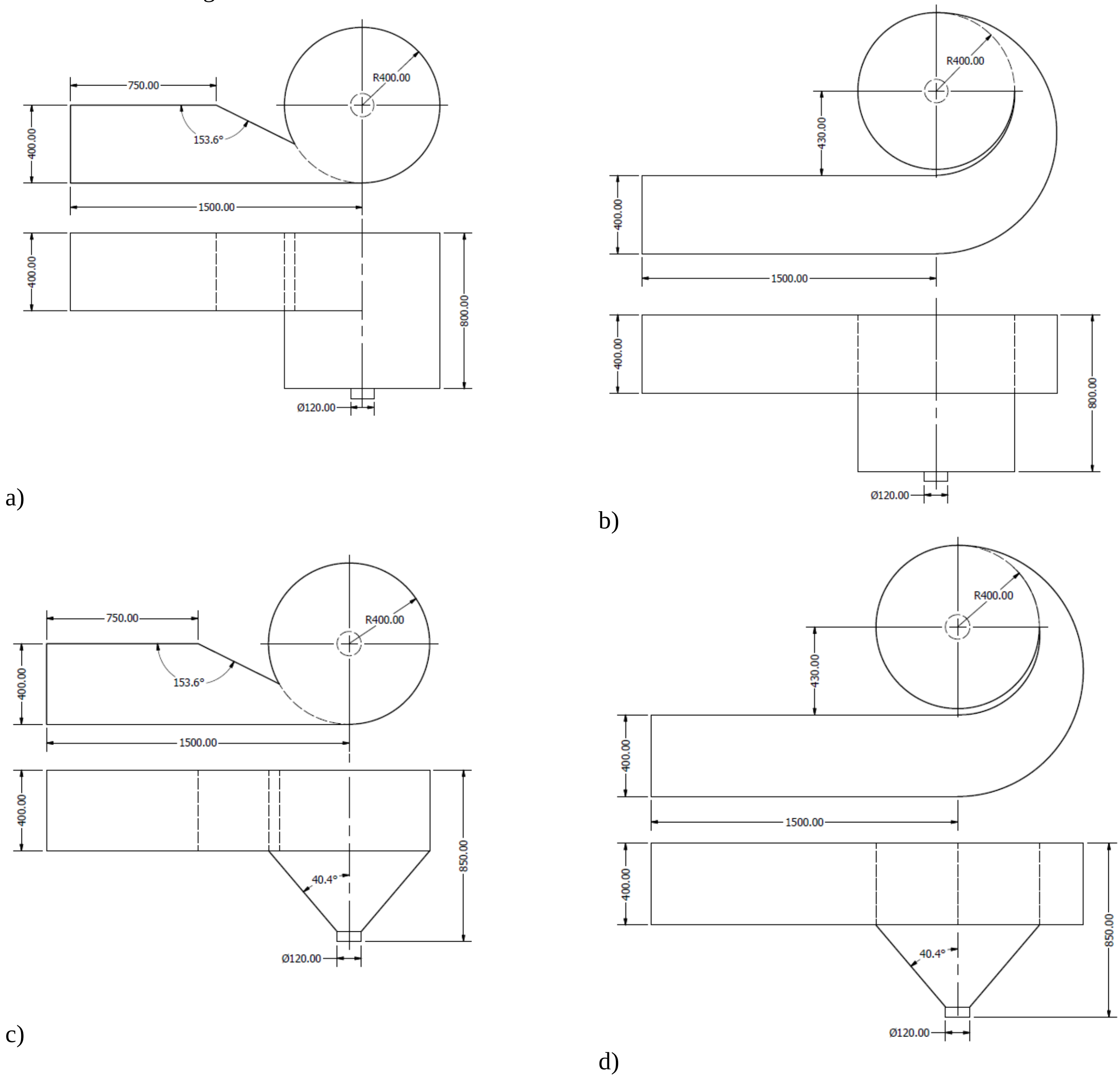


Fig. 1. Geometrical configuration of the inlet channel and basin. a) Tangential inlet with cylindrical basin, b) wrap-around inlet with cylindrical basin c) tangential inlet with conical basin, d) wrap-around inlet with conical basin.

The models had an orifice at the bottom centre. For the four models, the inner diameter (D) of the basin was 800 mm, and the diameter of the hole (d) at the bottom of the basin, 120 mm. The d/D was taken as 0.15. An optimum ratio d/D in the range of 14%-18% for low and high head sites, respectively, has been claimed in cylindrical basins in the past for strong vortex formation [18-21]

The height (H) of the cylindrical and conical basin was 800 mm. The inlet channel length was 1500 mm. In turn, the channel width and height were 0.5 H; therefore, theses geometrical parameters were equal to 400 mm. For models with conical basin, the cone angle was assumed to be 40.4°.

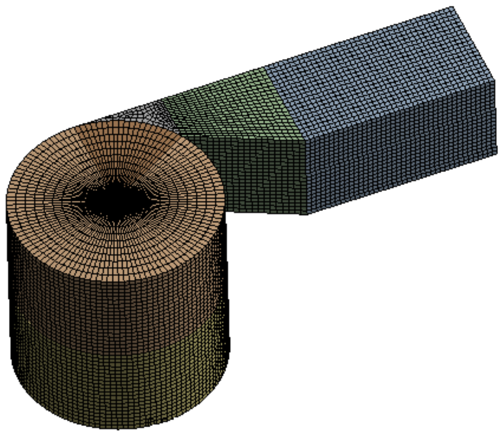
2.1 Numerical analysis

In this study, CFD was used to simulate and compare the vortex formation in four geometrical configurations of the inlet channel and basin of a gravitational water vortex power plant. The turbine was not introduced in the analysis; therefore, its effect on the vortex formation was not considered in the numerical simulation. In theses studies, three-dimensional unsteady flow analyses were performed by considering the free surface. The Reynolds-averaged Navier-Stoke (RANS) equations were taken as the governing equations with the $\boldsymbol{k-\varepsilon}$ turbulence model. These equations were discretized by the finite volume method using the commercial CFD package Ansys Fluent software. The convergence criterion for the whole set of equations was 10^{-4} [22].
The type of analysis to be performed was of transitory nature, which allowed observing the changes in the velocity and pressure field, from the beginning of the vortex formation to its stability. Gravity, with a magnitude of 9.81 m/s^2, was considered in the analysis. The working fluids were water and air. The vortex velocity field and height were evaluated using the referred software.

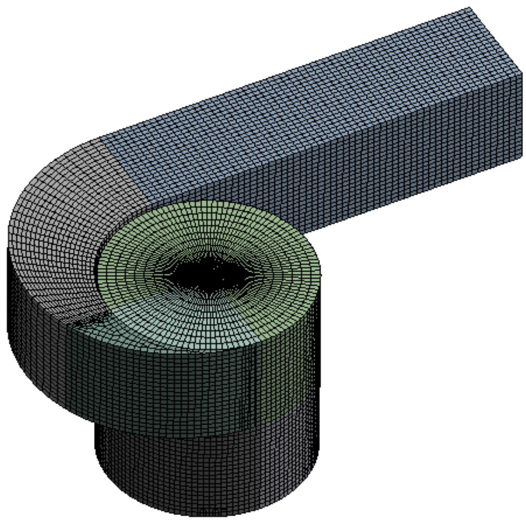
A computational grid for the four models are illustrated in Fig 2. The entire volume of each model was divided into around 14 main volumes in order to mesh the computational domain. A structured mesh was used in this study with hexahedral elements. A study of the grid independence was conducted to ensure the achievement of the solution convergence. The number of elements used in the final computational domain for the simulation of models 1, 2, 3 and 4 were 843052, 961014, 720216 and 901779, respectively.

As boundary conditions for the whole set of models, the inlet velocity (0.1 m/s) was given to the inlet boundary; in addition, open boundary (total pressure of 0 Pa for the inflow or relative static pressure of 0 Pa for the outflow) was considered to the outlet boundary. Furthermore, the upper surfaces of the channel and basin were set to open boundaries (relative static pressure of 0 Pa), so that air could enter and exit freely; i.e., the upper surfaces of computational domain were subjected to atmospheric pressure. Moreover, the wall surface was set to the non-slip condition.

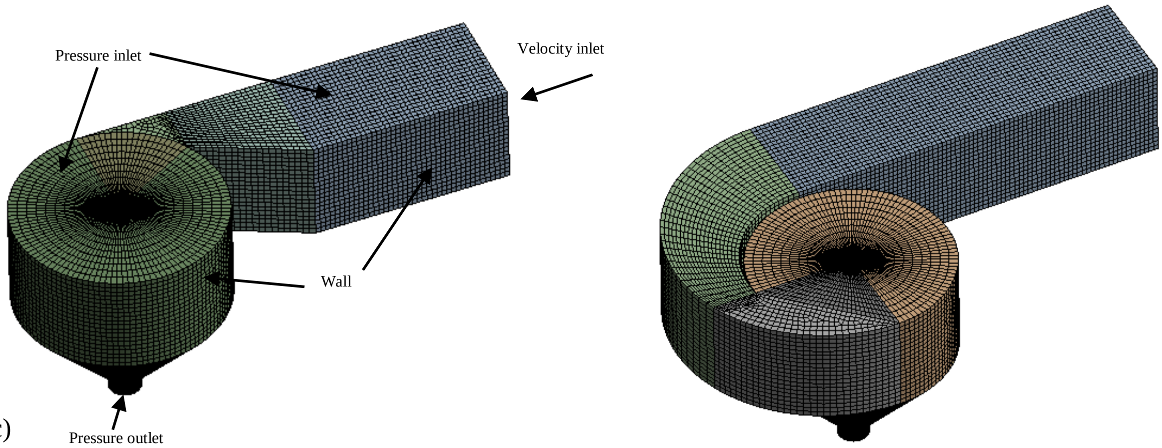
In the unsteady flow analysis, a temporary step of 0.1 seconds was used for a total simulation time of 300 seconds; time that was sufficient for the vortex of the four models to be formed and stabilized. Fig. 3 represents the changes in the output mass flow as a function of the simulation time. For the models with wrap-around inlet, the time required for the mass flow to be stabilized (maintaining a constant flow in the gravitational vortex of 16 kg/) was observed to be less than that for models with tangential inlet.



a)



b)



c) d)

Fig. 2. Computational domain of the inlet channel and basin. a) Tangential inlet with cylindrical basin, b) surrounding inlet with cylindrical basin, c) tangential inlet with conical basin, d) surrounding inlet with conical basin.

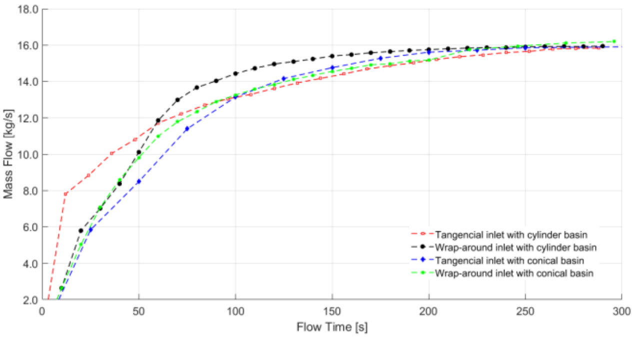
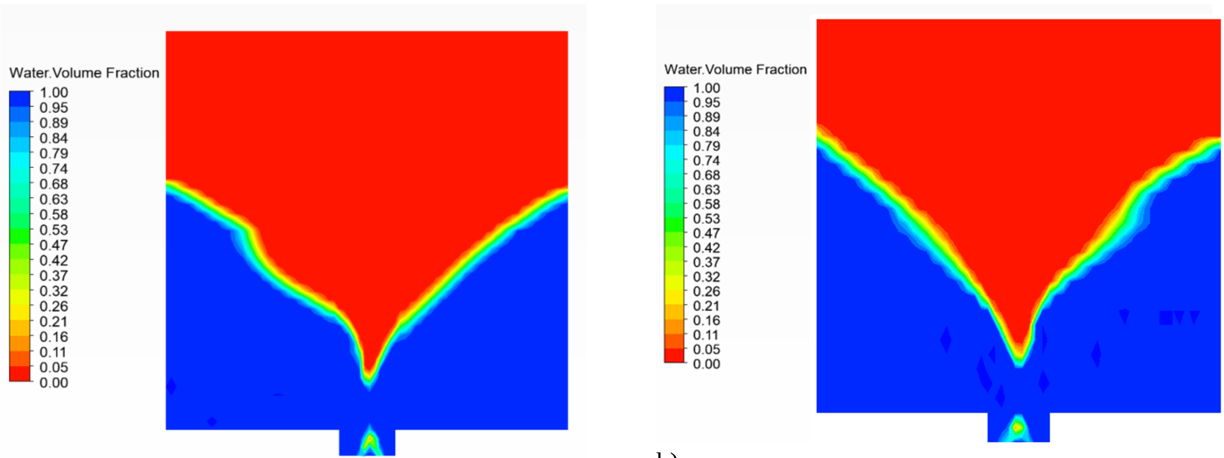


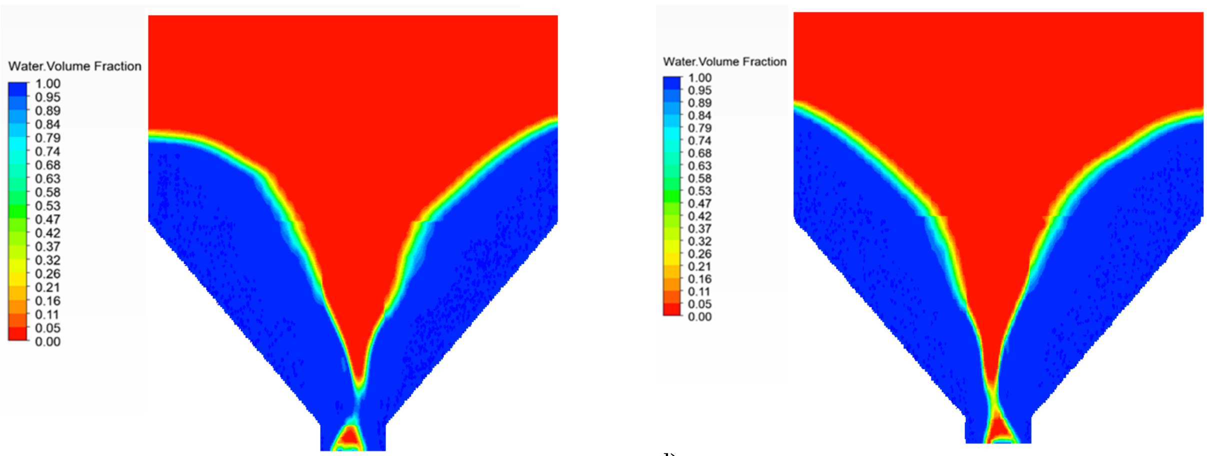
Fig. 3. Mass flow as a function of the time.

It is noteworthy that depending on the design of the GWVT basin, the vortex profiles created are different. Fig. 4 shows the volume fraction of water and air at 300 s. Water in Fig. 4 is represented by the red color, while air, by the blue color. Fig. 4 illustrates the vortices, which are perfectly formed. The vortex of model 4 (i.e., the model with wrap-around inlet and conical basin) can be observed to be more symmetrical and higher than those ones obtained with the other evaluated models.

3. Results and discussion



a) b)



c)

d)

Fig. 4. Water volume fraction at 300 s. a) Tangential inlet with cylindrical basin, b) wrap-around inlet with cylindrical basin, c) tangential inlet with conical basin, d) wrap-around inlet with conical basin.

Fig. 5 shows that the conical basin in both inlet geometries produces a symmetric and stable vortex. It is important to note that a symmetric vortex causes a radial force of lesser magnitude. Additionally, radial steering forces are responsible for creating moments of flexion in the shaft of the turbine, which reduce its efficiency and durability [23]

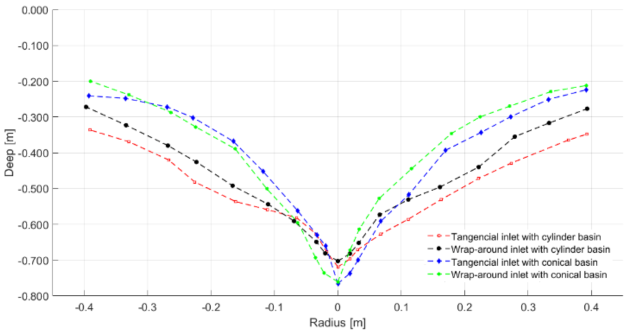


Fig. 5. Vortex profile for different basins and inlets.

The tangential velocity component is one of the most important characteristics of the vortex flow. The tangential velocity distribution along the radial direction is represented in Fig. 6. It was found that, from the radius of the vortex core, the tangential velocity increases to a maximum value, which is reached at a radius that is approximately equal to 50% of the basin radius. Furthermore, the wrap-around the inlet with conical basin configuration was observed to provide the largest values for tangential velocities of 1.55 m/s when the radius was 0.22 m.

In general terms, from the flow simulation, the average velocity in the conical basin was higher than that in the cylindrical basin for similar conditions of head and discharge. This can be explained as a consequence of the inflow area decrease in the conical basin. Velocity increases, thereby, maintaining a constant flow rate. From the results obtained, the same turbine should be expected to extract much more power from the conical basin than from the cylindrical one since the power output is influenced by the vortex height and the water flow rate.

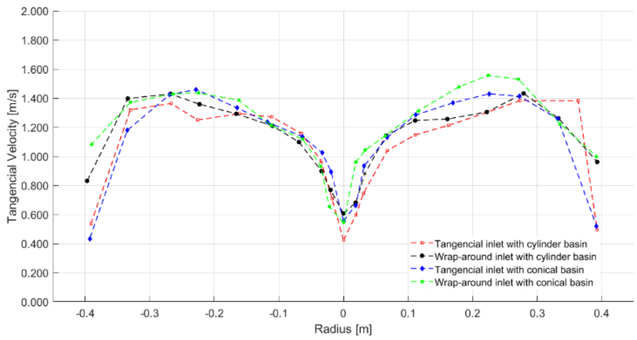


Fig. 6. Tangential velocity distribution along the radial direction for different basins and inlets.

Thus, the computational study suggests that the conical basin is much better than the cylindrical one for the provided head and discharge. It is highlighted that several researchers also conducted a number of tests on the basin [12, 15, 24]. They found that the vortex strength in the conical basin was stronger than in the cylindrical basin.

4. Conclusion

Gravitational water vortex power plants can be a suitable option for rural electrification. This system is an emerging technology in the context of low head hydropower plants. The channel design and basin are important parameters for effective vortex generation; therefore, CFD analysis were conducted on the inlet channel (tangential or wrap-around inlet) and the basin (cylindrical or conical) of a GWVT in order to discern the effect of the combination of geometrical configuration of these components. Four configuration with diameter and height of the basin of 0.8 m were modelled. The performances of the models based on the tangential velocity and the quality of the vortex produced were studied. It was found that a conical basin with an orifice at the bottom centre was the most suitable configuration to create larger kinetic energy in the vortex.

Additionally, it was observed that model 4, defined by a wrap-around inlet and conical basin, was the most suitable basin since it provided better and more uniform velocity compared to the other models evaluated.

Furthermore, from the result analysis, it was evidenced that model 4 configuration provided the maximum tangential velocity, which is a relevant component to drive the turbine blade. This velocity was proportional to the power output. On the other hand, it is important to note that knowing the location of the highest velocity allow identifying the optimum point of a rotor installation, since a greater extraction of energy from the flow is possible at this point.

Acknowledgement

The authors gratefully acknowledge the financial support provided by the Colombia Scientific Program within the framework of the call Ecosistema Científico (Contract No. FP44842- 218-2018).

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