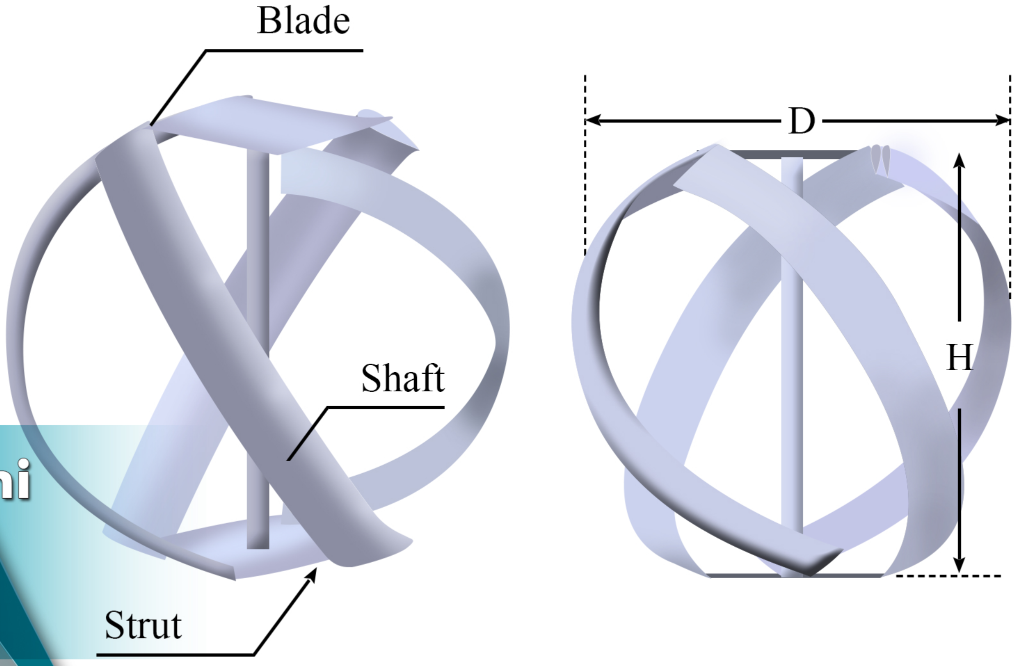
VERTICAL AXIS HYDROKINETIC TURBINES: NUMERICAL AND EXPERIMENTAL ANALYSES



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Vertical Axis Hydrokinetic Turbines: Numerical and Experimental Analyses

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Vertical Axis Hydrokinetic Turbines: Numerical and Experimental Analyses

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PREFACE

In recent decades, global demand for energy has increased with the expanding world economy. For this reason, excessive use of non-renewable energy sources has been noticed. Climate change, air pollution, and carbon dioxide emission were considered as the principal disadvantages of the excessive use of fossil energy sources. To avoid the excessive exploitation of fossil energy sources, sustainable energies, which are produced by natural resources of energy, are recommended. Hydraulic energy, which is a sustainable energy source, is within this context. Hydraulic rotors ensure the generation of electrical energy from streams, canals of irrigation, or rivers. Indeed, hydraulic rotors convert the water kinetic energy into mechanical power. Afterward, the mechanical power is converted into electrical energy by a generator. Hydraulic rotors are categorized as hydraulic rotors with a horizontal axis of rotation and others with a vertical axis of rotation. Many researchers have noted that hydraulic rotors with a vertical axis of rotation present many benefits with regard to the ones with a horizontal axis of rotation. The simplicity of the geometric form, the easy maintenance, and the independence of the direction of the water are the major benefits of hydraulic rotors with a vertical axis of rotation.

This book focuses on the performance optimization of different proposed configurations of vertical axis water rotors. The book is composed of four chapters.

In the first chapter, the technology of the water turbines is presented. We introduce the water turbines' background and classification, the basic parameters that characterize the water turbines, and their performance characteristics formulations. A brief literature review is also recapitulated to provide an idea about the improvement techniques carried out by researchers to boost the efficiency of the vertical axis water turbines, to situate the present work, and justify the novelty of our investigations.

In the second chapter, we discuss the governing equations and the numerical methods used in Ansys Fluent as the adopted CFD software. Indeed, the impact of the numerical parameters on the efficiency of different forms of hydraulic rotors is presented. Furthermore, the meshing, the turbulence model, and the rotating domain size effects are determined. The validation of the numerical model has been done with anterior results.

In the third chapter, we have conducted experimental and computational investigations of a V-shaped Darrieus hydraulic rotor. The experimental results are used to validate the computational fluid dynamics model. The spiral angle of the V-shaped blades has been varied. For each configuration, we present and discuss the hydrodynamic characteristics of the water such as velocity field, magnitude velocity, and turbulence characteristics behind the considered hydraulic rotor.

In the fourth chapter, the betterment of the performance parameters of spiral Savonius turbine and spherical Darrieus turbine is investigated through the addition of an aerodynamic appendage. In fact, two deflector systems are suggested around the turbines.

Finally, we summarize the different findings obtained in light of the current study to optimize the Darrieus rotor. We also propose new perspectives, which will be the subject of further work.

CONFLICT OF INTEREST

The author declares no conflict of interest, financial or otherwise.

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CONSENT FOR PUBLICATION

Not applicable.

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CHAPTER 1

Bibliographic Study

1. INTRODUCTION

Recently, electricity is known to be an essential requirement indicating the modernity of a society. It is considered a needed component in the development of a country. In fact, basic human needs, such as health, transport, food, and education, are based on electrical energy (Jorgenson *et al*., 2014). There are several technologies accessible that could be used to provide electricity to the whole world. Fossil fuels are among the most important sources of energy. People use coal, petroleum, oils, and natural gas to fulfill their needs in terms of powering vehicles and electricity production.

As a consequence of the extreme utilization of non-renewable energy sources, the exhaustion of these sources has become threatening to humanity. The continued demand has grown beyond its peak in recent years. Owing to the extravagant utilization of non-renewable energy sources, the world also has been facing environmental problems related to the emission of a huge amount of pollutants (Apergis *et al*., 2014). The utilization of sustainable energy sources is necessary to lower greenhouse gas emissions in the atmosphere (Chang *et al*., 2003). The solar, geothermal, biomass, water, and wind sources are considered important sources in many areas of applications. Among these sources of green energy, hydropower is a renewable energy source that will possibly be developed in the future (Paish, 2002). Although hydropower can not completely replace the traditional sources of energy, it can be an interesting and green substitute.

2. HYDROPOWER

The hydrological cycle, which is also known as the water cycle, fuels hydropower. In fact, the heat produced by the solar radiation evaporates the water contained on the earth's surface, which turns into clouds and rain (Yüksel, 2010). Water runoff is produced by the rain which falls on the land surfaces. Waterpower is a sustainable and renewed source of energy as long as the sun shines since solar energy powers the hydrological cycle. Since antiquity, it has been used by humans to survive. In fact, there are different types of applications (Peng and Guo, 2019).

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Fig. (**1**) presents the share of renewable energy sources in the global electricity system in 2016. From this Figure, it has been noted that waterpower is the most widely used for electricity generation (16.6%) compared to wind, solar, and other renewables. Hydropower plants can be classified into four major kinds, such as run (Killingtveit, 2019).

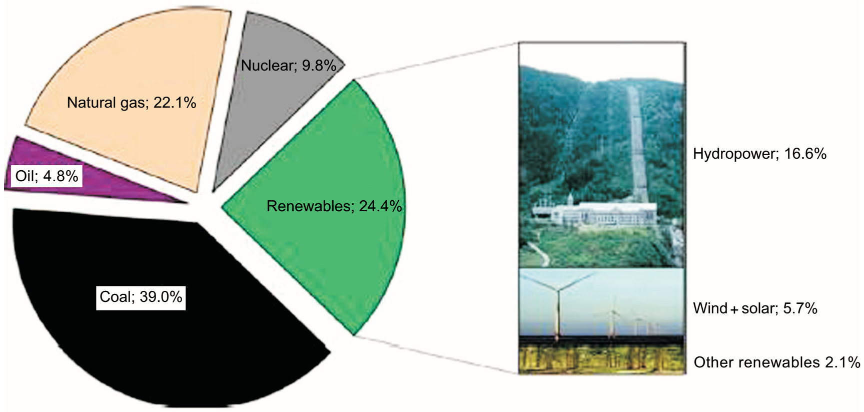

Fig. (1). Share of renewables in the global electricity system 2016 (Killingtveit, 2019).

2.1. Run-of-river Hydropower Plants

A run-of-river hydropower plant is a hydroelectric system that generates electrical power from the available flow of the river. In fact, the water current is diverted from the river and guided in a penstock, as shown in Fig. (**2**). The run-of-river hydropower plant differs from other hydropower plants types in the absence of a reservoir and large dam. However, a small dam can sometimes be used to ensure enough water goes in the penstock. In addition, some storage capacity can be used for a few hours.

2.2. Storage Hydropower Plants

This water power plant is characterized by the presence of a water tank, as presented in Fig. (**3**). The confined water is released for eventual consumption. The stored water in the reservoir furnishes flexibility to produce electrical power on need and lowers dependency on the water current change. A huge reservoir could stow water for a long time. However, the used reservoir for a storage hydropower plant is designed for seasonal storage. Compared to the run of river water power plant, the storage water power plant presents various advantages such as:

Fig. (2). Run-of-river hydropower plant (Breeze, 2018).

Fig. (3). Storage hydropower plant (Breeze, 2018).

- Provides the possibility to stow big volumes of energy.
- Provides the possibility to control water flows.
- The storage reservoir is a multipurpose system.

2.3. Pumped-storage Waterpower Plants

This waterpower plant is used by the systems of electrical generation for load balancing. In fact, water is pumped from a lower reservoir into an upper reservoir when production surpasses the need, as shown in Fig. (**4**). When the demand for electricity is high, the stored water in the upper reservoir is released back into the lower reservoir in order to spin turbines that generate electricity. This cycle could be repeated various times per day. The pumped-storage hydropower plant is

CHAPTER 2

Numerical Parameters Effect

1. INTRODUCTION

Due to the rising costs incurred in the experimental studies of the design process of the cross-flow rotors, researchers have adopted numerical methods, such as the CFD (Computational Fluid Dynamics) technique. The CFD method offers the possibility to visualize the turbulent properties and the water comportment upstream and downstream a hydraulic turbine, which are tough to be examined through experimental techniques. For example, a computational investigation of a Savonius hydraulic turbine, which was characterized by spiral vanes with various helix angles (From 0° to 25°), was developed by Kumar and Saini (2017). They tested the impact of the vanehelix angle increment and the variation of the Reynolds-number on the operational parameters of the Savonius hydraulic turbine. In conclusion, the authors confirmed that a Reynolds number increases the efficiency of the Savonius hydraulic turbine. Using a spiral Savonius turbine with a helix angle of 12.5°, the peak value of the power-coefficient (PC) reached 0.39 at a water flow velocity of 2 $m.s^{-1}$. Moreover, the authors noticed that the helix angle affects the turbulent properties of the flow upstream and downstream of the Savonius hydraulic turbine, *i.e.,* the streamlines of the velocity and the static pressure. An experimental investigation of a Savonius hydraulic turbine was carried out by Sarma *et al*. (2014). In addition, they developed a computational investigation based on Ansys Fluent to examine the operational parameters of the Savonius hydraulic turbine at feeble values of water speed. A computational investigation was developed by Basumatary *et al*. (2018). They tested a Savonius hydraulic turbine with a novel vane form. In conclusion, they noted that the operational parameters of the Savonius hydraulic turbine were improved using the novel vane form. Indeed, the peak value of the PC of the Savonius hydraulic turbine attained 0.284 at a tip-speed ratio (TSR) of 0.6. In our work, ANSYS FLUENT software has been considered to carry out the different computational investigations and then to visualize the turbulent properties of the water around hydraulic turbines.

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2. STRUCTURE OF THE CFD CODE

A CFD solver presents three principal parts, which are the pre-processor, the solver, and the post-processor. The first part is composed of the input of the workflow to computational fluid dynamics code using an operator-friendly interface. The input is then converted into an appropriate form to be used by the solver. At the pre-processing step, the user defines the computational domain, the grid generation, the fluid properties, and the boundary conditions.

For the solver, it includes the discretization methods: the FDM (finite difference method), the FVM (finite volume method), the FEM (finite element method), and other methods used in specific applications, mainly the vortex method. ANSYS Fluent 17.0 provides further two computational solver techniques:

- The pressure-based technique

- The density-based technique

It is known that the pressure-based method is used for incompressible fluids at low speed. Although the density-based method is used for compressible fluids at high speed. Recently, the pressure-based and the density-based approaches have been reformulated to be operated with wide variety of flow conditions. The pressure-based solver utilizes an algorithm wherein the mass conservation constraint of the velocity field is achieved by solving a pressure equation. This equation came from the continuity and the momentum equations so that the continuity of the velocity field is achieved. The relation between the pressure and the velocity in the overall domain can be inferred in the entire computational domain. The pressure-based solver involves iterations where the governing equations are resolved continuously until the convergence of the solution. For post-processor, Ansys Fluent 17.0 is equipped with adaptable data visualization packages that include the plot of contours for 2D and 3D, vectors, streamlines, forces monitoring, and other available output data.

3. MATHEMATICAL FORMULATION

The main advantage of a commercial CFD code is that it is able to model the laminar or the turbulent fluid flow. In fact, a physic problem can be solved based on steady-state or transient simulations. In the present chapter, three-dimensional (3D) unsteady investigations were performed. The water flow upstream and downstream, a hydraulic turbine modeling is based on resolving the Navier-Stokes (NS) equations that govern it. The NS equations according to a Newtonian fluid are prescribed under the continuity, momentum, and turbulence model equations. In many important applications, including turbulence, these equations must be modified or otherwise approximated analytically in order to excerpt any estimation.

3.1. Continuity Equation

The continuity equation could be expressed as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho\, u_i)}{\partial x_i} = 0 \tag{1}$$

Where

u_i : Velocity component along i axis,

p : Fluid density,

x_i : Cartesian coordinate,

t : Time.

3.2. Momentum Conservation Equations

The momentum equations can be written as follows:

$$\frac{\partial (\rho\, u_i)}{\partial t} + \frac{\partial (\rho\, u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_j}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i}\right)\right] + \frac{\partial (-\rho\, \overline{u_i^{'} u_j^{'}})}{\partial x_j} + F_i \tag{2}$$

Where

p : Pressure,

F_i : External forces.

$\overline{u_i^{'} u_j^{'}}$ are the turbulent stress and can be written as follows:

$$-\rho \overline{u_i^{'} u_j^{'}} = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\rho\, k\, \delta_{ij} \tag{3}$$

CHAPTER 3

Investigation of Spiral Darrieusturbine

1. INTRODUCTION

The water turbines can be classified into two major kinds: the axial-flow rotors (AFR) and the cross-flow rotors (CFR). The simplicity of the blade shapes and the independence of the water current direction give the advantage to the CFR for the generation of small-scale hydropower with regard to the AFR. With the aim of performance enhancement of CFR, numerous computational and experimental tests were conducted recently. For example, Moghimi and Motawej (2020) carried out a computational test of a twisted Darrieus water rotor (TDWR). They investigated the impact of the twist angle on the operational parameters of the TDWR. In conclusion, the lowest coefficient of power value was obtained with a 120° twist angle. However, the peak one was recorded with a 30° twist angle at a tip-speed ratio value of 3.5. Based on the FLUENT solver, Elbatran *et al*. (2017) investigated a hydraulic turbine without and with a deflector system. In conclusion, they confirmed that the value of 0.4375 was the optimal diameter ratio of the deflector system. Moreover, they affirmed that the performance of the hydraulic rotor could be risen by 78% using a ducted nozzle. The peak value of the coefficient of power reached 0.25 at a TSR of 0.73. Gorle *et al*. (2016) computationally and experimentally tested a Darrieus water turbine. They analyzed the field of the fluid flow in the vicinity of the rotor and the performance parameters of the Darrieus rotor. Derakhshan *et al*. (2017) conducted computational and experimental tests of a novel CFR. In conclusion, adequate operational parameters were obtained for the area with height ratios and for a distance of 13×D between neighbor turbines in a four turbine farm. Using Ansys CFX, Marsh *et al*. (2017) studied the effect of two and three-dimension domain selection and the turbulence model on the performance characteristics of CFR. They confirmed that the use of the three-dimension domain and k-ω SST model with a boundary layer meshes near the rotor vanes provides accurate computational results. Thakur *et al*. (2019) numerically tested a hydraulic turbine with and without an impinging jet duct design. In conclusion, the proposed configuration improves the operational parameters of the hydraulic turbine. The peak value of the coefficient of power reached 0.35 at a TSR of 0.64 for a conventional turbine. Nevertheless, it reached 0.5 at a TSR of 0.61 using the

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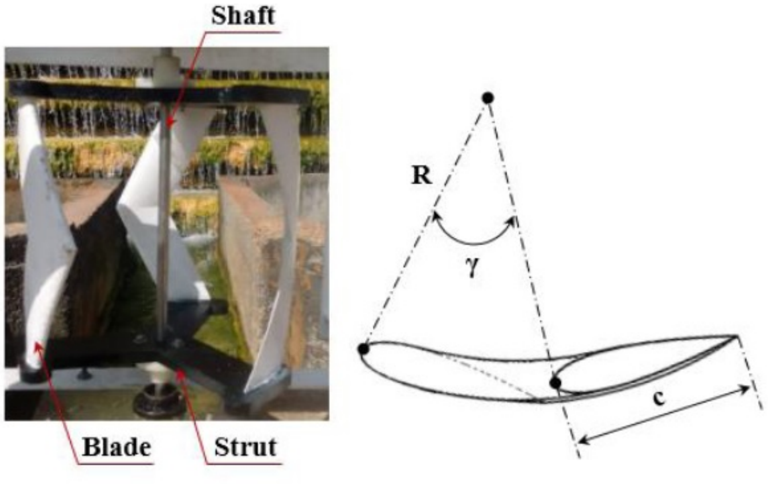
proposed design. Fertahi *et al*. (2018) conducted computing investigations on the Savonius-Darrieus rotor. The influence of the rotor speed direction on the performance parameters of the hybrid rotor was assessed. In conclusion, they noted that the hybrid turbine with identical rotor speed direction for Savonius and Darrieus turbines outperformed the other hybrid-studied designs. Liang *et al*. (2017) studied a combined Darrieus-Savonius rotor. Computing investigations were performed using the URANS equations. The tested Darrieus turbine presented a NACA 0012 profile with a chord of 220 mm. Two-semicircle vanes with an overlap distance of 0.1 characterized the Savonius rotor. In conclusion, they affirmed that the attachment angle, the Darrieus turbine vanes number, and the radius ratio affected the performance parameters of the hybrid rotor. The optimal design for the combined turbine presented a two-bladed Darrieus turbine, a radius ratio of 0.25, and an attachment angle of 0°. The peak value of the power coefficient (PC) of the optimal design reached 0.363. Al-Dabbagh and Yuce (2018) presented a computational test of spiral water rotors. The spiral rotors are with four different solidities of 0.15, 0.2, 0.25, and 0.3. Computational results confirmed that the rotors with the solidity values 0.15 and 0.2 outperformed the other two cases in terms of coefficient of power. As revealed by several published papers, scientists have focused on various kinds of cross-flow rotors. Several methods can be used to improve the efficiency of the cross-flow rotors, such as the variation of the rotor geometrical parameters and the optimization of the test bench form. This work attempts to explore the blade form optimization method for the better efficiency of spiral Darrieus turbine's (SDT). Computational transient investigations were performed with the use of ANSYS Fluent software to show the influence of the blade form techniques on the aerodynamic performances of the SDT.

2. EXPERIMENTAL METHODOLOGY

2.1. Spiral Darrieus Turbine

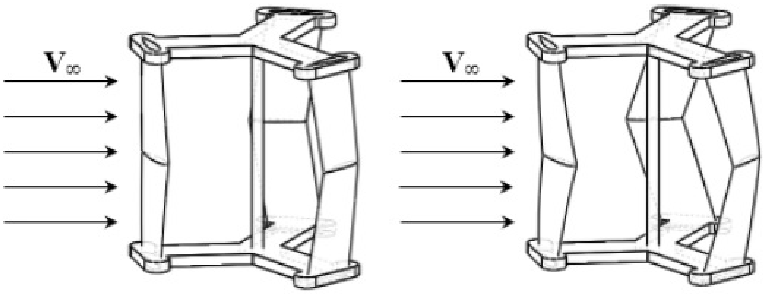
Due to the form complexity of the SDT, it is found that the 3D printing technology is more suitable as a manufacturing process. In fact, the additive manufacturing method is based on building up objects additively layer by layer, starting from a three-dimensional digital model. The main components of the SDT include three spiral blades mounted over a central shaft. Fig. (**1**) illustrates the design of the SDT.

The overall geometrical parameters of the SDT are shown in Table **1**. The optimization of the blade shape of the spiral Darrieus hydraulic rotor is investigated with the aim of performance betterment. For that, four spiral angles are suggested and put to tests to compare their characteristics. The proposed spiral angles covered under this study are shown in Fig. (**2**).

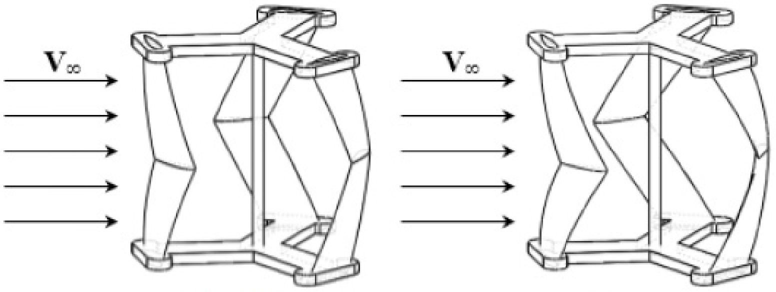


(a) Delta blades rotor (b) Top view of blade

Fig. (1). Spiral Darrieus turbine.



(a) γ=10° (b) γ=20°



(c) γ=30° (d) γ=40°

Fig. (2). SDT with various spiral angles.

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CHAPTER 4

Performance Investigation of Spiral and Spherical Turbines

1. INTRODUCTION

Nowadays, various studies have shown different methods to enhance the efficiency of the Savonius turbine (ST) and Darrieus turbine (DT) based on computational and experimental techniques, such as the variation of the design parameters of the turbine. The aspect ratio (AR), the gap distance, the vanes profile, and the number of the vanes are the prime parameters that affect the performance of ST and DT. Patel *et al*. (2017) presented an experimental investigation of a Savonius water turbine. They studied the impact of the AR, the gap distance and the end disk. They investigated various gap distances (From 0 to 0.174). For a piece gap distance, they tested different ARs. In conclusion, they noted that the performance parameters of the ST could be enhanced using end disks. Moreover, they confirmed that the ST efficiency rises with the rise of the AR. The peak value of the power coefficient (PC) of the ST was reached for a gap distance of 0.11 with an AR inferior to 0.6. Nevertheless, for AR values greater than 1.8, the PC of the ST reached 0.2. Hassanzadeh *et al*. (2013) tested a spiral Savonius turbine (SST) and a standard ST computationally. In conclusion, they noted that the SST outperformed the standard ST in terms of PC. A computational investigation of ST was performed by Kerikous and Thévenin (2019). The influence of the vanes formed on the efficiency parameters of the ST was assessed in their investigation; the summit PC value was recorded with a vane form flatter on the concave side. Additionally, other investigations proposed other methods for efficiency parameters of ST and DT, *i.e.,* the placement of a deflector system (DS) upriver the turbine. Using ANSYS FLUENT, Ramadan *et al*. (2021) assessed the influence of a DS on the efficiency parameters of ST. In conclusion, the installation of the DS upriver the ST improved the efficiency of the turbine by 84%. Shimokawa *et al*. (2012) experimentally assessed the effect of the placement of DS round DT. In conclusion, they suggested that DS enhanced the performance parameters of the DT. Amongst all suggested tactics, the DS could boost the flow speed upriver the turbine and provides a pressure variation through the turbine. Indeed, DS, a technique that receives little regard, could be considered for better performance parameters of ST and DT.

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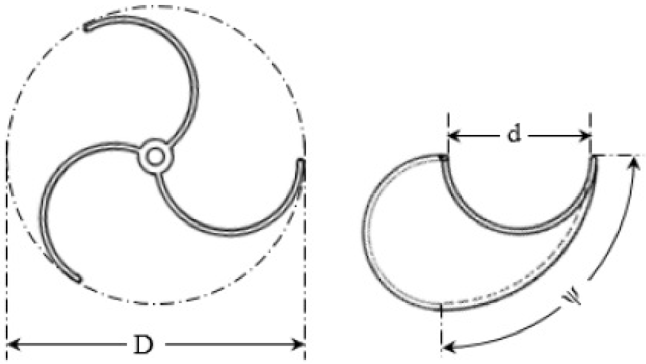
The major objective of this chapter is to experimentally investigate a spiral Savonius turbine (SST). The performance betterment of the SST and the spherical Darrieus turbine, which is presented in chapter two, using DSs is the second objective.

2. SPIRAL SAVONIUS TURBINE

2.1. Experimental Methodology

Due to the form complexity of the SST, a three-dimensional (3D) printer has been considered for the SST fabrication. Fig. (**1**) illustrates the SST model details. Indeed, three spiral vanes (With a spiral angle of 90 degrees) fixed around the rotational axis characterize the SST. The SST height and diameter are 16 cm and 18.2 cm, respectively. Table **1** provides the geometric details of the SST.

(a) 3D Model (b) SST



(c) Geometrical details

Fig. (1). SST design.

Table 1. Geometric details of SST.

Parameter	Value
SST diameter	18.2 cm
SST height	16 cm
End disk diameter	19.6 cm
Shaft diameter	2 cm
Vanes number	3
chord of the vane	9 cm
Thickness of the vane	0.4 cm
spiral angle	90°

To assess the efficiency parameters of SST experimentally, experiments are realized in a canal of irrigation (Situated in El-Hamma government, Tunisia). The flow speed in the considered canal is 0.87 m/s. Fig. (**2**) illustrates the measuring system used to determine the efficiency parameters of the SST (PC and torque coefficient (TC)).

N°	Reference
1	Weighing pan
2	Shaft
3	Graduated disc
4	Structure
5	Spring balance
6	Nylon string
7	Pulleys
8	Savonius rotor
9	Bearing

Fig. (2). Measuring system.

To boost the performance parameters of the spiral Savonius turbine, a DS upriver the SST is suggested and investigated computationally. Fig. (**3**) illustrates the DS considered in this study which is composed of a straight blade (Airfoil: NACA 0020) and a deflector plate. The deflector plate has a fixed part parallel to the direction of the water flow. To optimize the suggested DS, various configurations are investigated. The angle of deflection and the distance between the deflector plates are the variable geometric parameters for the DS design. Table **2** provides the geometric details of the various configurations of the DS.

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Glossary

$\mathbf{C_m}$	torque coefficient dimensionless
$\mathbf{C_p}$	power coefficient dimensionless
$\mathbf{C_{1\varepsilon}}$	constant of the k-ε turbulence model
c	blade chord m
d	rotating zone diameter m
D	rotor diameter m
$\mathbf{D_i}$	converging section diameter m
$\mathbf{D_o}$	pipe section diameter m
e	blade overlap
$\mathbf{F_i}$	force components N
$\mathbf{G_k}$	production term of turbulence kg.m^{-1}.s^{-3}
h	fixed domain height m
H	rotor height m
k	turbulent kinetic energy m^{2}.s^{-2}
l	fixed domain length m
$\mathbf{L_i}$	converging section length m
$\mathbf{L_o}$	pipe section length m
M	rotor torque N
p	pressure Pa
P	rotor power W
S	rotor swept area m^{2}
t	time, s
$\mathbf{u_i}$	velocity components m.s^{-1}
$\mathbf{U_i}$	fluctuating velocity components m.s^{-1}
$\mathbf{V_\infty}$	water velocity m.s^{-1}
w	fixed domain width m
$\mathbf{x_i}$	Cartesian coordinate m
x	Cartesian coordinate m
$\mathbf{y^+}$	non dimensional parameter
y	Cartesian coordinate m
z	Cartesian coordinate m
ε	dissipation rate of the turbulent kinetic energy W.kg^{-1}

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$\boldsymbol{\mu}$	dynamic viscosity Pa.s
$\boldsymbol{\mu}_t$	turbulent viscosity Pa.s
$\boldsymbol{\rho}$	density kg.m^{-3}
$\boldsymbol{\omega}$	rotor revolution speed rad.s^{-1}
$\boldsymbol{\lambda}$	tip-speed ratio
$\boldsymbol{\sigma}_k$	constant of the k-ε turbulence model
$\boldsymbol{\sigma}_\varepsilon$	constant of the k-ε turbulence model
$\boldsymbol{\delta}_{ij}$	Chroneker indices

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SUBJECT INDEX

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