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Numerical Optimization of the Blade Surface Geometry in a Wave Turbine System

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Environmental physics deals with energy demand problems and investigates the possible contributions of renewables to energy supply. Wave energy is one of the renewable, environmentally friendly types of energy sources. To convert the wave energy into the electrical energy, wave energy converters are used, such as the oscillating water column systems. Oscillating water column consists of air chamber, air turbine and generator. Air turbine is the main component of such system. It is a special type of turbine, called Wells turbine, which differs from others by its surface geometry. In the Wells turbine, blade surface geometry affects the efficiency enormously. An increased turbine efficiency with optimized turbine blade surface will contribute to environmental protection. In this study, it is aimed to increase the efficiency of an oscillating water column type wave turbine by using the dimpled blade surface instead of a flat blade surface. Numerical optimization is performed under Spalart Allmaras turbulence model in the commercial code ANSYS Fluent. Numerical results show that surface with dimples has higher efficiency when compared to flat blade surface.

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PACS/topics: environmental physics, optimization techniques, oscillating water column wave turbine, finite volume analysis, system efficiency

1. Introduction

The increase in the human population brings with it new demands. Energy is one of those demands and it is of strategic importance. In this context, energy supply is a crucial problem. Making an improvement in energy supply means a lot for human beings, from this point of view. In terms of the usable quality of the energy in the daily life, the most commonly used type of energy is the electric energy. As a result, energy of any type needs to be converted into electricity. This conversion is done with intermediate mechanisms or systems. Getting a higher efficiency from these mechanisms is another useful way to solve the energy demand problem. This is the principle of efficient use of limited energy resources.

When looking at the world, a wide variety of forms of energy can be seen. Wave-based systems are the first ones coming to mind when the energy source problem is considered. To get the wave power and to convert it into electricity is a promising subject with a number of existing solutions.

In this study, a well-known solution is selected and is improved by original contributions. Our improvement is related to the mechanism of the oscillating water column (OWC) system [1–6]. A Wells turbine is a self-rectifying air turbine which is expected to be widely used in wave energy devices with OWCs [7]. It is the most commonly used option in OWCs, the main characteristic of which is the ability to constantly spin in one direction regardless of the air flow direction [8].

Wells turbine is an axial-flow turbine that was invented in the mid-1970s to extract energy from a reciprocating air flow [9]. This system consists of an air compression chamber, a turbine including a diffuser (Wells turbine), and an electric generator [10]. Improving the efficiency of one of these components will directly affect the total efficiency.

The aim of this study is to improve the efficiency of the OWC by optimizing the surface of the blades of the turbine. There are a few works directly related to the blades. In these studies, the blade geometry was inspired from the nature, and some additional accessories were installed. In this case, the weight effect emerges as another issue. In this work the blade geometry has, for the first time, undergone a modification as a single whole. An innovative surface with dimples is proposed as new means for increasing the efficiency of the system.

NACA 0015 airfoil is selected as the blade profile. 154 (Case 2) and 310 (Case 3) dimples with the same diameter of 4.33 mm were applied separately to the selected two NACA 0015 airfoil geometries. The maximum number of dimples that can be applied on the surface of this blade is 310. The aim of applying 154 dimples is to use the half of the surface area. Efficiencies of both cases are compared with that of the undimpled NACA 0015 blade (Case 1) [11].

The advantage of applying dimples, which are used for the passive boundary layer control, is to delay the stall that decreases the efficiency of the Wells turbine.

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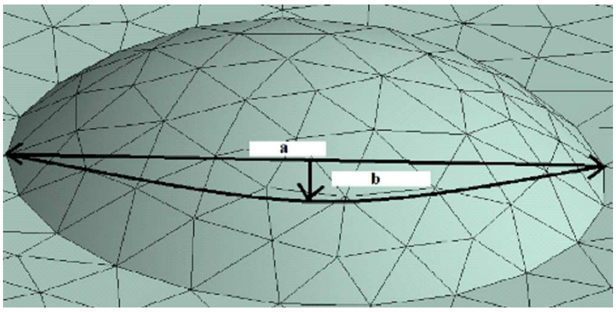

Fig. 1. Dimensions of the meshed dimple ($a = 4.33$ mm, $b = 0.7$ mm).

The dimensions of a dimple are given in Fig. 1. The dimensions of the dimples are selected from the standards for the golf balls [12].

2. Theory

In order to simulate the conditions under which the data are obtained some of the classical turbine definitions have been used. Tip speed ratio is defined as the ratio of the flow velocity on the blade to the peripheral velocity on the blade tip, calculated using Eq. (1):

$$\phi = v_{\mathrm{r}}/v_{\mathrm{e}}, \tag{1}$$

where v_{r} and v_{e} represent the velocity of flow and environmental velocity, respectively. The expression for the efficiency of Wells turbine is given by Eq. (2):

$$\eta = \frac{M\omega}{\Delta PQ}. \tag{2}$$

In Eq. (2), η is efficiency, M is moment, ω is angular velocity, ΔP is pressure difference between the inlet and outlet of the Wells turbine, and Q is volume flow rate.

3. Numerical analysis

A three-dimensional boundary value problem was considered to find the efficiency of the turbine using ANSYS Fluent. It is a commercial software for solving the continuity and momentum (Navier-Stokes) equations based on the finite volume method:

$$\nabla V = 0, \tag{3}$$

$$\frac{\partial V}{\partial t} = -\nabla(VV) - \nabla p + \nu\nabla^2 V + g. \tag{4}$$

In Eqs. (3) and (4), V is velocity, p is pressure, ν is kinematic viscosity, g is gravity [13]. In this problem three-dimensional, unsteady, viscous, incompressible conditions were taken into account. CFD analysis has been done by the finite volume method. Turbulence model has been set to Spalart Allmaras. Air flow velocity was assumed to be constant, 7 m/s.

In this analysis, a pressure-based solver was selected. Pressure-velocity coupling, second order upwind and SIMPLE schemes were used for pressure, momentum and volume-fraction equation discretization, respectively.

Cases with/without dimples have been meshed and the meshes are shown in Figs. 2 and 3. Detailed properties of the mentioned meshes are given Tables I and II.

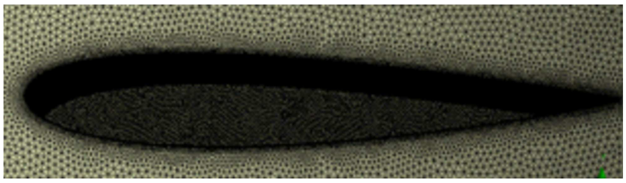

Fig. 2. Meshed domain of Case 2.

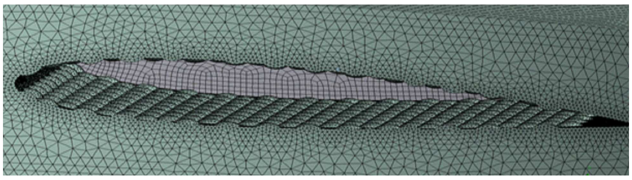

Fig. 3. Meshed domain of Case 3.

TABLE I

Mesh properties of the Case 2.

Skewness	1.9405×10^{-7}
Number of elements	6.373150×10^{7}
Number of nodes	1.920254×10^{7}

TABLE II

Mesh properties of the Case 3.

Skewness	1.759×10^{-7}
Number of elements	12.627862×10^{7}
Number of nodes	5.881483×10^{7}

Three types of NACA 0015 blade and their stall conditions are shown in Figs. 4–6.

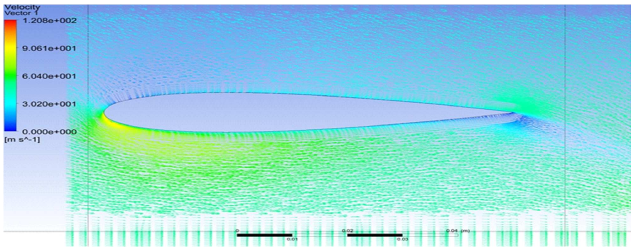

Fig. 4. Stall observation for Case 1.

Stall has a negative effect on the blade efficiency, as it can be seen in Fig. 4. In undimpled blade, stall starts from the center of blade surface and goes a long way on the blade surface to the tail. In Fig. 5, for the Case 2, the location of stall occurrence is closer to the tail, which means the efficiency was increased and stall affects less the blade surface.

In Fig. 6, for the Case 3 with more dimples, the stall occurrence zone is further away from the surface, which increases again efficiency and turbulence. In this case

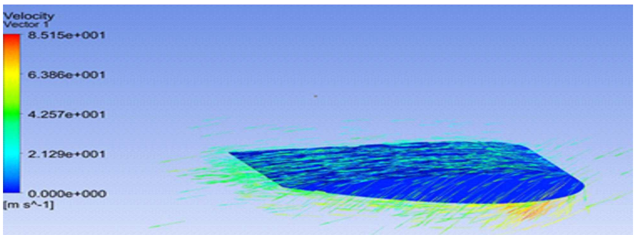

Fig. 5. Stall observation for Case 2.

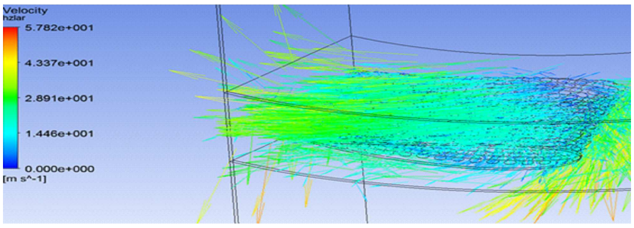

Fig. 6. Stall observation for Case 3.

stall is observed on minimum part of blade surface. Table III shows the efficiencies for the different tip speed ratios and revolutions per minute, for the investigated cases. It is clear that among the considered cases, the maximum efficiency has been obtained in the Case 3 with a value of 61%.

TABLE III

The efficiencies for the considered cases at different tip speed ratios.

ϕ	Case 1	Case 2	Case 3	Revolutions per minute
0.15	0.39	0.29	0.47	2875
0.16	0.33	0.4	0.51	2650
0.18	0.32	0.35	0.61	2465
0.20	0.30	0.3	0.32	2100
0.25	0.12	0.24	0.21	1725

4. Results and discussions

The results described above are summed in Fig. 7. In the figure, three lines indicate three different cases. Horizontal and vertical axis represent efficiency and tip speed ratio. In the Case 1 (without dimples), the maximum and minimum efficiencies are 33% and 12%, respectively. The maximum obtained efficiencies were 40% and 61%, for Case 2 (with 154 dimples) and Case 3 (with 310 dimples), respectively. It is shown that the efficiency can be increased by up to 29% by using dimpled blades.

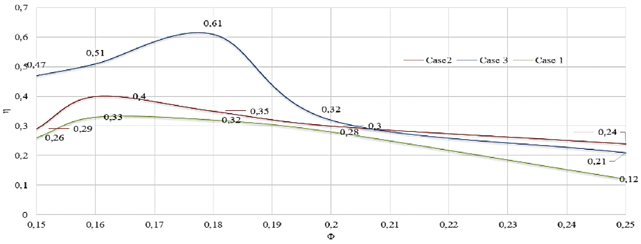

Fig. 7. Efficiencies vs. tip speed ratio.

5. Conclusions

In this study a three dimensional, numerical simulation of the efficiency of Wells turbine for OWC has been investigated with and without dimples on the blades. The finite volume method, based on commercial ANSYS Fluent solver, has been used to demonstrate the improved efficiency. Three cases have been considered to find the efficiency values. As a result, it has been found that using dimples increases the turbine efficiency significantly.

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