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Experimental Investigation of Air Turbine for Utilization of Wave Energy †

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Abstract: Working toward replacing conventional fossil fuels with alternative renewable energy, offshore renewable energy technologies give promising solutions, even though each of the types (wind, wave, tidal and thermal) is at a different stage of development and with its own unique challenges and opportunities. This paper is focused on sea wind wave energy harvesting through a hybrid system that combines both a water turbine with oscillating blades and "Wells"-type air turbine. A test bench was designed and tested at different flow rates to study the performance of the hybrid system and more precisely the "Wells"-type turbine. Experimental studies of the main parameters of a turbine were conducted, which demonstrated the efficiency of the turbine and its good practical application. The experimental results show good agreement with the preliminary performed numerical simulations, as well as with the published data.

Keywords: air turbine; Wells-type turbine; wave energy; renewable energy

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1. Introduction

Fighting the impacts of global climate change and achieving the goals of the Paris Agreement, efforts are aimed at harnessing and efficiently using alternative energy sources to satisfy the net-zero commitment [1,2]. Among the existing renewable technologies, offshore renewable energy remains largely unexplored, despite its substantial potential to contribute to the replacement of carbon-based sources of the energy system [3,4]. Offshore renewable energy encompasses four primary types: wind, wave, tidal, and thermal, each at varying stages of development and presenting distinct challenges and opportunities. While offshore wind, including floating technologies, has attained commercial maturity, tidal and wave energies are still in development.

Among the various prototypes of wave converters, oscillating water column (OWC) devices are regarded as one of the most promising technologies [5]. These devices are partially immersed hollow structures that create an air chamber with an underwater opening. This type of system most commonly consists of two subsystems: the system that captures and converts the energy of wave motion into air energy to produce a bidirectional air flow, and a turbine that harnesses this energy and is driven by the generated airflow, converting the energy of the air flow into electrical energy [6–8]. This configuration represents the advantage of achieving a relatively simple construction of the facilities and the safe operation of the system.

Another possibility toward better utilization of offshore energy is to combine two types of turbines: a water turbine, more precisely, a water turbine with oscillating blades that captures the wind waves' power installed along with an oscillating water column equipped

with an air turbine, namely a Wells-type turbine (citations of our works). The proposed design integrates two distinct runners, effectively mitigating their respective drawbacks. The first exhibits a high starting torque and low efficiency, while the second features low starting torque and high efficiency. Additionally, taking into account the density difference between saltwater (approximately 875 times denser than air), the hydraulic turbine with oscillating blades is expected to generate significantly more electrical power compared to the Wells turbine. This idea is called a hybrid system for wind wave energy harvesting, and was developed at the Technical University of Sofia by the authors of this paper.

The current paper aimed to test the designed Wells turbine itself, as well as the Wells turbine in conjunction with a water turbine with oscillating blades (WTOB).

2. Experimental Setup

The experimental setup of the hybrid system was designed to simulate the simultaneous work of the two types of turbines, namely Wells-type air turbine and water turbine with oscillating blades. The test bench allowed for both turbines to be tested separately or in collaboration.

The turbines are powered by a hydraulic station that drives a hydraulic motor, which, in turn, transfers the motion to the turbines. In the case that only the WTOB is running through a steel cable coupled to the hydraulic motor and a crank, it simulates the movement of waves in seas and oceans. When the generated water wave rises and falls, the flow passes through the runner and accelerates the turbine, allowing the blades to adapt their angle of attack. In order for the second part of the stand with an air turbine of the "Wells"-type to operate, it is necessary, once again, to simulate (reproduce) an air flow, which, in turn, will impact the blades of the turbine below and transfer its energy to the turbine. To create the needed air flow toward the turbine, a movable "flap" was designed to move up and down, sucking in and, respectively, pushing the air flow toward the blades. A butterfly valve was provided to stop the lower airflow to the turbine. The principal 3D schemes of the test bench are presented in Figures 1 and 2.

In the current study, attention was focused on testing the Wells-type air turbine, designed and manufactured with the following parameters represented and described in the figures below. In Figures 3 and 4, an isometric view and a view facing the blades are illustrated, respectively.

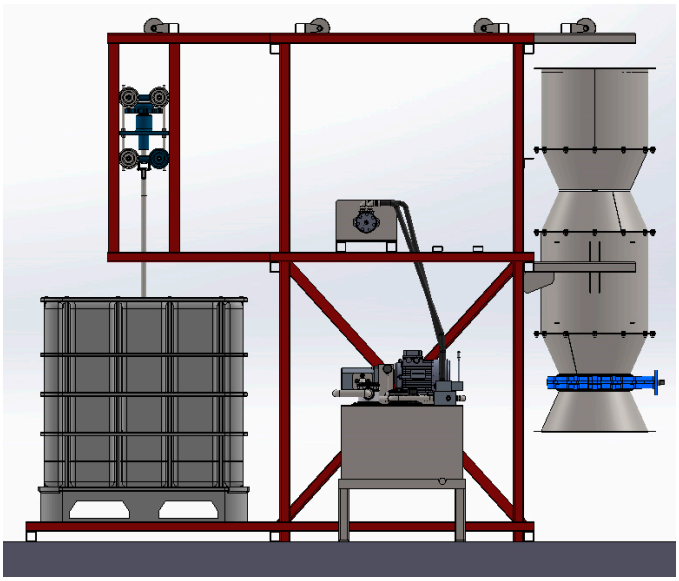


Figure 1. Hybrid system of the sea wave energy harvesting test bench.

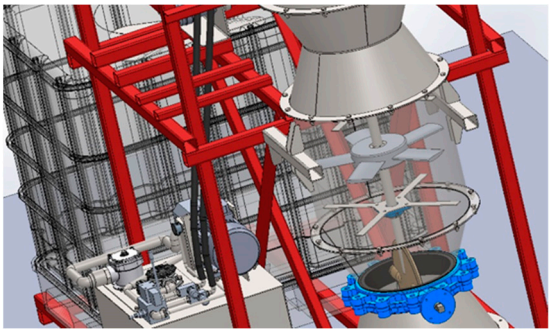


Figure 2. Hybrid system of the sea wave energy harvesting test bench; detailed view of the Wells-type turbine.



Figure 3. View facing the blades of the "Wells"-type turbine.

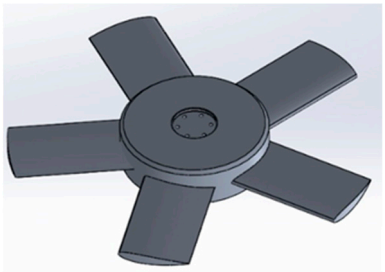


Figure 4. Isometric view of the "Wells"-type turbine.

A schematic diagram for harnessing wave energy through a "Wells"-type turbine is presented in Figure 5, and in this way, the test bench for testing the turbine was designed and constructed.

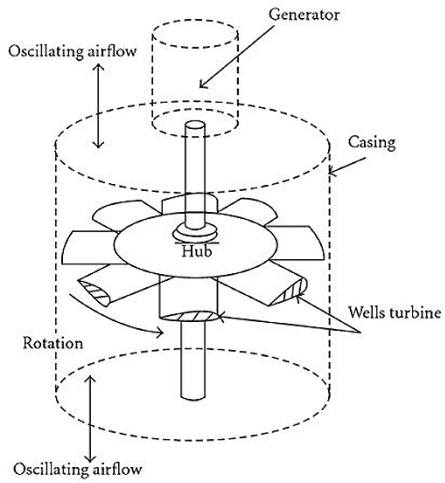


Figure 5. Principal scheme of the "Wells"-type turbine installed in a duct as part of the test bench.

The key dimensions of the air turbine are demonstrated in Figure 6, where the rotor diameter, the hub diameter, the length of the chord, and the span are outlined.

The "Wells"-type turbine is designed with blades with a symmetrical profile NASA0015 (Figure 7).

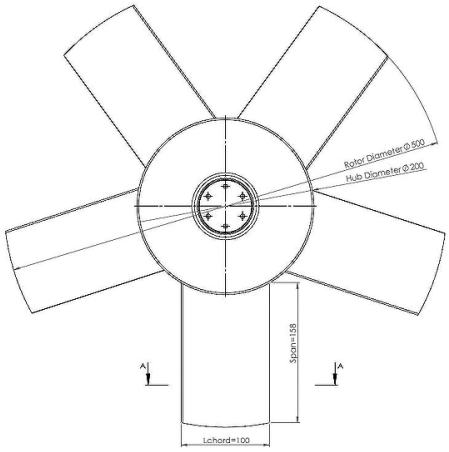


Figure 6. Key dimensions of the "Wells"-type turbine.

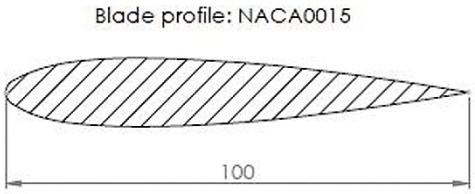


Figure 7. Working blade of the "Wells"-type turbine.

The measurements were taken during the operation of the system with probes with high-frequency characteristics, using anemometers, a torque meter, rotation sensors, temperature sensors, and others.

The parameters of the "Wells"-type turbine, designed, manufactured, and implemented in the test bench, are presented in Table 1.

Table 1. Wells-type turbine parameters.

Technical Data	
Blade profile	NASA0015
Rotor diameter	500 mm
Hub diameter	200 mm
Chord length	100 mm
Tip clearance	1 mm
Blade number	5
Rotation speed	2000 rpm

In Figure 8, the velocity triangles at the inlet and outlet of the working wheel are presented, with the incoming flow represented on both sides by "INFLOW" [8–10].

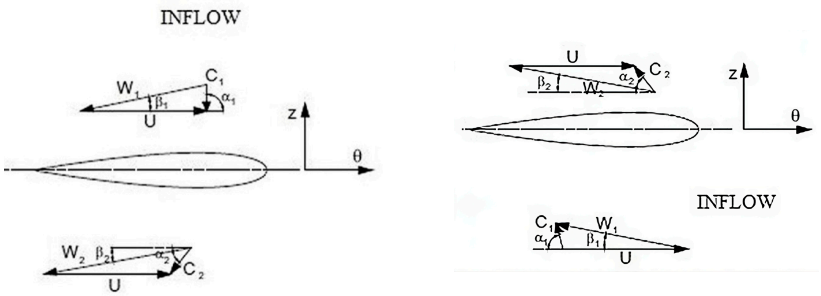


Figure 8. Velocity triangles at the inlet and outlet of the working wheel depending on the flow rate.

3. Wells-Type Air Turbine Testing Method

As shown in Figures 1 and 2, on the right side of the experimental stand, an additional fan was mounted to the system to test the Wells-type turbine. Through it, different higher speeds and flow rates could be delivered to the turbine wheel. The fan was equipped with control that allows for setting different flow values that the turbine wheel needs to process. The parameters of the implemented flow were measured by precision anemometers, manometers, as well as additional equipment for measuring the turbine shaft's revolutions and its torque, and calculating the power it generates.

4. Experimental Results and Analysis

The tests conducted on the constructed test bench allowed for the momentary characteristics of the entire system to be obtained during the incoming and outgoing flow before and after the rotor of the "Wells"-type turbine. The decrease in static pressure across the rotor and the rotating torque realized on the turbine shaft were utilized in obtaining the momentary characteristics of the turbine.

The characteristics of the "Wells"-type turbine can be presented in terms of driving power, torque, and a decrease in static pressure with respect to the momentary flow rate. In this setup, characterized by an oscillating flow, the flow velocity was not easy to be determined, assuming that the flow at the inlet of the turbine is axial and that the effects of compressibility are negligible. The results of the conducted tests are presented with different flow rates at the turbine inlet [10], as well as the realization of different inlet velocities, with these parameters determined by the following Equations (1)–(3) [11]:

Static pressure coefficient:

$$P_k = \frac{\Delta P_0}{\left(\rho.\omega^2.r_t^2\right)}. \quad (1)$$

Rotating torque coefficient:

$$T_k = \frac{T_o}{\left(\rho.\omega^2.r_t^5\right)}. \quad (2)$$

Discharge coefficient:

$$Q_k = \frac{Q}{\omega.r_t^3.\pi} = \frac{v}{\omega.r_t}. \quad (3)$$

Efficiency:

$$\eta = \frac{T.\omega}{\Delta P_0.Q}, \quad (4)$$

where Δp_0 is the pressure processed by the turbine, ρ is the air density, ω is the speed of the turbine rotor, r_t is the radius of the turbine, Q is the volume flow rate passing through the turbine, and T is the torque realized by the turbine.

The effect of fluid compressibility is neglected due to low flow velocities. The experimental results are presented in Table 2.

Table 2. Experimental results.

q	Q	Po	v	n	ω	T	P	η
Mass Flow Rate kg/s	**Volume Flow Rate m^3/s**	**Pressure Pa**	**Air Velocity m/s**	**Turbine Revolutions min^{-1}**	**Angular Velocity rad/s**	**Turbine Torque Nm**	**Power W**	**Efficiency %**
0.167	0.150	99.86	0.91	1.5	0.16	0.000246	0.18	0.16
		199.36		1.8	0.19	0.000250	0.35	0.33
		286.37		2.3	0.24	0.000260	0.51	0.50
		428.65		3.5	0.37	0.000248	0.76	0.71

Table 2. *Cont.*

q	Q	Po	v	n	ω	T	P	η
Mass Flow Rate kg/s	Volume Flow Rate m^3/s	Pressure Pa	Air Velocity m/s	Turbine Revolutions min^{-1}	Angular Velocity rad/s	Turbine Torque Nm	Power W	Efficiency %
0.258	0.232	186.65	1.41	5.8	0.61	0.000297	0.51	0.24
		359.68		10.5	1.10	0.000299	0.99	0.46
		654.36		22.6	2.37	0.000312	1.79	0.88
		894.16		23.3	2.44	0.000316	2.45	1.22
0.515	0.464	486.36	2.81	49.5	5.18	0.004870	2.67	5.1
		796.35		63	6.60	0.004970	4.36	8.5
		1351.95		115	12.04	0.005160	7.41	15.0
		2218.59		180	18.85	0.005390	12.16	25.8
0.773	0.696	536.78	4.22	259	27.12	0.005530	4.41	4.3
		893.65		296.5	31.05	0.005540	7.35	7.1
		1569.12		326.7	34.21	0.005600	12.90	12.6
		2439.74		389.1	40.75	0.005870	20.06	20.6
1.030	0.928	1672.17	5.63	420.5	44.03	0.44	18.33	7.8
		1736.45		480.1	50.28	0.88	19.03	16.4
		1893.41		560	58.64	0.96	20.75	19.6
		2680		723	75.71	1.29	29.38	37.1
1.288	1.160	1845	7.04	780	81.68	0.98	25.28	15.6
		2123		837	87.65	1.45	29.09	26.5
		2568		935	97.91	1.90	35.18	42.0
		2754		1069	111.95	2.52	37.73	59.8

The test results show good agreement with the data described in the literature, which leads to the conclusion that the methodology used is effective and can be applied in practice. Figures 9–11 present the dependence between the main turbine parameters studied.

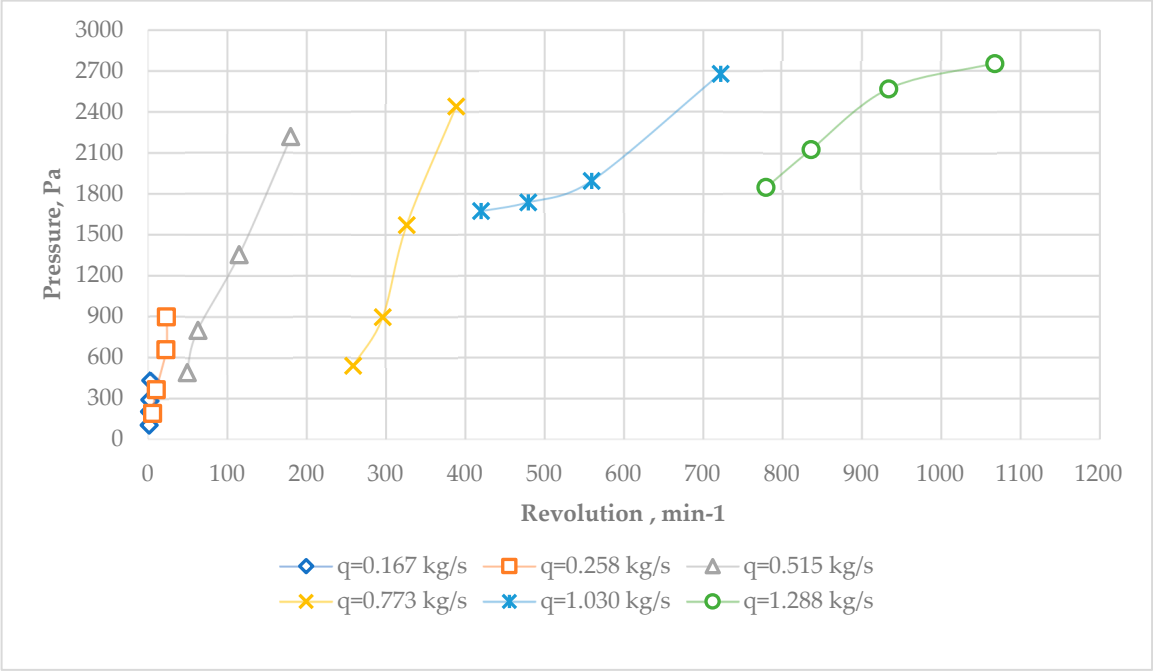


Figure 9. Pressure–revolution change at the studied flow rates.

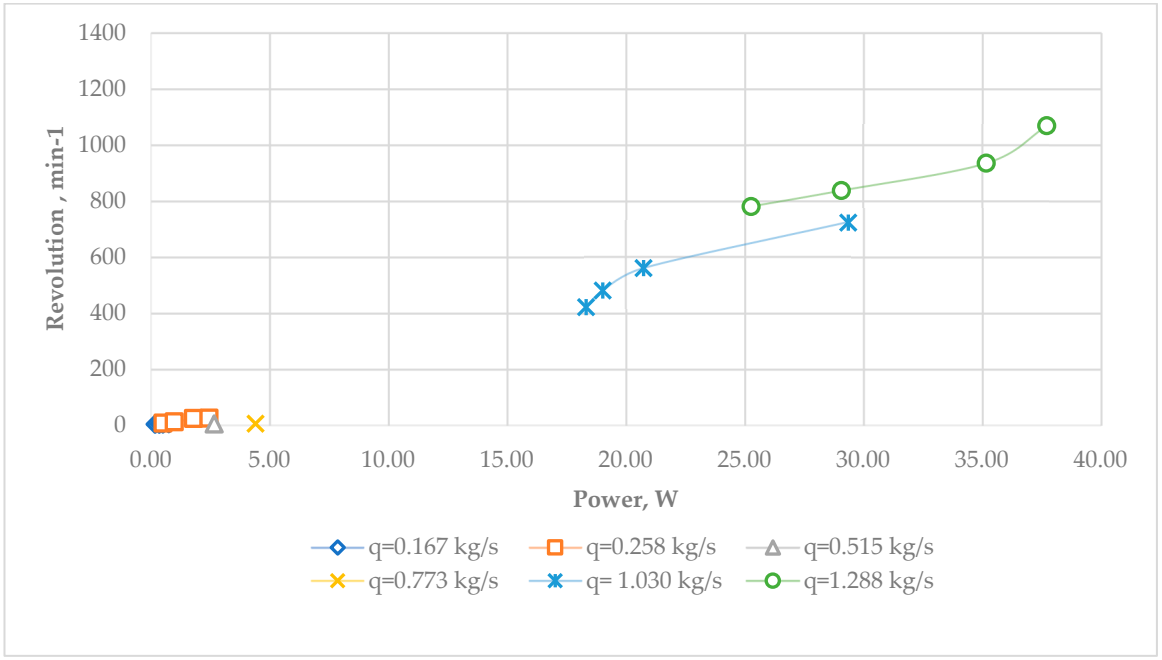


Figure 10. Revolution–power change at the studied flow rates.

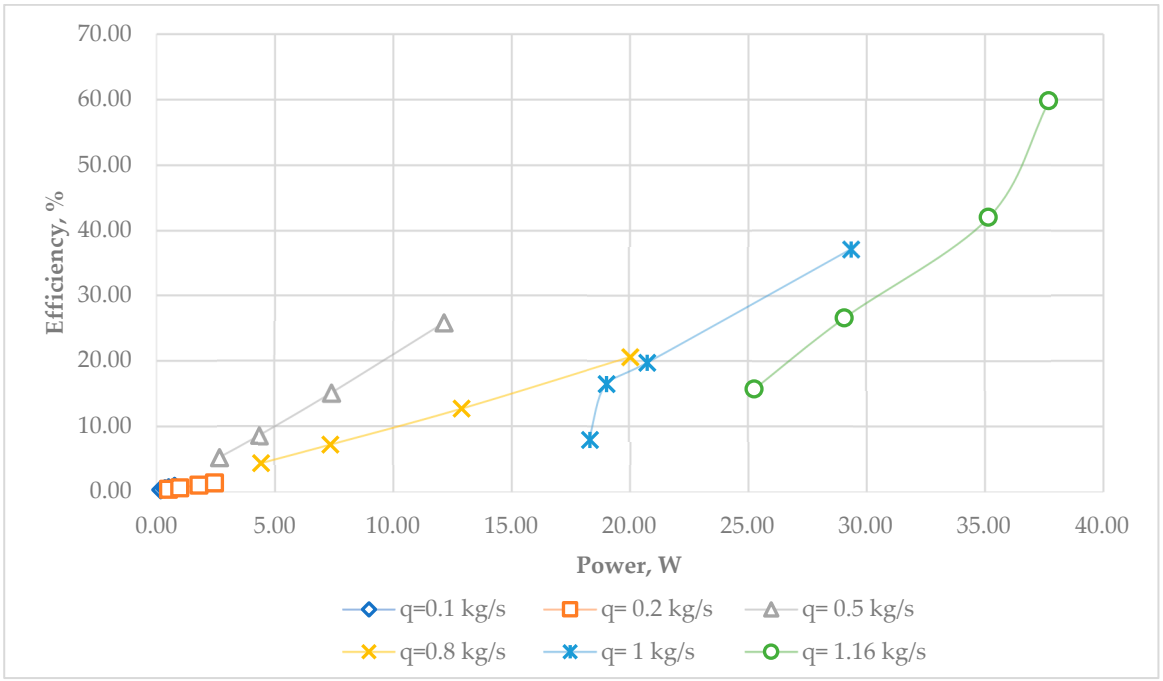


Figure 11. Power–efficiency change at the studied flow rates.

From the test results, it can be interpreted that the higher the incoming air volume flow rate toward the "Wells"-type turbine, the greater the actual realized power, and, as a consequence, the higher the turbine efficiency. The overall efficiency of the hybrid system for wave energy harvesting requires high wave characteristics, i.e., a large wave amplitude and a relatively short wave period. The efficiency of the overall hybrid system is directly proportional to the dimensions of the two turbines, the WTOB and the "Wells"-type turbine, respectively.

5. Conclusions

The idea of the presented hybrid system that combines water turbine with oscillating blades and a Wells-type air turbine is new and promising. The results of the tests performed on the test bench developed show good agreement with the published literature data. From the obtained results of the turbine main parameters, it can be concluded that with the increase in the flow rate, the considered parameters increase as well. This is due to the fact that when the fluid mass is larger, the thrust force is also greater, which leads to better driving of the air turbine.

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Conflicts of Interest: The authors declare no conflicts of interest.

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