

Article

Parametric Study on Ducted Micro Wind Energy Harvester

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Abstract: Micro wind energy harvester (MWEH) can provide eco-friendly and sustainable energy for low-power electric devices like wireless sensors. The performance of the wind turbine can be enhanced by applying a duct with a brim. In this work, the characteristic study was performed when the duct is applied to the MWEH through the computational fluid dynamics analysis of the internal and external flow of the duct. The power generation performance for various cases was evaluated using the wind tunnel test. It is confirmed that the ducted MWEH is robust to the change of the wind direction and its performance can be further enhanced by the brim.

Keywords: micro wind energy harvester; ducted wind turbine; wind tunnel test; diffuser brim; computational fluid dynamics

1. Introduction

Today, various types of sensors are being used to monitor the health of structures, and small, low-power consuming sensors are required. However, since the battery needs to be replaced periodically for long-term monitoring, studies applying energy harvesting technology are receiving a lot of attention. Energy harvesting is a technology that converts wasted energy sources into electrical energy. There is a vibration of structures, solar power, wind power, etc. [1]. Among them, wind energy technology is expected to play an important role in the maintenance of civil structures because it is more environmentally friendly than other technologies and has fewer restrictions on system installation [2–8].

Park et al. [9] installed an electromagnetic rotor-based micro wind energy harvester (MWEH) as a power source for a wireless sensor installed under a cable-stayed bridge and verified its feasibility experimentally. In their work, it was confirmed that it can supply sufficient power to a low-power wireless sensor for structural health monitoring (SHM) of the bridge. Jung et al. [10] proposed an MWEH for the power supply of the sensors using the piezoelectric material. The rotation of the blade by the wind was transmitted to the piezoelectric cantilevered beam through the impact stick and converted into electrical energy. The charging circuit for the proposed device was also developed. However, this method showed its limitation when the wind speed is low. Therefore, the researchers studied stable electricity generation at low wind speeds. The representative approach is to utilize ducted wind turbines (DWT), which accelerates wind speed by installing ducts around the rotor. Since the output powers by wind power generators are theoretically in proportion to the cube of the wind speed, it is possible to increase the output power by accelerating the wind speed by using a duct [11,12]. In this regard, studies on the blade position and duct shape of a wind turbine using the one-dimensional flow theory for the DWT have been conducted [13,14]. Liu and Yoshida theoretically discussed the physical mechanism behind the DWT [15]. Khamlaj and Rumpfkeil supplemented the conventional flow theory equations for DWT and compared them with experimental results [16]. In addition, studies on improving the performance of diffuser-augmented wind turbines and



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CFD analysis have been conducted. The research to derive the optimal shape through CFD analysis of rotor blade contours in wind turbines with ducts was presented [17–20]. It was confirmed that the performance of the diffuser type duct varies depending on the yaw angle of the inlet [21–24]. Finally, numerical model and CFD analysis studies of the diffuser-augmented wind turbine were performed [25–29]. In the end, the ducted wind turbine system increases the power generation performance by creating a pressure difference according to the shape of the duct and blade [30–33].

In previous studies, research on the mechanism and optimal shape of the DWT applied on the macro-scale wind power generators has been conducted, but studies on the ducted MWEH have not yet been performed. The ducted MWEH has merit in its small size and hardly risks excessive load due to the augmented duct on the supporting structure and at the same time, exploits the enhanced output power. The characteristics of the ducted MWEH should be studied for the actual implantation as an efficient power source for wireless sensors for structural health monitoring and building IoT platforms. Therefore, in this study, we investigated the features of the ducted MWEH and presented its merits via a numerical and experimental study. Specifically, we dealt with the effect of the existence of a duct at the changing wind direction and enhancing output power by the brim angle.

The paper is organized as follows. Section 2 describes the basic theory and ducted MWEH considered in this study. The numerical simulation using CFD analysis is covered in Section 3, and experimental validations with wind tunnel tests are shown in Section 4. Finally, the discussion on the performance of ducted MWEH is described in Section 5.

2. Ducted MWEH

The blade-rotor type wind power generation system can be expressed as a one-dimensional generalized actuator disk. In this paper, it is assumed that the wind flows one-dimensionally and the fluid is inviscid. By using Bernoulli's equation, the relationship between the velocity, pressure, and potential energy of the fluid can be expressed. Therefore, the energy equations can be expressed for the change in pressure and speed of the front and rear parts of the rotor [34]. Figure 1 shows the schematic of ducted MWEH. When the flow rate, Q through the wind turbine and the energy loss due to blade rotation and pressure drop are given, the output power W can be determined. Therefore, the efficiency of the wind turbine can be expressed as

$$\eta_t = \frac{W}{(P_1 - P_2)Q} \quad (1)$$

The output power coefficient takes into account the wind turbine loss and can be obtained by the product of the input power coefficient, C_p and the efficiency as follows [35].

$$C_w = \frac{W}{\frac{1}{2}\rho V_a^3 A} = \eta_t C_p \quad (2)$$

where ρ is the air density, V_a is the input wind velocity, and A is the inlet airflow section area. The input power coefficient of the ducted wind turbine depends on the duct shape, the area ratio, and the counter-pressure coefficient. In order to improve the power coefficient of the wind turbine system, studies have been conducted that consider the shape of the duct to collect and accelerate more wind [35,36]. In their works, wind velocity distribution and static pressure distribution for the design parameters are compared using experiments. As a result, it was confirmed that the diffuser-type duct had the best performance, and its dimensions were suggested as well. In addition, the following equation was proposed considering two performance coefficients, C_{pb} and C_{pd} related to the pressure change [35]:

$$\frac{C_p}{1 - Y^2} = \Psi K^3 = \Psi \left[\frac{1 - C_{pb}}{1 - C_{pd} + \Psi} \right]^{3/2} \quad (3)$$

where Y is the hub ratio, that is, the ratio of hub diameter to rotor diameter, Ψ is the load coefficient, K is the inflow velocity ratio, C_{pb} is the backpressure coefficient of the brim, and C_{pd} is the pressure recovery coefficient of the diffuser. It can be seen that the two coefficients affect the inflow velocity ratio K . If both the inlet shroud and the brim are employed, it was reported that the wind speed can reach 1.6–2.4 times higher in comparison to otherwise [31].

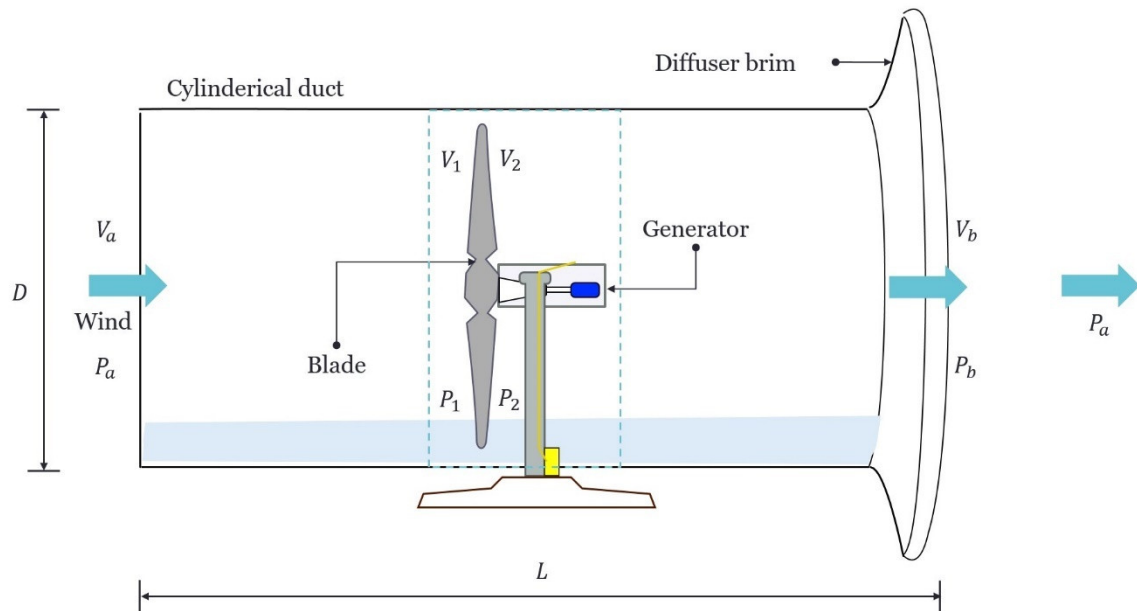


Figure 1. The proposed ducted micro wind energy harvester.

In this study, based on the previous studies, the duct which combines a cylindrical duct and a diffuser brim was considered as shown in Figure 1. The introduction of the diffuser brim can magnify C_{pd} . It means the increase of the difference between the pressure at brim (P_b) and the rear pressure of turbine (P_2). The cylindrical duct is utilized for the rectification of the wind flow and the protection of the core part. Table 1 shows the parameters considered in this study. The duct dimensions of $L/D > 3$ are desirable but $L/D \leq 2$ is practical [24]. Thus, the duct dimension was determined to be $L/D = 1.8$. The three cases of oblique angles of the diffuser brim angle (flat, 30° , and 60°) are considered.

Table 1. Design parameters.

Parameter	Value
Length of duct (mm)	90
Diameter of duct (mm)	50
Angle of brim (degree)	$0^\circ, 30^\circ, 60^\circ$

3. Numerical Simulation

This section deals with numerical analysis of ducted MWEH. The commercial CFD (Computational Fluid Dynamics) software, SOLIDWORKS® Flow Simulation 2019 was used. For the boundary condition in the CFD analysis, the wind speed of 7 m/s, which is the median value to be used in the wind tunnel test, was considered as the boundary condition of the inlet, and total pressure condition was considered for the outlet. And the wall was set as stationary. The detailed simulation parameters are listed in Table 2. In the numerical analysis, the length of the cylindrical duct was 90 mm, the diameter was 50 mm, and the diameter of the blade was 45 mm. The dimensions of the model in the numerical analysis are the same as those of the experimental model. First, when the MWEH was

placed in the wind direction, the wind speeds and the pressure differences of the cases with and without duct were compared as shown in Figure 2. As a result, there was a slight difference in wind speed and pressure difference. It seems that the flat duct, that is, zero brim angle, hardly enhances the pressure recovery and it can be predicted that there will be no significant difference in the power generation performance because the pressure drop at the outlet of the duct is not large.

Table 2. Simulation parameters.

Parameter	Value
Dynamic viscosity	1.51×10^{-5} Pa·s
Wind speed	7 m/s
Number of cells	73,819
Time step	0.05 s
Rotation speed	2500 rpm
Boundary conditions	Inlet (Volumetric velocity): 7 m/s Outlet (Total pressure): 101,325 Pa Wall: Stationary
Turbulence model	k- ϵ
Governing equation	RANS

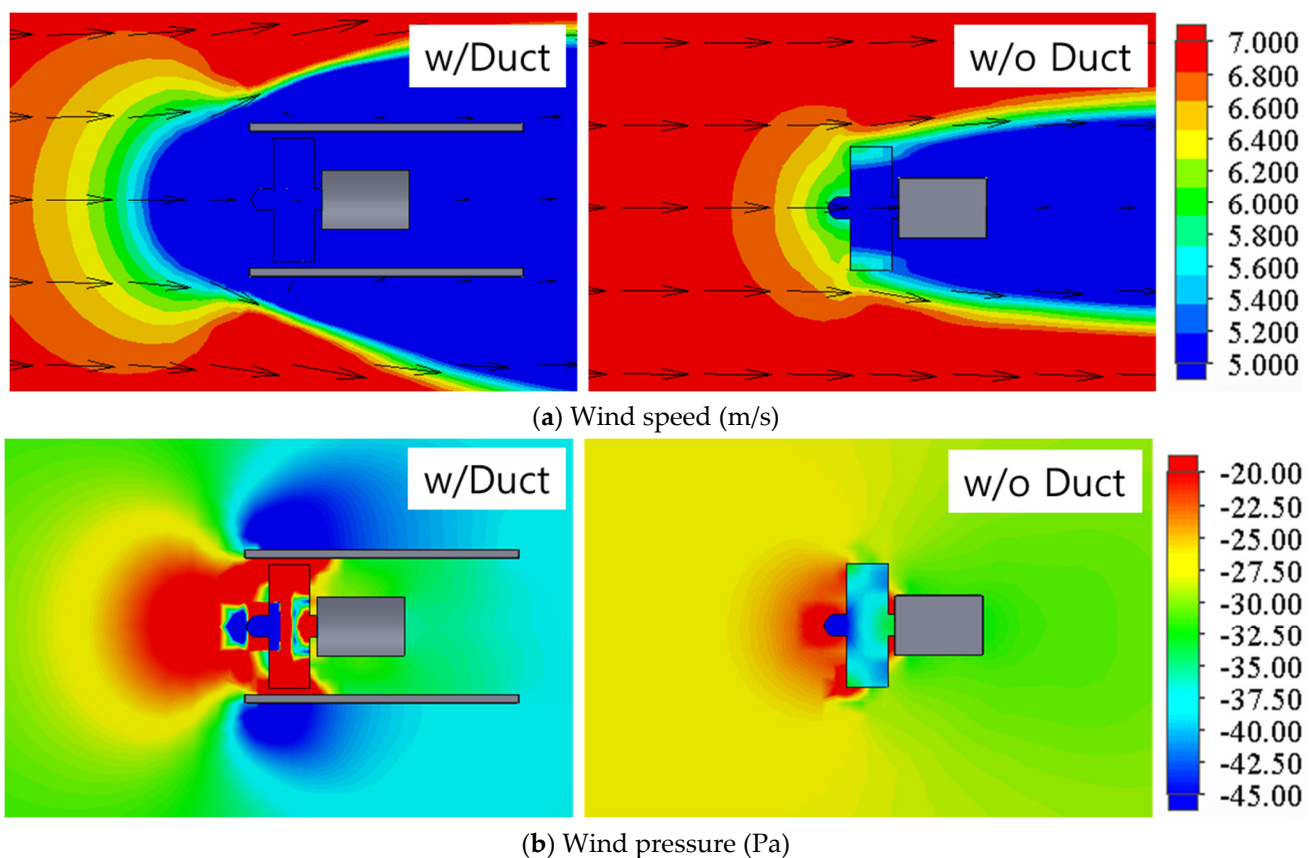


Figure 2. Comparison of wind speed and pressure according to the presence or absence of ducts.

Next, the wind speed and the pressure of MWEH with and without duct placed at an angle to the wind direction were simulated. In general, wind turbines are designed to automatically face changing winds, utilizing methods such as tail vanes, since they are at their maximum efficiency when placed in the wind direction. However, in the case of

MWEH, since it is installed in the gap of a structure, it is easy to be affected by aerodynamic instability. In order to confirm the power generation performance in the case where the turbine does not face the wind direction, numerical analysis was performed for the case where the turbine was placed at an angle. In this numerical model, brim angle was not considered and only the presence or absence of duct was compared. The results when the system was placed in the wind direction were illustrated in Figure 2, and the wind speeds and pressure differences when the system is inclined at 20 and 40 degrees with respect to the wind direction are shown in Figures 3 and 4, respectively.

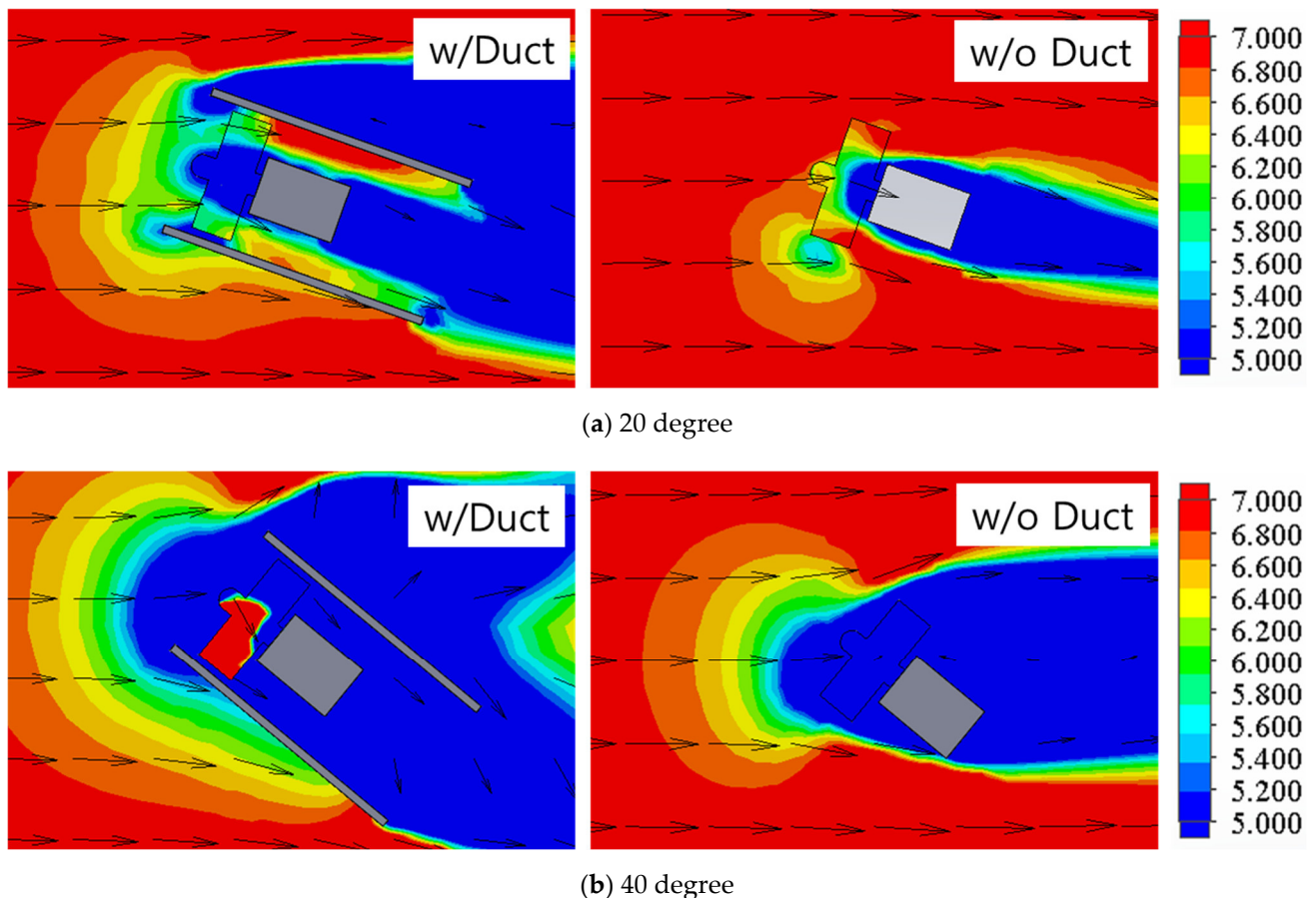


Figure 3. Comparison of wind speed (m/s) for wind direction change.

Although the open rotor was placed at an angle to the wind direction, the wind speed and pressure distribution were similar to those in Figure 2. However, for the ducted MWEH, it was observed that the pressure difference between the inlet and outlet increased with the yaw angle. Therefore, the MWEH can achieve stable power harvesting even when aerodynamic instability occurs in the structure gap.

Finally, numerical analysis for the brim angle was performed as shown in Figure 5. It was confirmed that a diffuser brim installed at the outlet of the duct can maximize the pressure difference between the inlet and outlet, thereby it can increase power generation efficiency. As the angle of the brim increases, it is shown that the low-pressure area at the outlet is expanded and the wind permeability increases.

So far, the numerical analyses for the wind speed and pressure of the MWEH according to various cases have been performed. It is shown that the application of the cylindrical duct can enhance the performance of MWEH especially when the wind direction is changing. It is necessary for the MWEH since it is very small and difficult to utilize tail vanes or other mechanisms which adjust the wind direction and it is often installed in a narrow space in civil structures where the proportion of turbulence is high. Moreover, it is confirmed that

the increase in the angle of the diffuser brim can enhance the power generation efficiency by sharply strengthening the pressure difference between the inlet and outlet.

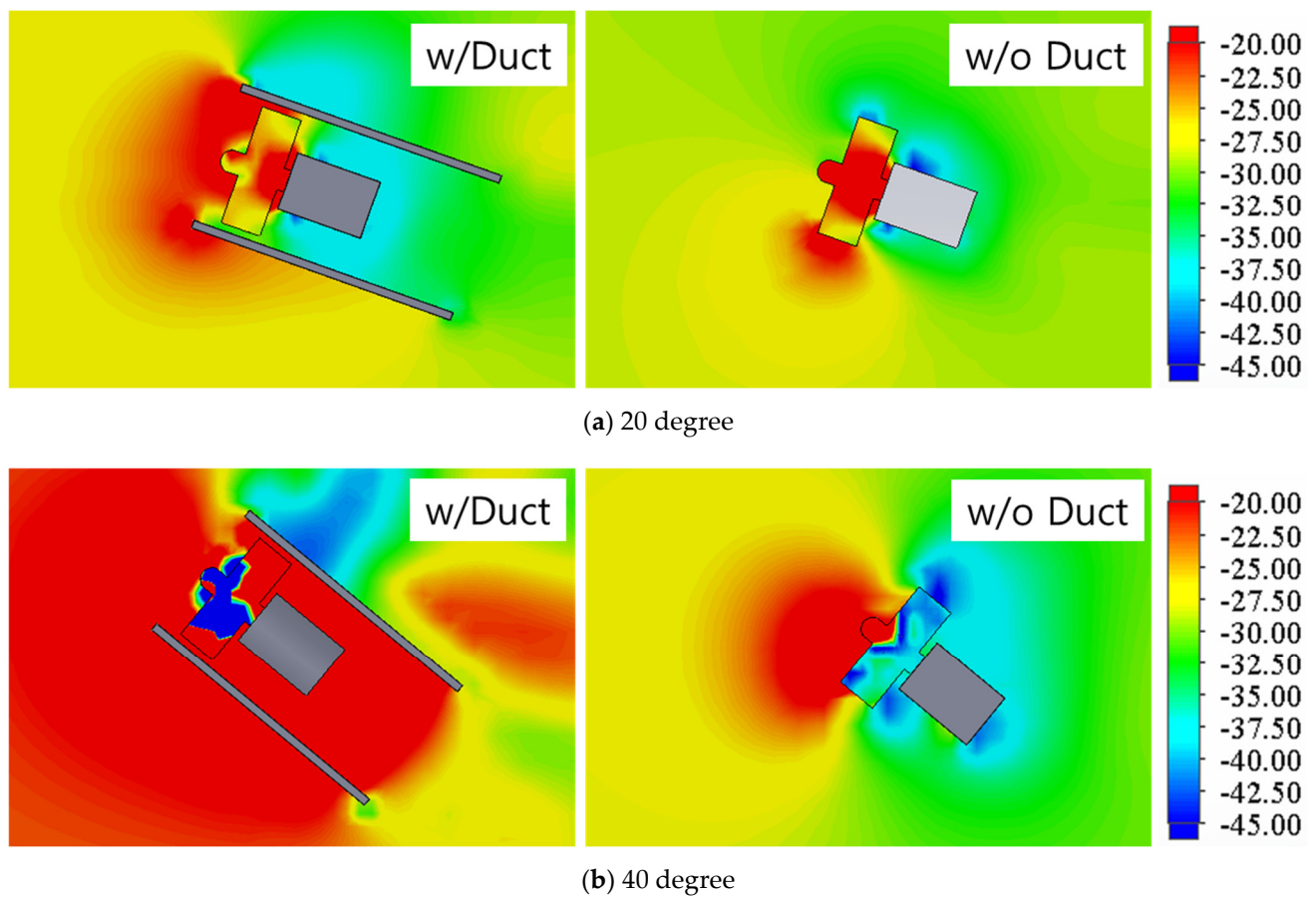


Figure 4. Comparison of wind pressure (Pa) for wind direction change.

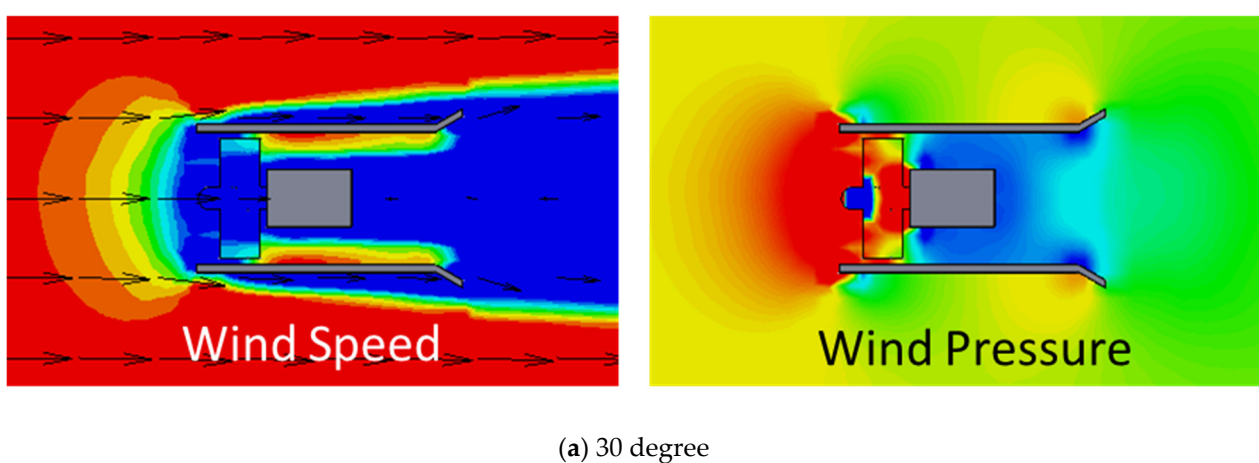
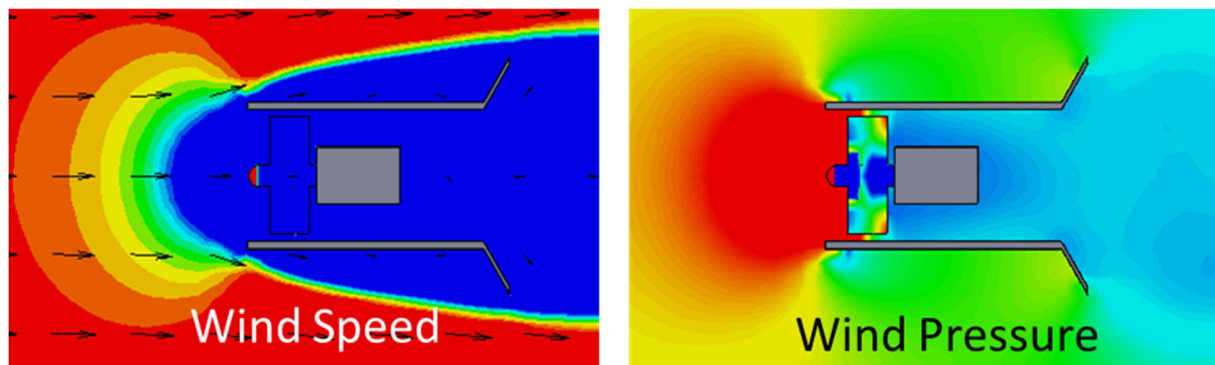


Figure 5. Cont.



(b) 60 degree

Figure 5. Wind speed (m/s) and pressure (Pa) for the brim angle at the outlet (the legends are identical to those in Figure 2 and omitted here).

4. Wind Tunnel Test

If a ducted MWEH is installed for powering a sensor and operated for a long time in a real environment, its durability and power generation performance can be verified. However, this is costly, time-consuming, and difficult to characterize the system. Therefore, a wind tunnel test was carried out to validate the power generation performance of the ducted MWEH. The small wind tunnel has a size of 30(W) × 30(H) × 200(L) cm and simply consists of an air blower (1.5 kW single-phase motor), a flow rectification filter, and a control box as shown in Figure 6. The control box adjusts the wind speed by manually turning the knob. The maximum wind speed of the test section is 15 m/s, and the wind speed can be measured by installing a hot wire type anemometer (Kanomax #6332D) in the upstream section.

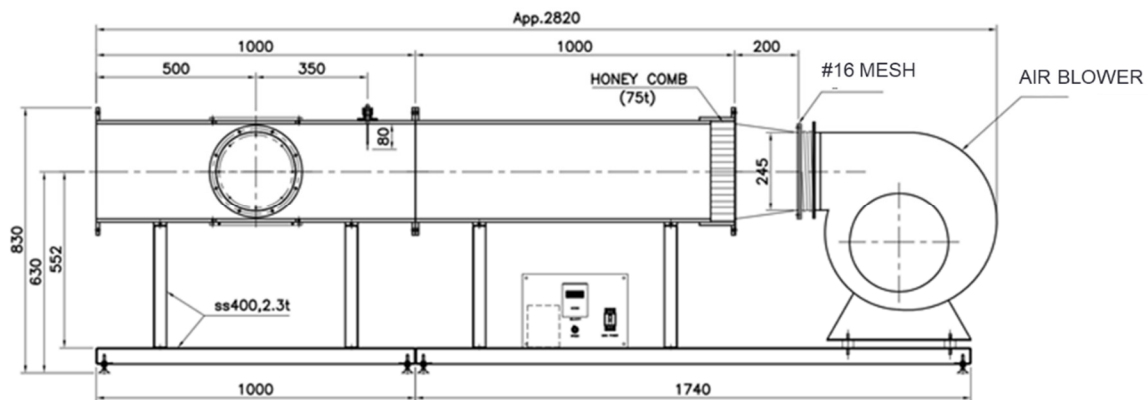


Figure 6. Schematic of small wind tunnel.

Figure 7 shows the experimental setup considering the design parameters of a ducted MWEH. The generator used for energy harvesting is a coreless type motor (Maxon #110128) which is free from cogging torque and can be used as an energy harvester. The electricity produced by the generator passes through a variable resistor (Fuyang ZX21) and is measured in a power meter (Yokogawa WT330). The proposed system is located between the anemometer and the outlet in a small wind tunnel, and the line connected to the power meter is not obstructed by the wind flow. And the angle of the system corresponding to the direction in which the wind blows was measured by the protractor attached to the base. If the resistance of the load is increased, a higher proportion of the source power is transferred to the load, but the magnitude of the overall power production reduces due to the increase of the circuit resistance. In this study, the optimum load resistance for maximum power was selected as 3000 ohms and utilized in the experiment.

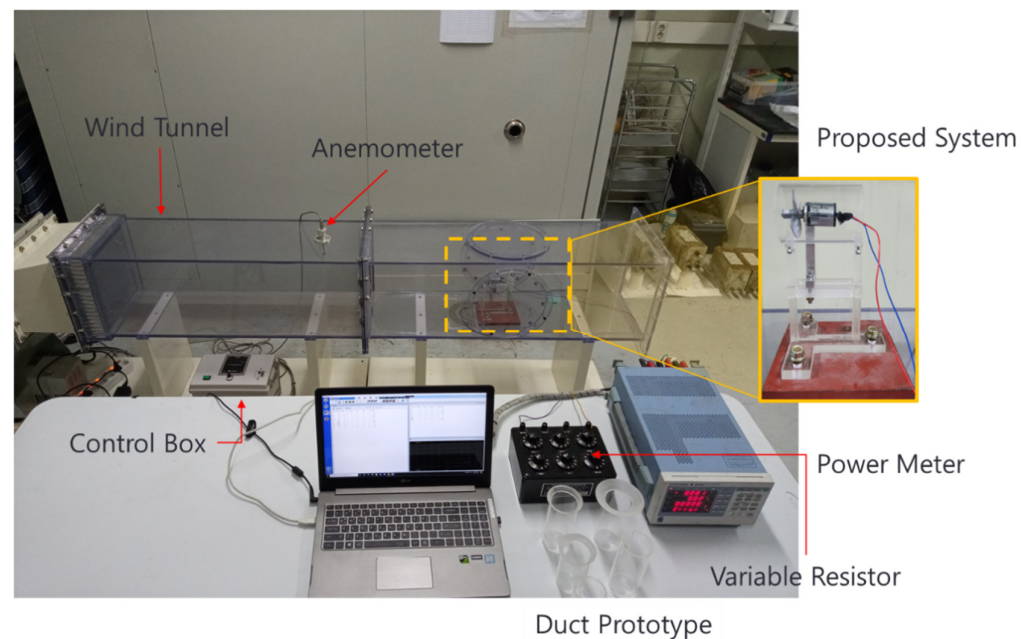


Figure 7. Experimental setup.

First, a power generation performance was tested on the presence or absence of duct for MWEH. Figure 8 shows the comparison of measured powers with and without duct through the wind tunnel test. The power values obtained from the wind speed under 5 m/s were negligible and omitted from the graph. An MWEH with a duct produced a slightly larger amount of electricity than the case without a duct at the medium wind speed of 5–8 m/s, and similar at higher wind speeds above that. The benefit from the enhanced pressure difference found in the numerical analysis appeared to have been offset by the air friction caused by the duct at high wind speed.

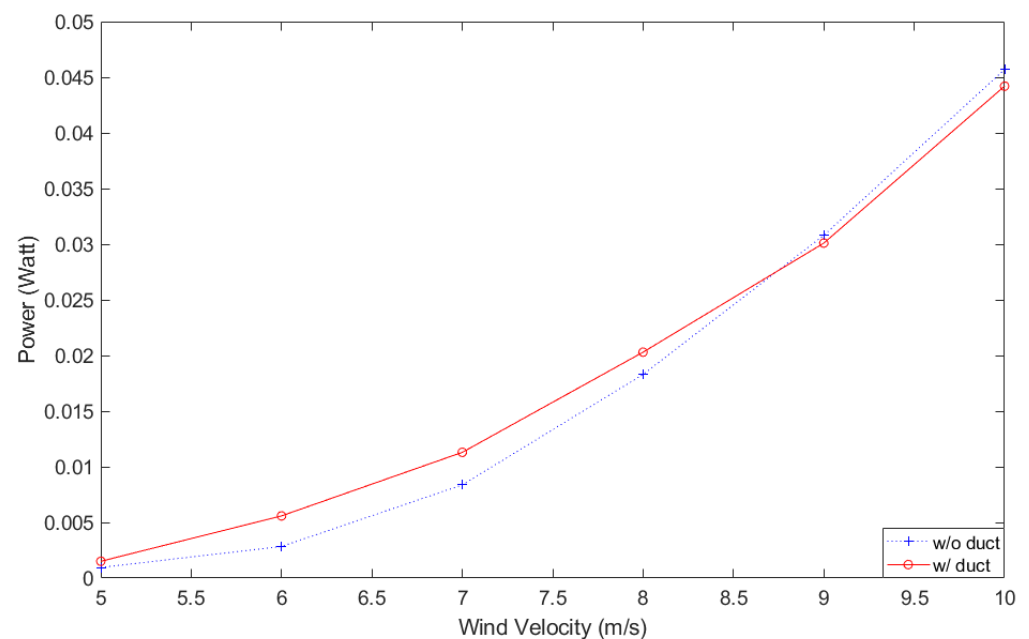


Figure 8. Power generation performance of micro wind energy harvesters with and without ducts.

Figure 9 compares the power measurement results according to the angle of the turbine placed in the wind direction. The turbine was tested by considering three angles as the numerical simulation. From the experimental results, it was confirmed that, in the absence

of a duct, when the angle of the turbine with respect to the wind direction is changed, the output power gradually decreases, whereas in the existence of a duct, the produced power increases. From the numerical analysis of the case of a ducted harvester placed with an oblique angle, the areas for asymmetric wind speed and low pressure are developed. They can be the main reason for the experimental results.

The effect on the angle of the brim attached to the outlet is considered in the system with the duct. Figure 10 compares the generated powers according to the brim angle. As the angle of the brim attached to the outlet of the duct increases, the pressure drops at the outlet and the power generation efficiency increases. It also minimizes the possibility of turbulent boundary layer flow in the wake of the blade and duct, allowing enhanced power extraction. This was also confirmed in the experiment that the power produced increases as the angle of the brim increases.

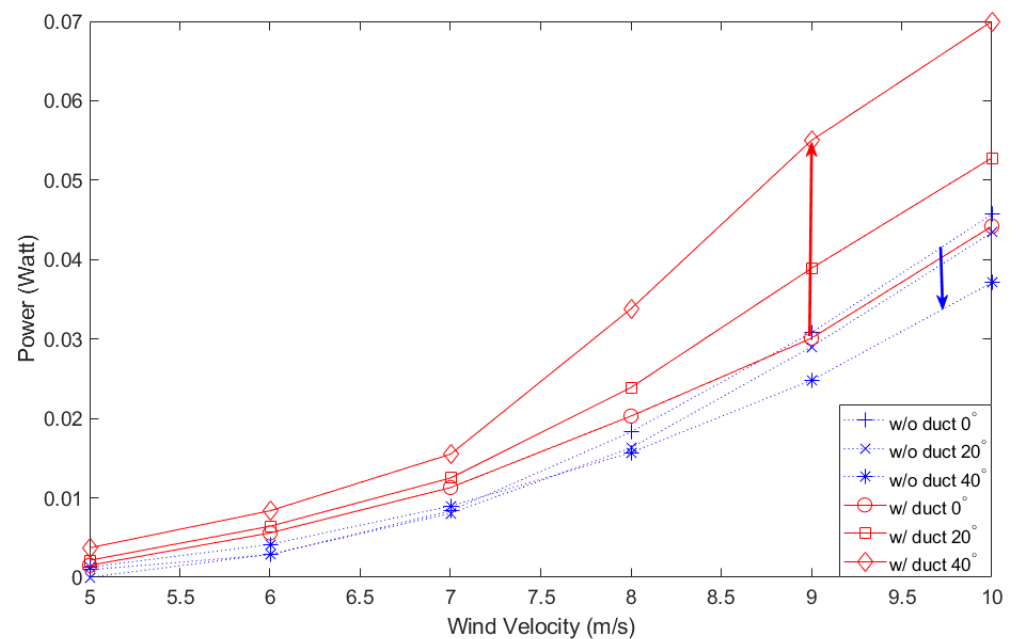


Figure 9. Power generation performance of a micro wind energy harvester with an angle corresponding to the wind direction.

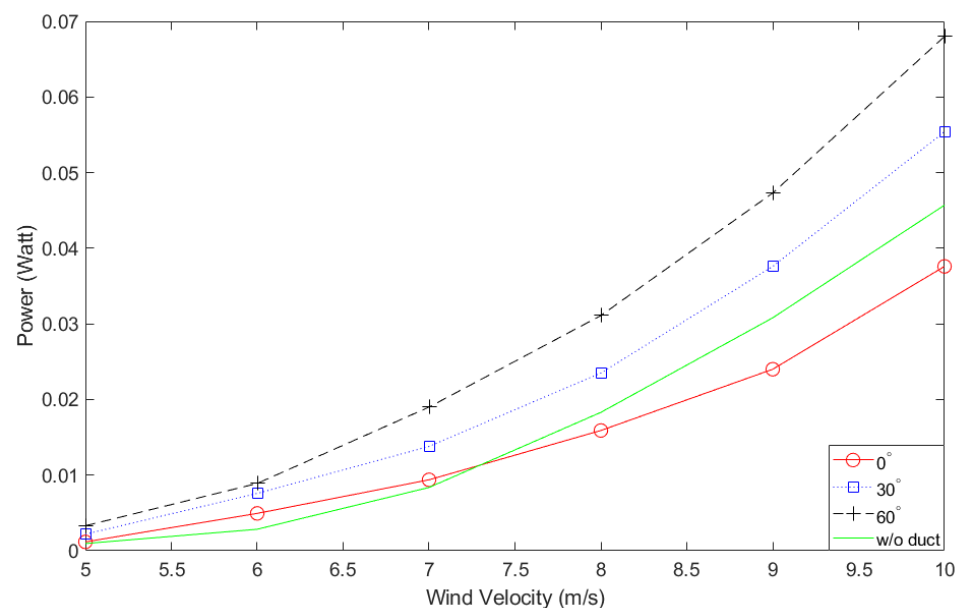


Figure 10. Power generation performance for the brim angle of the outlet.

Finally, the comparison of the output power coefficients of the ducted MWEH according to the brim angle of the outlet was illustrated in Figure 11. The output power coefficients can be calculated using Equation (2) from the experimental results. It is seen that the output power coefficients increase as the brim angle. If the brim is flat, the output power coefficient becomes similar to that of the open rotor.

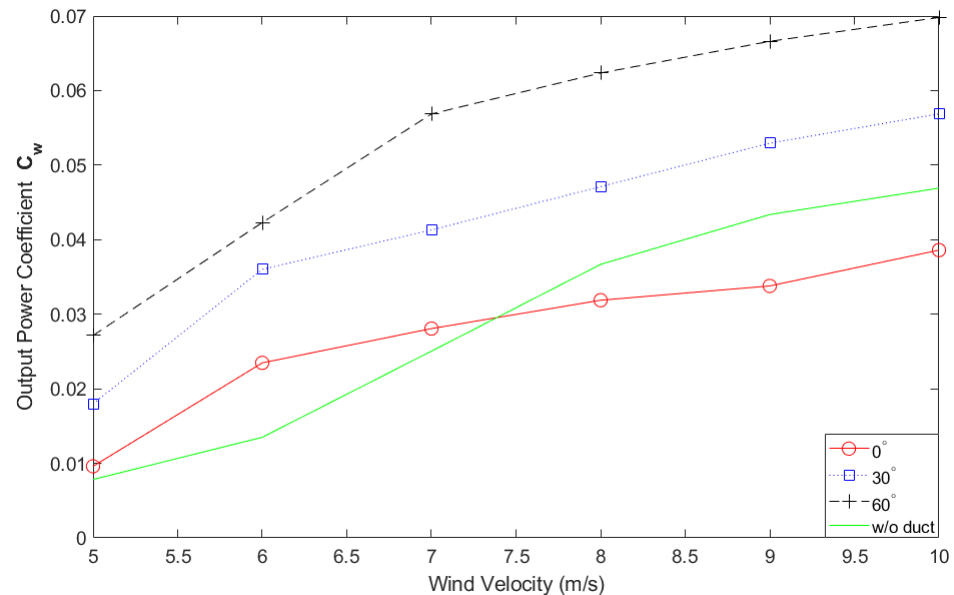


Figure 11. Comparison of output power coefficient.

5. Discussion

In this study, the parametric studies of the ducted MWEH were performed to be used as a power source for IoT sensors. Considering previous studies on the power generation efficiency of wind turbines with duct, a cylindrical duct with the diffuser brim was proposed. The parametric study considered the existence of duct, the oblique angle of the system to the incoming wind, and the brim angle. The performance verification of the system according to the design parameters was conducted through numerical simulation and wind tunnel experiments.

Through numerical analysis, wind speed and pressure difference distributions for various conditions were derived and compared. When there is a duct, it is confirmed that the pressure difference between the inlet and the output was slightly increased. This means that power production efficiency can be affected by applying a duct. Next, an analysis was performed on a case in which the MWEH was placed in a different direction to the wind considering the situation that it was difficult to automatically align to the wind direction. Since many researchers mainly deal with large wind turbines which have the adjusting mechanism, for example, tail vane, such parameters may not be considered, but when MWEH are installed in real environments, this can be an important factor in the power performance. As a result of numerical simulation, we found that the areas for the asymmetric wind speed and low pressure are developed with the oblique angle. If the MWEH is placed in such an environment as the continual change of wind direction, it is possible to enhance power production efficiency by applying a duct. Finally, in the analysis of the brim angle, it was confirmed that as the angle increased, the pressure at the outlet of the duct dropped rapidly and the possibility of turbulence was reduced.

A wind tunnel test was performed to verify the power generation ability of the MWEH and to compare it with the numerical simulation results. The power was measured by the power meter with a load resistor, when the wind speed conditions varies from 5 to 10 m/s. In case of the presence or absence of duct, similar outputs were obtained. It seems that the benefit of the duct is canceled due to the wind resistance which is apparent in the micro-sized wind turbines. When the MWEH is in the oblique position to the incoming

winds, it was confirmed that the duct can change the direction of the airflow and enhance the output power. This shows that the ducted MWEH attached to the narrow space of the structure would not be affected by frequent wind direction changes, that is, no decrease in output. When the brim angle changed, it was confirmed that the output gradually increased.

Finally, the feasibility of using the ducted MWEH as the power source of the wireless sensor for structural health monitoring was estimated. Wireless sensors have different power consumption depending on their types and applications. The typical power consumption of MEMS sensors is less than 10 μ Wh. The sensor for structural health monitoring usually utilizes sleep/wake mode to reduce power consumption and measures when an event occurs. Considering that the event occurred once a day, we can calculate the time required for a ducted MWEH to compensate for a power consumption of 10 mWh. As a result of the estimation, 8.5 h at 5 m/s wind speed, 2.0 h at 7 m/s, and 1.1 h at 9 m/s were required. Therefore, it can be concluded that the ducted MWEH proposed in this study can be used as a power source for the MEMS type oath for structural health monitoring.

A further step in this study is to verify long-term performance by installing a ducted MWEH on the structure. It is necessary to consider the installation location, the composition of the charging circuit, and the output power according to the shape of the blade.

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