INTRODUCTION

One of the current key challenges in wind sciences is to understand the physics of airflow during power generation using wind turbines. The research area includes the study of wakes originating from wind turbines, wind farms, and even the effects of wakes over a geographical area. Lundquist found that, under stable stratified atmospheric conditions, the wake can extend more than 50 km downwind, causing millions of dollars of economic losses in a time span of six years. A wind farm in Texas (USA) suffered about 5% power losses. Satellite and aircraft measurements have observed more wakes extending to more than 50 km from the offshore wind farms. These longer offshore wakes may interact with wind farms from multiple countries. The Paris climate agreement states that, if the world wants to keep the global temperature rise below 2°C, the share of coal in electricity generation needs to fall by more than 30%. In northern China, winter heating needs to be supported by coal-fired power generation.

Abstract

This paper explores the wake of a wind turbine yaw and its influence on the output power of the downstream wind turbine. A wind turbine model (hub height and diameter of 1.2 m and 1.0 m, respectively) was used in the experiments, and the yaw angle of the upstream wind turbine was successively varied through values of 0°, 15°, and 30°. The wind speed and the intensity of turbulence in the wake region were measured using a hot-wire anemometer. The measuring positions were changed to 3, 5, and 7 rotor diameters behind the upstream wind turbine. In addition, the output power of the downstream wind turbine model was measured using the rotational speed torque meter. The results show that, in the case of large-angle yaw of the upstream wind turbine, the recovery of the wind speed in the wake area was greatly improved, and up to 30% recovery was achieved. The power output of the downstream wind turbine was also significantly increased. Under the yaw conditions of 15° and 30° for the upstream wind turbine, the average output power of the downstream wind turbine increased by 17.6% and 21.6%, respectively.

KEYWORDS
power generation, turbulence intensity, wind tunnel, wind turbine wake, yaw
However, the presence of abundant wind resources provides a new choice for winter heating. In order to tap into this renewable energy resource, the number of wind farms needs to increase. However, limited by land prices, the density of wind turbines has also increased. In addition to improving the efficiency of wind power generation by improving the accuracy of wind power prediction and using geographic information system (GIS) and spatial multi-criteria analysis (SMCA) for more efficient wind farm locations, improving the control strategy of wind turbines is also a way to increase the overall power generation from wind turbines.

For the wind farm in planning phase, the optimal installation location of the wind turbine can be determined by analyzing the topographic features and wind conditions of the area. In recent years, in order to minimize cost or maximize power generation, many scholars have optimized the (installation) positions of wind turbines through heuristic optimization algorithms such as genetic algorithm (GA) or particle swarm optimization (PSO). Noise control of wind farms and optimization under a variety of constraints are also key challenges to improving the performance of wind farms. Particle swarm optimization algorithm can optimize the power grid to reduce power consumption cost and environmental pollution.

The research shows that the whole wind farm would not be optimized even if all the wind turbines run at their individual optimum operating points. Therefore, for the completed wind farm, either the energy loss due to the effect of wake can be reduced by changing the pitch angle and tip speed ratio of the wind turbine in operation or the overall power generation can be increased by making the wind turbine actively yaw.

It is essential to study the wake flow of wind turbines whether it is to optimize the location of wind turbines or to improve the power generation by controlling the running state of wind turbines or to meet other goals. As early as 1985, some scholars provided a research method to evaluate the influence of wind turbine wake on a wind farm and pointed out that the wake effect would result in a 10% loss in power generation. In 2003, Vermeer et al thoroughly studied and analyzed the wake aerodynamics of wind turbines through experiments. In 2007, A Jimenez used LES (large eddy simulation) to determine the wake effect, compared it with the field experimental data obtained by Sexbierum (the Netherlands) wind farm, and reported a good agreement between the calculated results and the field data, indicating that the LES method can analyze the influence of wake of wind turbines. In order to produce the wake and study the variation in flow characteristics, a wind turbine model was introduced. In 2013, Mo et al used the LES method to analyze the wake characteristics of a pair of wind turbines in a virtual wind tunnel that focused more on the turbulent structure. In the same year, Smolikho et al used lidar to study the wake of wind turbines and found that, at high wind speeds, the rate of dissipation of turbulent energy increased by more than two times, resulting in a reduction in the length of the wake by half. In 2015, Kress et al studied the yaw stability of downwind wind turbines. In 2016, the Technical University of Denmark conducted a review of six widely used wake models. In recent years, the study and control of wind turbine wake under yaw condition have become a hot research topic. Howland et al used the principle of actuating disk to explore the accuracy of a model under yaw condition of wind turbines, and pointed out that the asymmetry of wake flow must be considered in the yaw condition of wind turbines. Ouyang et al developed a new wind direction predicting model to facilitate the yaw control of wind turbines. Jin et al used a wind tunnel to explore the influence of freestream turbulence in the wake of a wind turbine model and studied the distribution law of turbulence structure. In 2019, Astolfi et al improved the power generation of a 2-MW wind turbine through active wake control. The experimental results show that the use of the principal component regression (PCR) method to control the yaw of the wind turbine can increase the total power generation by 1% per year. In 2020, Dou et al proposed a new wake model to predict wind turbine wake under yaw conditions, and conducted experiments on offshore wind farms. The same authors used an intelligent optimization algorithm to control the yaw of wind turbines, and achieved a power increase of up to 7%. Dai et al used the computational fluid dynamics (CFD) method to further explore the principle that the yaw of wind turbines affects the power generation performance and the blade load of wind turbines.

Due to the high cost and long operational cycle of wind tunnel experiments, most of the experiments on wind turbine wake are conducted using either a virtual wind tunnel or a small-sized wind tunnel and wind turbine model. In 1980, Vermeulen used the computational fluid dynamics (CFD) method to study the wake flow of a single wind turbine. The empirical expression for the length of near-wake region was obtained by combining with several groups of wind tunnel test data. Moreover, the length of the near-wake area was determined to be about 2-4 times the diameter of the wind turbine. In 1997, Glant et al used a 900-mm diameter wind turbine model and laser measuring equipment to determine the detached vorticity in the wake of a wind
turbine under yaw conditions. In 2009, Chamorro and Porte-Agel\textsuperscript{32} used a hot-wire anemometer to determine the wake of a modeled wind turbine with a hub height of 114 mm. The average velocity, turbulence intensity, and moving shear force in the wake region were measured experimentally, and it was found that the asymmetry of turbulence intensity was more obvious on the rough surface. In 2013, Zhang et al\textsuperscript{33} used the stereoscopic particle image velocimetry (S-PIV) system to study the wake wind speed attenuation of a wind turbine with a hub height of 105 mm. The experiment created convective boundary layer (CBL) conditions by heating the ground and cooling the air, so as to study the influence of CBL on wind turbine wake. In 2013 and 2014, Iungo and Viola\textsuperscript{34,35} used wind tunnels to conduct linear stability analysis of wind turbine wake flow and stability analysis of eddy-viscosity models, which were also calibrated using wind tunnel data. In 2015, Bastankhah and Porte-Agel\textsuperscript{36} employed a wind turbine model with a hub height of 125 mm to perform experiments on wind turbine wake under yaw conditions, and used a particle image velocimetry (PIV) system to display the characteristics of wake. The experiments verified that yaw caused an increase in the wake recovery speed. In 2016, Iungo\textsuperscript{37} used a wind turbine model with a hub height of 127 mm to measure the hub vortex instability in the near-wake region. Further measurements were made using lidar. In 2018, Sun and Yang\textsuperscript{38} proposed a new three-dimensional (3D) wind turbine wake model, and verified it using wind tunnel experiments that employed a model wind turbine with a hub height of 312 mm. In the same year, Bartl and Muhle et al\textsuperscript{39,40} conducted wind tunnel tests on wind turbine wake under yaw conditions, measured the inflow turbulence, and redefined the wake width. The wheel hub height of the wind turbine model was 820 mm. In 2019, Fu et al\textsuperscript{41} used six wind turbine models with hub heights of 140 mm each to test the pitch and roll vibration of wind turbines, and pointed out that vibration can increase the total output power of wind farms under certain conditions. Xu et al\textsuperscript{42} proposed a method to calculate the yaw angle of wind turbine under the action of wake and studied the interference mechanism of the effect of wake on yaw angle using dual-beam wind radar. On this basis, combined with the wake superposition model, the equivalent inflow wind speed of wind turbine under the influence of wake could be determined. This enabled the model to predict the power output of wind turbines under the effect of a wake.

To the best of authors’ knowledge, the wind tunnel experiments of wind turbine yaw are mainly focused on single wind turbine, and it is still unclear how much energy is raised by the downstream wind turbine. In addition, the scale of the experiments has been generally small, whereas it is widely accepted that the size (of the model) has a greater impact on the accuracy of experimental results. The present study employs the largest possible wind tunnel model to obtain the most accurate wake flow and power output data. In addition, two wind turbine models are used for experiments to study the power generation of downstream wind turbines under the condition of yaw of upstream wind turbines. Section 2 of the paper details the experimental facilities and experimental design. Section 3 presents and discusses the experimental results. Lastly, Section 4 summarizes the main outcomes of the study.

2 EXPERIMENTAL FACILITY

The experiment was carried out in a backflow boundary layer wind tunnel of State Environmental Protection Key Laboratory of Atmospheric Physics Simulation and Pollution Control at the National Environmental Protection Research Institute for Electric Power, China. The wind tunnel mainly consisted of a power section, a rectifier section, and a test section. The length, width, and height of the test section were 24 m, 4 m, and 3 m, respectively. The wind speed was adjustable and lied
within the range of 0-30 m/s. Meanwhile, the boundary layer with a thickness of 1.5-2 m could be formed. Figure 1 shows the schematic and a photograph of the experimental site.

NREL Wind pact 1.5 MW wind turbine was adopted as the prototype wind turbine, which had a rotating diameter of 70 m. The blade parameters of the wind turbine are presented in Table 1. The wind tunnel experiment was produced using 3D printing technology. The diameter of the wind turbine model was 1000 mm, whereas the height of the model was 1200 mm. The wind turbine model was driven by an XD31SRZ 24V DC motor, which was placed in the hub to reach the working speed. The downstream wind turbine was installed with a speed torque meter to collect the power data.

In the experiment, hot-wire anemometer was used to acquire data, and the sampling frequency was 300 Hz.

The measurement points were arranged in the X-Y and X-Z planes and lied directly behind the wind turbine. The data were collected at the height interval of \( Z = 200-2100 \) mm, and the data collection was done once every \( \Delta z = 100 \) mm. The sampling period was 30 seconds. The overall layout of the experiment is shown in Figure 2. The torque and speed measuring instruments were installed at the hub nacelle position of the downstream wind turbine, whereas the power generated by the downstream wind turbine was obtained through calculations. In the power test, after the wind tunnel was operated, the average data collected after every 90 seconds were collected for 15 minutes (11 times) to simulate the working conditions of the wind farm under various wind speed conditions.

The wind shear inflow condition was created by adding a row of rough sources at every 300 mm near the ground in the wind tunnel test section. There were a total of 15 rows of rough sources, and each row had a total of 7 rough sources. The layout of rough sources is shown in Figure 3. The incoming wind speed at the hub height was \( V_{hub} = 7 \) m/s, and the blade tip speed ratio was 5.7. The ambient temperature in the wind tunnel was 20 ± 2.0°C. The hot-wire anemometer was calibrated before each experiment, and it was ensured that the indoor temperature remained almost constant during the data collection period. All the data presented in the current paper are dimensionless. The incoming wind speed and turbulence intensity measured using hot wire are shown in Figure 4.

### Table 1 Geometrical parameters of the blades of the wind turbine model

| Location | Airfoil | Proportion | Torsion angle |
|----------|---------|------------|---------------|
| 5%       | Cylinder | /          | 10.5          |
| 7%       | Cylinder | /          | 10.5          |
| 25%      | S818    | 0.33       | 10.5          |
| 50%      | S825    | 0.24       | 2.5           |
| 75%      | S825    | 0.21       | 0.0           |
| 100%     | S826    | 0.16       | −0.6          |

![Figure 2](image-url) Layout of the experiment

![Figure 3](image-url) Layout of the experiment

![Figure 4](image-url) Layout of the experiment
3 | RESULTS

In this section, various experimental results, such as average wind speed, turbulence intensity, and output power, are presented.

3.1 | Analysis of the wake flow behind the wind turbine: average wind speed

Figure 5 shows the velocity distribution profile of the wake flow field in the horizontal direction at the hub height of the upstream large wind turbine. The velocity distribution was symmetrical, indicating that the changes on both sides of the axis were roughly the same. The velocity values at the blade tips on both sides of the wind wheel reached the peak values, which were close to the incoming wind speed. In Areas II and III, as in the turbine area, rapid changes in wind speed (a downward trend overall) were observed. Away from the hub center and in Area II, the wind speed increased slightly to about 0.8 times the incoming wind speed. Since Areas I and IV were not subjected to the influence of wind turbines, the wind speed remained unchanged in these areas. In addition, the wind speed was closely related to the yaw angle and decreased with the increase in yaw angle. With the increase of yaw angle, the wind speed recovered faster, whereas the speed loss behind the wind wheel was relatively low. Due to the coordinated movement in the upwind direction, the downstream fan may not be able to perceive the substantial change in average momentum. It was found that the variation in speed was the largest near the hub height. The decrease may be due to the large-scale vibrations caused by the rotation of wind wheel and the energy redistribution of the flow structure.

Figure 6 shows the velocity distribution curves at three positions of $x/d_T = 3$, $x/d_T = 5$ and $x/d_T = 7$ under 0°, 15°, and 30° yaw. It can be seen that, in Area IV, the height was less than the height of the lower blade tip, and the wind speed increased with the increase of the height. In Areas II and III, the speed began to decay, and under the influence of an upstream fan with wake conditions, the speed loss was about 10%. In Area I, when the height
exceeded the height of the upper blade tip, the influence of wake flow became relatively small, and the speed began to recover gradually. In general, after working on the wind turbine, the velocity of the fluid decreased sharply in the direction directly behind the wind turbine. The greater velocity loss of the near-wake flow field of the downstream wind turbine was attributed to the smaller inflow velocity of the downstream wind turbine, which was due to the influence of the wake velocity attenuation of the upstream wind turbine. However, in the far-flow field, the speed recovered faster because the additional turbulence generated by the rotation of the upstream wind turbine promoted the exchange of momentum between the wake of the downstream wind turbine and the external flow field.

3.2 Analysis of the wake flow behind the wind turbine: turbulence intensity

In this paper, turbulence intensity is calculated based on average wind speed, which is given in Equations (1)–(4). Where $I_T$ is the turbulence intensity of free flow, $I_{T,W}$ is the turbulence intensity of wake effect, $m$ is the Wohler contrast index of the material of the structural component under consideration, $N$ is the number of adjacent wind turbines, $P_w$ is the probability of the head wake condition, $x_i$ is the distance to the $i$th wind turbine, $D$ is the diameter of the wind wheel, $v$ is the average wind speed, and $\sigma$ is the standard deviation of wind speed.

$P_w = 0.06$  
$s_i = \frac{x_i}{D}$  
$I_{T,W} = \sqrt{\frac{1}{(1.5+0.3s_iV)^2} + I_T^2}$  
$I_T = \frac{\sigma}{\bar{V}}$

$\text{FIGURE 5} \ \text{Mean wind speed in the wake zone at different positions in the horizontal direction, from top to bottom as area I - IV, similarly hereinafter}$

$\text{FIGURE 6} \ \text{Mean wind speed in the wake zone under different yaw conditions of the wind turbine in vertical direction}$
was at different yaw angles. The variation trend of turbulence intensity was generally symmetrical. However, the turbulence intensity in Areas I and IV that were not affected by the wind wheel significantly reduced from the peak value. The turbulence intensity in Area I reduced by about 20%, while that in Area IV reduced by about 30%. In addition, it can be seen that the turbulence intensity was closely related to the yaw angle of the upstream large wind turbine, whereas the turbulence intensity gradually decreased with the increase of the yaw angle.

Figure 8 shows the turbulence intensity distribution profiles for $x/d_T = 3$, $x/d_T = 5$, and $x/d_T = 7$ at $0^\circ$, $15^\circ$, and $30^\circ$ yaw. It can be seen that, for Area IV below the height of the lower blade tip, the turbulence intensity increased with the increase in height. When the height reached the lower blade tip, the turbulence intensity began to decay by about 20%, and the turbulence intensity decreased in the area directly behind the wind wheel. When the height exceeded the upper blade tip, the turbulence intensity increased gradually with the increase of the height. With the increase in horizontal distance, the turbulence intensity recovered faster.

### 3.3 Downstream wind turbine’s power output

The results presented in Table 2 show that, when the upstream wind turbine yawed, the power output of the downstream wind turbine increased. This was mainly due to the reason that, when the upstream fan yawed, the downstream fan was less affected by the upstream wake of the wind turbine, thus increasing the power output for the downstream turbine. Moreover, when the yaw angle was $15^\circ$, the overall power output increased by 12.34% compared to when there was no yaw. Furthermore, when the yaw angle was $30^\circ$, the power output of the downstream turbine increased by 21.58% compared to the upstream wind turbine. Therefore, it can be inferred that proper yawing can improve the power output of the downstream wind turbine. Additionally, when the speed was relatively low, the increase in the power output was more obvious. This could be due to the reason that, when the wind speed was low, the wake effect was relatively small, due to which the power output was higher.
4 | CONCLUSIONS

In this paper, experiments on a wind tunnel indicated that the effect wake flow on wind turbines under yaw conditions may be greater than previously suggested. When the yaw angle of the wind turbine model was 15°, the rate of wake recovery at 3 m position was almost the same as that without the yaw. However, the recovery rates at 5 m and 7 m positions increased by 5% compared with that without yaw. When the yaw angle of the wind turbine model was 30°, the recovery rate of wake increased by 10%. The study on turbulence intensity shows that yaw greatly affected the speed at which turbulence intensity changes. It should be noted that, in the downstream wind turbine output power experiment, under the yaw of 15° of the upstream wind turbine, the output power increased by 17.6% on average, whereas the maximum increase in power output was 39.0%. When the yaw angle of the upstream wind turbine was 30°, the output power of the downstream wind turbine increased by 21.6% on average, and the maximum increase reached 71.6%. The power output of the downstream wind turbine exceeded the expectations of the experiment. The comprehensive experiment under large-angle yaw of the wind turbine model illustrates the accuracy of the wake model for predicting the output of a wind turbine with yaw conditions. The study also highlights some of the challenges in the operation of wind farm with wake and yaw conditions. Although the regulation and decision-making in the actual operation of the wind farm are much more complicated than those considered in the current work, the research is still important as it deepens our understanding about the factors influencing the power output of wind farms. In future work, the authors will try to use wind turbine models of different sizes to further explore the influence of the arrangement of wind turbines on the overall power output, and consider adding vertical axis wind turbines. This kind of research helps in furthering the potential of wind farms while increasing the density of wind turbines.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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