INTRODUCTION

Wind turbines can be classified into horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs) in accordance with the installation position of the primary shaft relative to the ground. VAWTs are increasingly preferred because of their simple structure and the absence of yaw systems. However, the large-scale and commercial development of VAWTs has been hindered because the actual wind energy utilization ratio of a wind turbine is 33%-35% lower than the theoretical value of 64%. The reason for this problem is that the blades in the upwind zone interfere with the flow field in the downwind zone during the rotation process of the wind turbine. Consequently, the overall performance of VAWTs deteriorates, particularly the wind energy utilization ratio. To address the problem of low wind energy utilization ratio, various measures have been taken to improve the aerodynamic performance of VAWTs. One of the effective methods is to install split flaps at the trailing edge of the blade. Split flaps can change the Kutta-Joukowsky trailing edge boundary condition, which increases the flow circulation around the airfoil. Also, split flaps can increase the positive pressure difference in the upwind area and reduce the negative pressure difference in the downwind area, which significantly improves the aerodynamic performance of VAWTs.

KEYWORDS
aerodynamic performance, fluent, orthogonal design, split flap, VAWT
utilization ratio of VAWTs, considerable research has been conducted to improve airfoil, optimize the wind turbine structure, and control local flow. Flow control technology can be divided into active flow control and passive flow control. Active flow control technology includes synthetic jet, plasma exciter and deformable flap, and so on, which can be accurately controlled at the required time and position. Zhang et al. and Zhuang et al. have carried out in-depth research on the application of deformable trailing edge flap in the aerodynamic load control of blades and found that it can effectively reduce the aerodynamic load fluctuation and the excessive loads that cause damage of blades. However, this method is more suitable for low-speed conditions of horizontal axis wind turbines and large vertical axis wind turbines. The small H-type VAWT studied in this paper has fast rotating speed and complex flow field distribution, so it is difficult to realize the control and execution of the device by using active flow control. Passive flow control will be more suitable. Osman et al., Jing, and Yan et al. have studied the wind concentrator outside the wind turbine, analyzed the influence of different structures on improving the aerodynamic performance of the wind turbine, and found that it has obvious effect on improving the starting performance. Greenblatt has conducted an inboard/outboard switching control technology and an electromechanical system to control dynamic stall and improve wind energy efficiency by using plasma actuators. Kogaki et al., Zhang et al. and Lijun et al. found that the vortex generator has a very significant effect on the wind energy utilization ratio as well. Rezaeieha et al. and Sasson and Greenblat used a slot located near the blade leading edge to suppress the flow separation and avoid the formation of dynamic stall vortices, and significantly increased blade lift. In addition, tip winglets, flaps, slotted airfoils, bionic nodules, and grooves are also commonly used passive flow control devices. In the late 1970s, the aircraft flap was first applied to modify the trailing edge of wind turbine blades by NASA Lewis Research Center to achieve local flow control, which has great potential for development, including Gurney flaps, simple flaps, and split flaps. Among them, the Gurney flap was first discovered by the racing driver Gurney, Pastrikakis et al., and Karthikeyan et al. found that the Gurney flap significantly improved the flow field and pressure distribution around the blade, and effectively increased the blade lift. Jose pointed out that the gaps caused by the addition of simple flaps may have a negative impact on the performance of wind turbine. Also, Lackner and Kuik found that simple flaps can reduce blade flapping torque by 12%-15%. For split flaps, Teick and Wenzinger studied aerospace airfoils with a split flap through a wind tunnel experiment. The split flap could effectively reduce the speed and load shedding of the aerospace airfoils at a high tip speed ratio (TSR). Richter and Rosemann used experimental and numerical simulation methods to compare the effects of split flaps, Gurney flaps, and divergent trailing edges on the performance of aerospace airfoils. The results showed that the split flaps can increase the camber of the airfoil, extend the pressure distribution at the trailing edge, reduce airfoil resistance, and increase the lift-to-drag ratio, which is superior to that of the flexible trailing edge. Nurgroho et al. studied an aeronautical airfoil with split flaps in 2015 and determined the optimum flap deflection angle and angle of attack. The results also showed that wind speed and ambient temperature considerably influence the lift and drag of the airfoil. On the basis of these results, Yi applied split flaps to VAWT, established a starting mathematical model for a wind turbine, and found that servo split flaps can improve the starting moment without reducing efficiency during stable operation. Xiao et al. conducted a numerical simulation study on a vertical axis tidal turbine (VATT) with fixed and oscillating flaps, and found that turbine power coefficient reaches 28% enhancement as compared to the conventional blade turbine. Various of trailing edge flaps can improve the force of the blade to a certain extent and improve the aerodynamic performance of the wind turbine. However, considering the flow separation at high angle of attack and higher speed operation condition of VAWTs, there may be problems in the structural strength of simple flaps and Gurney flaps at the connection with airfoils. All things considered, among these flaps, split flaps are most suitable for flow separation at a high angle of attack due to their simple structure, smooth joint surface, and lack of additional control agency and actuator.

The aforementioned studies presented results for airfoils with split flaps. However, most of these studies have focused on aerospace or HAWT airfoils. By contrast, research on VAWT airfoils remains scarce. Moreover, given that the structure of VAWT differs considerably from that of HAWT, the effect of adding split flaps on improving the aerodynamic performance of VAWT still requires further study. Moreover, in consideration of the disorder of the flow field of VAWT, the aforementioned single airfoil oscillation research method, which is mostly used in studying split flaps, cannot effectively evaluate the overall performance of VAWT under severe flow separation conditions at high angles of attack. Therefore, to conduct a detailed study of VAWT after the installation of split flaps, the current study uses ANSYS Fluent software to carry out the 2D URANS calculation of VAWTs with fixed split flaps. First, the dimensional parameters and the influence degree of factors of the trailing edge split flap are preliminarily determined using the orthogonal design method. And then, the influence of the split flap on the performance of VAWT is studied in accordance with the order of influence from small to large, and the optimum design parameters of the split flap are obtained under the given conditions. On this basis, the mechanism of the split flap to improve the aerodynamic performance of the wind turbine is further explored through the changes of the flow field around
the blade. Finally, it provides a reference for the practical application of split flap as a passive flow control method in the field of VAWTs. The conclusions obtained in this paper may still have some difficulties in practical application and need to be further improved, but they are of great significance in theoretical guidance.

2 | VAWT MODEL AND MESHING

2.1 Wind turbine parameters and split flap model

This study is based on a 3.5 kW VAWT model. The major parameters of the model are listed in Table 1.

A 2D airfoil model with a split flap is shown in Figure 1A, which is modified with an NACA0015 airfoil. The joint between the flap and the base airfoil is optimized to a smooth surface. The partial detail diagram of the trailing edge split flap is shown in Figure 1B, wherein the flap’s length is 10% of the chord, the deflection angle is 10°, and the arrangement position 90% of the chord from the leading edge, the arrangement position 90% c represents the chord length 90% from the leading edge of the airfoil.

2.2 Meshing topology

The 2D calculation model is used to conduct wind turbine numerical simulation in this research. The division of the computational zone grid is shown in Figure 2. The upper and lower boundaries and the left boundary are set as velocity inlet conditions. The distance between the upper and lower boundaries is 10D. The distance between the left boundary and the center of rotation of the wind turbine is 5D. The right boundary is set as the pressure outlet condition, and the distance between the right boundary and the center of rotation of the wind turbine is 10D. The shaft and the blades are set under no sliding wall condition. Considering the influence of the rotating shaft on the internal flow field of the wind turbine, the entire computational zone is divided into three parts: external, internal, and rotating zones. The blades move with the rotating domain. The interface between each zone is set as the interface condition. The sliding mesh can be built by setting the angular velocity of the rotation domain. The azimuth of the wind turbine blades is shown in Figure 2.

To ensure the calculation accuracy of the complex flow near the wall, the airfoil surface is provided with a boundary layer mesh. The thickness of the first layer is determined using the following equation:

$$\Delta y = \mu y^+ / (\rho u_t),$$

where $\mu$ is the dynamic viscosity of air, $y^+$ is the dimensionless value of the wall distance, $\rho$ is the air density and $u_t$ is the wall friction velocity. Both the rotating zone and the static zone are divided with unstructured grid, as shown in Figure 3A.

For the modified wind turbine model with a split flap, the overall grid structure is consistent with those of the original airfoil model, as shown in Figure 3B.

2.3 Verification of the numerical simulation

The turbulence models commonly used in URANS include SST Transition model, Realizable k-ε model, Spalart-Allmaras model and SST k-ω model. They are applied to VAWT simulation, and the wind energy utilization ratio is compared with the experimental data, as shown in Figure 4.

In Figure 4, the wind energy utilization ratio corresponding to the SST k-ω model is in the highest agreement with the experimental data, which can better reflect the aerodynamic performance of the wind turbine under each tip speed ratio and can accurately predict the tip speed ratio corresponding to the maximum wind energy utilization ratio. The research of related scholars shows that the SST k-ω model is more consistent with the experimental results in the transitional

![Figure 1](A) NACA0015 airfoil with split flap. (B) Local detail of the split flap

| TABLE 1 | Major parameters of the VAWT |
|----------|--------------------------|
| Parameter | Value |
| Blade profile | NACA0015 |
| Blade height L (m) | 3 |
| Rotor diameter D (m) | 2.5 |
| Chord length c (m) | 0.4 |
| Setting angle $\beta$ (°) | 0 |
| Blade count | 3 |
| Wind speed V (m/s) | 10 |
| $Re$ | $2 \times 10^6$ |
flow regime. Therefore, SST k-ω model is selected to calculate in this paper.

Before the computational fluid dynamics (CFD) numerical simulation is conducted, the boundary layer grid around the airfoil and the rotating domain grid is refined to obtain the division of different numbers of grids, performing grid independence verification. The number of grids for each type of mesh (Mesh1-Mesh5) and the corresponding maximum $y^+$ value for the numerical simulation are provided in Table 2.

When TSR = 1.5, the blade moment coefficient curves that correspond to each type of mesh are obtained, as shown in Figure 5. The density of grids has a great influence on the numerical simulation results, and as the increasing of grid

**Figure 2** Computational domain diagram

**Figure 3** (A - a) Grid diagram (a) near the rotating core. (A - b) Grid diagram (b) near the airfoil. (A - c) Airfoil leading edge. (A - d) Airfoil trailing edge. (B - a) Airfoil with the split flap. (B - b) Airfoil leading edge. (B - c) Airfoil trailing edge
density, the trends of the blade moment coefficient curves tend to be stable. Among them, the curve of Mesh1-Mesh3 varies greatly, while the curves of Mesh4 and Mesh5 almost coincide completely. Therefore, to obtain numerical simulation results with high accuracy, achieve good observation of the changes of the flow field on the blade surface and have high computational efficiency, the number of grids used in this study is approximately 480,000.

To verify the accuracy of CFD, the 2D CFD simulation data of the 3.5 kW VAWT were compared with the McMaster University wind tunnel experimental data.37

In the numerical simulation, the wind speed of the velocity inlet condition is set as 10 m/s, and the direction is positive along the X-axis. The gauge pressure of the pressure outlet condition is 0 Pa. The wind turbine rotates counterclockwise. When the TSR of the wind turbine is 1.5, the corresponding rotation angular velocity of the wind turbine is 12 rad/s. The azimuthal increment is 1°, a total of 10 periods are calculated, and the convergence criterion is $1 \times 10^{-6}$.46

For the 2D numerical simulation model used in this study, the 2D unsteady incompressible equation of N-S and the pressure-velocity coupling scheme of SIMPLE are adopted. The SST k-ω model is selected as the turbulence model, which can better reflect the characteristics of the flow field compared with other turbulence models.34 The results are consistent with the experimental data. The governing equations are as follows:

$$\frac{\partial (\rho_m k)}{\partial t} + \frac{\partial (\rho_m u_i k)}{\partial x_i} = P_k - \frac{k}{l_{k-w}} + \frac{\partial}{\partial x_i} \left( \frac{\mu + \mu_t}{\sigma_k} \frac{\partial k}{\partial x_i} \right),$$

$$\left( \mu + \frac{\mu_t}{\sigma_{\omega_2}} \right) = a_2 \omega \left( 1 - F_1 \right) \frac{1}{\sigma_{\omega_2}} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i},$$

where $P_k$ and $P_\omega$ are turbulence generators; $F_1$ and $F_2$ are mixed functions; $S$ is the shear stress tensor constant term; $a_1$, $a_2$, $\beta_2$, and $\sigma_{\omega_2}$ are the empirical coefficients, and $a_1 = 2$, $a_2 = 0.44$, $\beta_2 = 0.0828$, and $\sigma_{\omega_2} = 0.856$; and $\mu_t$ is the eddy viscosity coefficient, which is determined by the following formula:

$$\mu_t = \frac{\rho_m a_1 k}{\max \left( a_1 \omega, S F_2 \right)},$$

where $a_1$ is a specific constant.

For comparison with the experimental data, the calculation condition is $R_e = 2 \times 10^5$ and the convergence criterion is that the residual error is less than $1 \times 10^{-6}$.

From the $C_p$-TSR comparison curves fitted by the spline curves between the simulated results and experimental data in Figure 6, the obtained wind energy utilization ratio is slightly higher than the experimental data because the 2D VAWT model disregards the aerodynamic calculation effects of the windward shear and the tip vortex. Besides, the VAWT model has been simplified before calculation and disregards the resistance of the support rod on the performance of the wind turbine. The experimental data may also have

---

**TABLE 2** Details of the computational grids for VAWT

| Grid size | Cells   | Maximum $y^+$ on blades |
|-----------|---------|-------------------------|
| Mesh1     | 142,671 | 5.7                     |
| Mesh2     | 241,457 | 4.4                     |
| Mesh3     | 368,761 | 3.1                     |
| Mesh4     | 482,159 | 2.4                     |
| Mesh5     | 626,553 | 1.5                     |
some deviations due to some problems such as measurement. However, the trend of the simulation data is consistent with that of the experimental data. The maximum wind energy utilization ratio occurs at TSR = 1.5, and the maximum deviation of wind energy utilization is only 5.1%. Therefore, the CFD method adopted in this study is reasonable and can effectively explain the basic law of the flow field. Moreover, it provides a basis for further research on the performance of wind turbines with split flaps.

3 ANALYSIS OF THE INFLUENCE OF SPLIT FLAP PARAMETERS ON THE AERODYNAMIC PERFORMANCE OF VAWT

3.1 Orthogonal design of split flap parameters

When VAWT is working normally, the length, deflection angle, and arrangement position of the split flap are the major factors that affect the performance of the wind turbine. The amount of work required for comprehensive calculation is considerably large if full calculations are performed because of the large number and wide range of values necessary in obtaining the optimum design parameters of a split flap. Moreover, the influence degree of each factor on wind turbine performance cannot be determined. The method in the experimental design is used for analysis considering that the orthogonal design can replace all the experiments with part experiments, assess the influences of different factors on the reference indexes, and preliminarily obtain an improved combination of different factors. Flap length, deflection angle, and arrangement position are selected as the three major factors of orthogonal design. However, excessive flap length and deflection angle will reduce the wind energy utilization ratio and degrade the performance of the wind turbine. Thus, each factor is selected to be studied within a small range, as shown in Table 3, where $A$ is the length of the flap, $B$ is the deflection angle, and $C$ is the arrangement position. The four-factor three-level orthogonal design table $L_9 (3^4)$ is selected for the study.

3.2 Calculation results and analysis

On the basis of the mean moment coefficient $C_{M\text{mean}}$ obtained through the simulation, the wind turbine moment $M$ and the wind energy utilization ratio $C_P$ can be calculated using the following equations:

\[ M = 0.5 \rho v^2 A L C_{M\text{mean}}, \]  
\[ C_P = \frac{M \omega}{0.5 \rho v^3 A_S}, \]

where $\rho$ is the air density, $v$ is the wind speed, $A_S$ is the sweep area, $L$ is the characteristic length, and $\omega$ is the rotating angular velocity.

To investigate the influence of the split flap on the performance of VAWT, $\Delta C_P$ and $\Delta \lambda$ are selected as the evaluation indexes. $\Delta C_P$ is the difference value of the wind energy utilization ratio $C_P$ between the wind turbine with the split flap and the prototype wind turbine. $\Delta \lambda$ is the difference value of the TSR range for the efficient operation between the wind turbine with the split flap and the prototype wind turbine. The efficient operation referred to here is defined as the TSR range that corresponds to $C_P > 85%$. Table 4 is the orthogonal experimental table, and it presents the corresponding $\Delta C_P$ and $\Delta \lambda$ values. The split flap causes $\Delta C_P$ and $\Delta \lambda$ to increase in most cases. However, $\Delta C_P$ and $\Delta \lambda$ are seriously degraded because the deflection angle is too large and the arrangement position is close to the leading edge.

After further analysis of the data in Table 4, the average and range value of each evaluation index are obtained, as provided in Table 5. In this table, $\bar{k}_i$ is the average value of all the corresponding values of $\Delta C_P$ or $\Delta \lambda$ when the factor is $j$, where $j$ is one of the factors of $A-C$. Moreover, when the value is large, the performance of the wind turbine is good. $R_{ij}$ is the range value that corresponds to the evaluation indexes $i$, which reflects the influence degree of factor $j$ on index $i$. For
The range value of the deflection angle is considerably larger than those of the two other indexes, satisfying $\Delta \theta_1 > \Delta \theta_3 > \Delta \theta_2$ and indicating that the deflection angle exerts greater influence on $\Delta C_p$. For $\Delta \lambda$, the range value of the deflection angle is slightly larger than those of the two other indexes, satisfying $\Delta \lambda_2 > \Delta \lambda_3 > \Delta \lambda_1$ and indicating that the deflection angle also exerts greater influence on $\Delta \lambda$.

The large values of $\Delta C_p$ and $\Delta \lambda$ correspond to good wind turbine performance, and $\Delta C_p$ can directly reflect the output power of the wind turbine. Therefore, on the basis of the average value $k_i$ that corresponds to each index in Table 5, the flap length is 20% $c$, the deflection angle is 10°, and the arrangement position is 90% $c$ from the leading edge. The best combination is $A_2B_1C_1$. Simultaneously, among the three split flap parameters that affect the performance of VAWT, deflection angle exerts the greatest influence on the performance of the wind turbine. Arrangement position is second, and flap length has the least influence on the performance of the wind turbine.

### 4.1 | Length of split flap

The results of the orthogonal design indicate that flap length exerts the least influence on the performance of VAWT. The deflection angle is maintained at 10°, the fixed arrangement position is kept at 90% $c$ (90% of the chord length) from the leading edge, and the flap length varies between 10% $c$ and 25% $c$.

Through 2D CFD simulation at TSR = 1.5, the $C_T-\theta$ curves (tangential force coefficient various with azimuth angle) of blade with different flap lengths are obtained, as shown in Figure 7. In Figure 7, the tangential force coefficients of blades with different flap lengths are different within the azimuth angle of 80°-135° and 190°-330°, but the overall trend is similar. In the upwind area, the $C_T-\theta$ curves of 10% $c$ and 15% $c$ are higher than those of other lengths and the prototype wind turbine, while in the downwind area, the curves of 20% $c$ and 25% $c$ become higher.

When $\theta = 270^\circ$, the flow diagrams of the wind turbine blade trailing edge with different flap lengths are obtained, as shown in Figure 8. In Figure 8, there is a vortex between the flap and the airfoil trailing edge compared with the prototype blade, which will gradually shift backward and expand with the increase of the flap length. When the air flows through the blade outer surface, due to the Coanda effect (considering the viscosity of the fluid, when the fluid tends to move away from the surface of the object, if the surface of the object is a protruding structure and the curvature is small, the fluid
will continue to flow on the protruding surface), the flow will continue to flow along the flap and vortex surface and then shift to the blade inner surface. That is, the fluid will bypass and gather to the blade inner surface around the initial trailing edge of the blade, and finally forms a new rear stationary point at the tail end of the split flap. Kutta-Joukowsky boundary condition is shown in Formula (7)

\[ L = \rho v \Gamma, \]

where \( \Gamma \) is flow circulation, \( \rho \) is the air density, \( v \) is the wind speed. Without changing the front stationary point of the blade, the fluid offset after applying split flaps will change the position of the rear stationary point of the blade, that is, change the blade flow circulation (the direction of the flow circulation is from the leading edge of the blade inner surface to the leading edge of the blade outer surface), so as to improve the lift and comprehensive aerodynamic performance of the blade. With the increase of the flap length, the vortex between the flap and the airfoil trailing edge continues to move and spread, and the fluid needs to bypass a longer distance to reach the new rear stationary point, so the increase of the flap length will continuously improve of blade lift force. According to data in Figure 7, the blade tangential force coefficient of 25% \( c \) is the largest when \( \theta = 270^\circ \).

Additionally, the increase of the flap length also changes the actual chord length of the airfoil, making it have a larger wind area. Furtherly selecting the flap length from 15% \( c \) to 25% \( c \), the \( C_p \)-TSR curves are fitted by the spline curves to obtain the maximum wind energy utilization ratio and the maximum efficient operating range, as shown in Figure 9. In Figure 9, the \( C_p \)-TSR curves of the wind turbine with different flap lengths are different. When TSR is low, the curves become higher with the increase of the flap length, while when TSR is high, the variation of curves becomes complex, in which the curve of 22% \( c \) is higher. And in the start-up phase (TSR = 1), the longer the flap length is, the greater the actual chord length and curvature of the airfoil is, and the better the start-up performance is. On the whole, the longer flap length (22% \( c \) and 25% \( c \)) can make the VAWT have higher wind energy utilization ratio at every TSR value.

Based on Figure 9, the major indexes of maximum wind energy utilization ratio \( C_{p_{max}} \), efficient operation range \( \Delta \lambda \), and starting moment \( M \) are selected to evaluate the performance of VAWT, where \( M \) is the moment value of the wind turbine at TSR = 1, as shown in Table 6. Table 6 shows that when flap length is increased from 15% \( c \) to 25% \( c \), \( C_{p_{max}} \) gradually increases and reaches a maximum value of 0.412 at 20% \( c \) and then remains unchanged. \( M \) also increases with flap length and reaches a maximum value of 377.82 N m at 25% \( c \). \( \Delta \lambda \) changes in fluctuations and the maximum value of 1.01 is obtained at 22% \( c \). The comparison of the evaluation indexes of the flap lengths of 22% \( c \) and 25% \( c \) shows that \( C_{p_{max}} \) remains unchanged and the \( \Delta \lambda \) of 22% \( c \) is increased by 6.3% compared with that of 25% \( c \). However, the \( M \) of 25% \( c \) is only increased by 1.5% compared with that of 22% \( c \). Therefore, considering the indexes of VAWT performance, 22% \( c \) is selected as the optimum flap length parameter.
TABLE 6  Performance indexes of wind turbine with different lengths of split flaps

| Length/Index | $C_{p_{\text{max}}}$ | $\Delta \lambda$ | $M/(N \cdot m)$ |
|--------------|---------------------|-----------------|----------------|
| 15% c        | 0.392               | 0.91            | 267.55         |
| 18% c        | 0.396               | 0.94            | 327.20         |
| 20% c        | 0.406               | 0.87            | 338.49         |
| 22% c        | 0.412               | 1.01            | 355.24         |
| 25% c        | 0.412               | 0.95            | 360.60         |

4.2  Arrangement position of the split flap

Based on the research results in Section 3.1, the flap length of 22% $c$, and the deflection angle of 10° are kept constant. The influence of the flap arrangement positions on blade tangential force coefficient is shown in Figure 10. In Figure 10, different arrangement positions have a certain influence on the blade tangential force coefficient. There is only a certain deviation within the azimuth angle of 80°-200° and 250°-320°, and the overall trend is similar. Within all the azimuth angles, the $C_T$-$\theta$ curves of flap arrangement positions of 80% $c$, 85% $c$ and 90% $c$ almost coincide. In the upwind area, only the curve of 95% $c$ is higher, while in the downwind area, it is still higher than that of prototype wind turbine but lower than that of others.

Furtherly observing the influence of different arrangement positions on the flow field at the trailing edge of the blade when $\theta = 270^\circ$, streamline diagrams are shown in Figure 11. In Figure 11, compared with the prototype blade, there are several vortices between the split flap and the airfoil trailing edge, of which the size is compressed and the number is reduced with the backward movement of the flap arrangement position. The split flap shifts the rear stationary point to the blade inner surface without changing the front stationary point, and within the arrangement position of 80% $c$-90% $c$, the closer the flap is to the trailing edge, the longer the distance of fluid flow through the flap and vortex surface is. Therefore, the flow circulation is increased and the blade performance is gradually improved. But when the vortex is too small, the fluid does not achieve the purpose of increasing the flow circulation in the rear half of the flap, and when $\theta = 270^\circ$, the tangential force coefficient of the blade of 90% $c$ is the largest.

Selecting the flap arrangement position from 85% $c$ to 95% $c$ to calculate, and the $C_p$-TSR curves of different arrangement positions are shown in Figure 12. In Figure 12, when TSR is low, the closer the flap arrangement position is to the trailing edge of the blade, the more significant the wind energy utilization ratio improvement of the wind turbine is, while when TSR is high, the $C_p$-TSR curves become complex, among which the curves of 90% $c$ and 92% $c$ are higher. Besides, the arrangement position which is near the blade trailing edge increases the actual chord length and curvature of the airfoil, so the starting performance becomes better.

The evaluation indexes that correspond to the wind turbine with different flap arrangement positions are listed in Table 7. When the arrangement position changes within 85% $c$-95% $c$, $C_{p_{\text{max}}}$ and $\Delta \lambda$ tend to initially increase and then decrease, and $C_{p_{\text{max}}}$ reaches the maximum value of 0.417 at 92% $c$ and $\Delta \lambda$ reaches a maximum value of 1.06 at 90% $c$ and 92% $c$. Moreover, $M$ gradually increases as the arrangement position of the flap approaches the trailing edge. Comparing the indexes of 90% $c$ and 92% $c$, the $C_{p_{\text{max}}}$ of 92% $c$ is increased by 3.2% compared with that of 90% $c$, and $\Delta \lambda$ is increased by 1.9%, but $M$ is reduced by 2.9%. Therefore, considering the indexes of VAWT performance, 92% $c$ from the leading edge is selected as the optimum flap arrangement position parameter.

4.3  Deflection angle of the split flap

The split flap with different deflection angles is studied on the basis that the optimum flap length is 22% $c$ and the optimum arrangement position is 92% $c$. The deflection angle of the split flap is changed within 5° and 20°, and the $C_T$-$\theta$ curves of blade are shown in Figure 13. In Figure 13, the $C_T$-$\theta$ curves of different flap deflection angles fluctuate greatly. In the upwind area, the curve of 10° is higher than that of other deflection angles and the prototype wind turbine, but becomes lower in the downwind area. Although the curve of 20° is much lower than that of prototype wind turbine in the upwind area, it shows better performance in the downwind area.

Furtherly observing the influence of different deflection angles on the flow field at the trailing edge of the blade at $\theta = 270^\circ$, streamline diagrams are shown in Figure 14. In Figure 14, there are several vortices between the split flap and the airfoil trailing edge compared with the prototype blade.
With the increase of the flap deflection angle, the vortex expands firstly and then decreases, moves backward firstly, and then moves forward. Although the changes of the deflection angle lead to the continuous shift of the rear stationary point of the blade to the inner surface, but when $\beta = 5^\circ$ and $15^\circ$, due to the vortex scale is small, the flow circulation in the back half of the flap has almost no increase and the performance of blade has almost no improvement as well.

To obtain the optimum flap deflection angle, selecting the flap arrangement position from $5^\circ$ to $15^\circ$ to calculate, and the $C_p$-TSR curves of different deflection angles are shown in Figure 15. In Figure 15, when TSR is low, the coincidence degree of the $C_p$-TSR curves is higher, while when TSR is high, the curve fluctuates greatly, and the higher $C_p$-TSR curve corresponding to the deflection angle of $5^\circ$ decreases obviously when TSR $> 2$. When the flap deflection angle is small, the start-up performance of the wind turbine is better, but with the increase of TSR, too large or too small flap deflection angle will reduce the overall aerodynamic performance of the wind turbine.

The evaluation indexes that correspond to the wind turbine with different flap deflection angles are listed in Table 8. In Table 8, when the flap deflection angle changes within the range of $5^\circ$-$15^\circ$, the $C_{p\text{max}}$ and $\Delta \lambda$ of the wind turbine tend to initially increase and then decrease, where $C_{p\text{max}}$ reaches a maximum value of 0.417 at $10^\circ$ and $\Delta \lambda$ reaches a maximum value of 1.02 at $8^\circ$ and $10^\circ$. Moreover, $M$ continues to decrease as the deflection angle increases. Comparing the deflection angles of $8^\circ$ and $10^\circ$, the $C_{p\text{max}}$ of $10^\circ$ is increased by 1.2% compared with that of $8^\circ$, $M$ is reduced by
Therefore, considering the indexes of VAWT performance, 10° is selected as the optimum flap deflection angle parameter.

### 4.4 Performance comparison of wind turbines with and without split flap

The research results presented in Sections 4.1-4.3 show that the optimum split flap design scheme for VAWT under the current working conditions can be obtained. The optimum length is 22% c, the optimum arrangement position is 92% c from the leading edge, and the optimum deflection angle is 10°.

The \( C_p \)-TSR curves of the wind turbines with and without split flap are compared in Figure 16. In Figure 16, the overall performance of VAWT is considerably improved after the installation of the split flap. The \( C_{p_{\text{max}}} \) value of the wind turbine with split flap is increased by 5.8% compared with that of the prototype, and \( \Delta \lambda \) is increased by approximately 25.9%. The split flap significantly improves the performance of the wind turbine, particularly at 1.5 < TSR < 2.5.

### 5 INVESTIGATION ON THE MECHANISM OF THE SPLIT FLAP TO IMPROVE WIND TURBINE PERFORMANCE

The research results in Section 4.4 show that when 1.5 < TSR < 2.5, the influence of the split flap on increasing the \( C_p \) of the wind turbine is significant. Therefore, the mechanism of the split flap that improves the performance of
the wind turbine under high TSR values should be investigated. In this section, TSR = 2 and the flow field around the wind turbine blades with/without split flap are analyzed via CFD-post. The blade operating azimuth range of 0°-180° is called the upwind zone, and the azimuth angle of 180°-360° is called the downwind zone.50

At TSR = 2, the blade moment curves of wind turbines with and without split flap are shown in Figure 17. The curves vary periodically with a change in the azimuth angle of the airfoil. Within the azimuth angle of 90°-150° and 210°-360°, the tangential force coefficients $C_T$ of the wind turbine with split flaps are higher than those of the prototype wind turbine. Within the azimuth angle of 0°-90° and 150°-210°, the two curves almost coincide.

When TSR = 2, the flow diagrams of the surface of the wind turbine blade located at different azimuth angles are shown in Figure 18. It is obvious that there are several vortices between the flap and the blade trailing edge after the split flap is installed. According to the Coanda effect, the Kutta-Joukowsky trailing edge boundary condition and the correlation analysis in Section 4.1-Section 4.4, the flap and the generated vortex increase the actual curvature of the airfoil and deflect the trailing edge fluid to the blade inner surface, which increases the flow circulation around the airfoil and improves the aerodynamic performance of the wind turbine. Furtherly observing the flow diagrams of the blade in Figure 18, the split flap hinders the flow of fluid on the blade inner surface within the azimuth angle of 90°-150°, which expands the high pressure vortex and increases the pressure on the inner surface.

Blade surface pressure coefficient curves are shown in Figures 19 and 20 when $\theta = 120°$ and 240°. When the blade is operated in the upwind zone under ideal conditions, its inner surface is the suction surface, and the outer surface is the pressure surface. The wind turbine will continue to rotate under the action of the pressure difference on both sides of the blade.51 However, when the blade is operated in the downwind zone, the inner and outer surfaces are subjected to the opposite pressure, that is, the inner surface is the pressure surface and the outer surface is the suction surface. In Figure 19, when $\theta = 120°$, the blade is located in the upwind zone, and the inner surface of the trailing edge of the blade is the suction surface, the pressure value is negative, while the outer surface is the pressure surface, the pressure value is positive. The pressure difference direction points to the blade rotation center, and the force produced is lift. After installing the split flap, because the fluid flow on the inner surface is hindered, the negative pressure on the inner surface decreases and the pressure difference increases, so the lift of the blade is increased. In addition, the flap also

| $\theta$ | TSR=2 | $\theta$ | TSR=2 |
|---------|--------|---------|--------|
| 90°     | Without split flap | With split flap | 210°   | Without split flap | With split flap |
| 120°    |                     |                   | 240°   |                     |                   |
| 150°    |                     |                   | 270°   |                     |                   |

FIGURE 17  Blade moment curves before and after adding flaps

FIGURE 18  Streamlines of the surface of the blade before and after the flap is added at TSR = 2
increases the chord length of the blade, so that the blade can get extra lift force.

In Figure 20, when $\theta = 240^\circ$, the blade is located in the downwind area, and the pressure coefficient curves of the blade surface crosses. At this time, the pressure on the inner surface of the leading edge of the blade is positive, which is the pressure surface. While the pressure on the outer surface is negative, which is the suction surface. In the middle and tail of the airfoil, the pressure on the inner surface of the blade increases and the pressure on the outer surface decreases. Although the pressure difference is negative, the direction of the pressure difference changes from back to the center of rotation to pointing to the center of rotation, and the force generated becomes resistance. After the installation of the trailing edge split flap, the resistance pressure difference of the trailing edge of the blade in Figure 20 decreases obviously. At the trailing edge flap, the pressure difference direction changes back to the rotation center, which is beneficial to the improvement of blade lift force. The flap also gets extra lift at the trailing edge, so the aerodynamic performance of the wind turbine is improved.

6 | CONCLUSIONS

1. To address the problem of the low wind energy utilization ratio of VAWT, a scheme that adds a split flap at the trailing edge of the blade is proposed. The CFD simulation of the wind turbine with split flaps is performed using the orthogonal design method. The results indicate that among the three design parameters of the split flap, the deflection angle of the flap exerts the greatest influence on the performance of the wind turbine, whereas the influence of flap length is minimal.

2. Comparing the $C_p$-TSR curves of VAWT with the split flap of different parameters and setting the maximum $C_{p_{\text{max}}}$, $\Delta \lambda$, and $M$ as research objectives, the optimum design parameters of the split flap are obtained as follows: the optimum length is 22% $c$, the optimum arrangement position is 92% $c$ from the leading edge, and the optimum deflection angle is 10°. Compared with the indexes of prototype wind turbine, $C_{p_{\text{max}}}$ is increased by 5.8%, and $\Delta \lambda$ is expanded by 25.9%.

3. According to the Coanda effect and the Kutta-Joukowsky trailing edge boundary conditions, the changes of flap length, arrangement position and deflection angle directly affect the shape of the vortex between the flap and the blade trailing edge, and increase the flow circulation around the airfoil. In addition, according to the change of pressure coefficient, the flap hinders the fluid flow on the inner surface of the blade, then increases the positive pressure difference on both sides of the blade in the upwind area, and reduces the negative pressure difference in the downwind area, and finally improves the aerodynamic performance of the wind turbine.

ORCID

Lijun Zhang https://orcid.org/0000-0002-5420-3554

REFERENCES

1. Haijiao T, Tielong W, Ying W. Summarize of the development of the vertical-axis wind turbine. Appl Energy Technol. 2006;11:22-27.
2. Chehouri A, Younes R, Ilinca A, Perron J. Review of performance optimization techniques applied to wind turbines. Appl Energy. 2015;142(4):361-388.
3. Paraschivoiu I, Chun L, Zhou Y, Wei G. Principle and Design of Vertical Axis Wind Turbine. Shanghai, China: Shanghai Science and Technology Press; 2013.
4. Gbadebo SA. Three-dimensional separations in axial compressors. ASME J Turbomach. 2005;127(2):457-469.
5. Guntur S, Sørensen NN, Schreck S, Bergami L. Modeling dynamic stall on wind turbine blades under rotationally augmented flow fields. Wind Energy. 2016;19(3):383-397.
6. Xu HY, Qiao CL, Yang HQ, Ye ZY. Delayed detached eddy simulation of the wind turbine airfoil S809 for angles of attack up to 90 degrees. Energy. 2016;118:1090-1109.
7. Mohamed MH. Performance investigation of H-rotor Darrieus turbine with new airfoil shapes. Energy. 2012;47(1):522-530.
8. Ramadan A, Yousef K, Said M, Mohamed MH. Shape optimization and experimental validation of a drag vertical axis wind turbine. Energy. 2018;151:839-853.
9. Ebrahimi A, Movahhedi M. Wind turbine power improvement utilizing passive flow control with microturb. Energy. 2018;150:575-582.
10. Zhang M, Yu W, Xu JZ. Aerodynamic physics of smart load control for wind turbine due to extreme wind shear. Renewable Energy. 2014;70(5):204-210.
11. Zhuang C, Yang G, Zhu YW, Hu D. Effect of morphed trailing-edge flap on aerodynamic load control for a wind turbine blade section. Renewable Energy, 2020;148:964-974.
12. Osman DA, Rosmin N, Hasan NS, et al. Savonius wind turbine performances on wind concentrator. Int J Power Electron Drive Syst. 2017;8(1):376-383.
13. Jing T. Study on the Influence of Round Table Type Wind Hood on the Start-up and Output Power of Vertical Axis Wind Turbine. Harbin, China: Northeast Agricultural University; 2016.
14. Yan L, Jing T, Kotaro T. Effect of round table type wind hood on start-up of vertical axis wind turbine. J Northeast Agric Univ. 2016;254(04):100-106.
15. Greenblatt D, Lautman R. Inboard/outboard plasma activation on a vertical-axis wind turbine. Renewable Energy. 2015;83:1147-1156.
16. Greenblatt D, Schulman M, Ben-Harav A. Vertical axis wind turbine performance enhancement using plasma actuators. Renewable Energy. 2012;37(1):345-354.
17. Kogaki T, Matsumiya H, Kieda K, et al. Performance improvement of airfoil for wind turbine by Vortex Generator. Wind Energy. 2002;28(1):73-76.
18. Zhang H, Zhao Z, Zhou G, Kang S. Experimental investigation of effect of vortex generator on aerodynamic performance of wind turbine airfoil. Acta Energiae Solaris Sinica. 2017;38(4):951-958.
19. Lijun Z, Huaibao Z, Jiawei G, et al. Effect of vortex generator on aerodynamic performance of vertical axis wind turbine airfoil. J Central South Univ (Sci Technol). 2020;51(02):540-550.
20. Rezaeiha A, Montazeri H, Blocken B. Active flow control for power enhancement of vertical axis wind turbines: leading-edge slot suction. Energy. 2019;189:116131.
21. Sasson B, Greenblatt D. Effect of leading-edge slot blowing on a vertical axis wind turbine. AIAA J. 2011;49(9):1932-1942.
22. Spera DA, . . . Wind Turbine Technology: Fundamental Concepts of Wind Turbine Engineering. New York, USA: ASME Press; 2009.
23. Pastrikakis VA, Steijl R, Barakos GN, Maleckij J. Computational aeroelastic analysis of a hovering W3 Sokol blade with gurney flap. J Fluids Struct. 2014;53:96-111.
24. Karthikeyan N, Murugavel KK, Kumar SA, Rajakumar S. Review of aerodynamic developments on small horizontal axis wind turbine blade. Renew Sustain Energy Rev. 2015;42:801-822.
25. Jose AI, Baeder JD. Steady and unsteady aerodynamic modeling of trailing edge flaps with overhang and gap using CFD and lower order models. In: Proceedings of 47th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Orlando, Florida; 2009:5-8.
26. Jose A, Mishra A, Baeder J. An investigation into the aerodynamics of trailing edge flaps with overhang and gap. In: American Helicopter Society Specialists Conference on Aeromechanics Proceedings, San Francisco, CA; 2008:10-12.
27. Lackner MA, Kuijk GV. A comparison of smart rotor control approaches using trailing edge flaps and individual pitch control. Wind Energy. 2010;13(2-3):117-134.
28. Weick FE, Harris TE. The Aerodynamic Characteristics of a Model Wing Having a Split Flap Deflected Downward and Moved to the Rear. Technical Report Archive & Image Library; May 1, 1932. http://hdl.handle.net/2060/19930081228. Accessed September 6, 2013.
29. Wenzinger CJ, Harris TA. Wind-tunnel Investigation of NACA 23012, 23021, and 23030 Airfoils with Various Sizes of Split Flap. Technical Report Archive & Image Library; January 1, 1939. http://hdl.handle.net/2060/19930091743. Accessed September 6, 2013.
30. Richter K, Rosemann H. Steady aerodynamics of miniature trailing-edge devices in transonic flows. J Aircraft. 2012;49(3):898-910.
31. Nugroho E, Sarjito ME. CFD Study the Air Flow Around Wing NACA0015 Equipped Split Flap. Thamess, Indonesia: Mechanical Engineering of Muhammadiyah University Surakarta; 2015.
32. Yi M. Research on Blade Airfoil of Low Wind Speed H-type Vertical Axis Wind Turbine. Harbin, China: Harbin Institute of Technology; 2010.
33. Xiao Q, Liu W, Inceck A. Flow control for VAWT by fixed and oscillating flap. Renewable Energy. 2013;51:141-152.
34. Zhonghe HAN, Yaley JIA, Hengfan LI, et al. Wind turbine split trailing edge flap aerodynamic performance. Trans Chin Soc Agric Eng. 2014;30(20):58-64.
35. Almohammadi KM, Ingham DB, Ma L, Pourkashan M. Computational fluid dynamics (CFD) mesh independence techniques for a straight blade vertical axis wind turbine. Energy. 2013;58(3):483-493.
36. Bhat SS, Govardhan RN. Stall flutter of NACA 0012 airfoil at low Reynolds numbers. J Fluids Struct. 2013;41:166-174.
37. Bravo R, Tullis S, Ziada S. Performance testing of a small vertical-axis wind turbine. In: 21st Canadian Congress of Applied Mechanics, Toronto, Ontario, Canada; 2007.
38. Yawei C. Aerodynamic performance analysis based on FLUENT axial flow vane. Fluid Mach. 2016;10:51-54.
39. Haitao S, Ying X, Lipan S. Numerical simulation of fluid-solid coupling characteristics of propeller. J Jiangsu Univ (Natural Science Edition). 2015;36(1):23-29.
40. Quanyong Y, Chun L, Yang Y. Research on active Control method of flow field in vertical axis wind turbine. Acta Energiae Solaris Sinica. 2019;40(01):219-225.
41. Kang J, Chun L, Jun Y. Study on dynamic aerodynamic characteristics and control strategy of trailing edge flap. Acta Energiae Solaris Sinica. 2017;7:1912-1920.
42. Sun Y, Zhang L. Numerical simulation of the unsteady flow and power of horizontal axis wind turbine using sliding mesh. In: Power & Energy Engineering Conference. IEEE; 2010.
43. Durrani N, Mian HH. A detailed Aerodynamic Design and analysis of a 2D vertical axis wind turbine using sliding mesh in CFD. In: 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition; 2011.
44. Castelli MR, Englaro A, Benini E. The Darrieus wind turbine: proposal for a new performance prediction model based on CFD. *Energy*. 2011;36(8):4919-4934.
45. Rezaeiha A, Montazeri H, Blocken B. On the accuracy of turbulence models for CFD simulations of vertical axis wind turbines. *Energy*. 2019;180:838-857.
46. Rezaeiha A, Montazeri H, Blocken B. Towards accurate CFD simulations of vertical axis wind turbines at different tip speed ratios and solidities: guidelines for azimuthal increment, domain size and convergence. *Energy Convers Manage*. 2018;156:301-316.
47. Zhixi L, Shuangkui D. *Experimental Optimization Design and Statistical Analysis*. Beijing, China: Science Press; 2010.
48. Jacobs EN, Sherman A. Airfoil section characteristics as affected by variations of the Reynolds number. *Tech Rep Arch Image Library*. 1937;8(2):286-290.
49. Kui C. *Experimental Design and Analysis*. Beijing, China: Tsinghua University Press; 2006.
50. Lijun Z, Xinhui Z, Hanxiang W, et al. Research on real-time high-efficiency angle of attack adjustment method for H-type vertical axis wind turbine. *J Mech Eng*. 2018;54(10):173-181.
51. Lijun Z, Xinhui Z, Dongchen M, et al. Research on vertical shaft wind turbine resistance type support rod. *Chin Mech Eng*. 2017;28(12):1449-1455.

How to cite this article: Zhang L, Gu J, Hu K, et al. Influences of trailing edge split flap on the aerodynamic performance of vertical axis wind turbine. *Energy Sci Eng*. 2021;9:101–115. [https://doi.org/10.1002/ese3.818]