Numerical simulation of wind farm flow field

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Abstract. Because of its high accuracy can be achieved and can reduce the gold investment, CFD calculations are widely used in wind farm construction projects. This paper uses the solver buoyantBoussinesqSimpleFoam of the open CFD software OpenFOAM to simulate the wind farm. First, we use the flat terrain and homogeneous Atmospheric Boundary Layer (ABL) flow, corresponding to the atmospheric boundary layer of a neutral state, stable state and unstable state was established three groups of numerical simulation models to correctness of the models. The results show that the three models used in this paper have ideal simulation results for the atmospheric boundary layer, and can accurately calculate the atmospheric boundary layer containing temperature and buoyancy effects. By comparing the calculation results of Askervein Mountain and Bolund Island with the experimental data, it is found that: The calculation model and solver used in this paper can better calculate the wind resource distribution under complex terrain conditions, and the calculation results are accurate, which is in good agreement with the experimental values.

1. Introduce

In recent years, with the continuous developing of wind power development and utilization, wind energy has become the fastest growing renewable energy source. In the basic work of wind farm construction, wind resource assessment is an extremely important part. The assessment of wind resources is directly related to the overall benefits of wind farms and economic indicators. With the rapid development of the wind power industry, more and more complex terrain has begun to attract the attention of builders. How to accurately evaluate the wind resources of these complex terrains has become a research topic for many researchers at home and abroad. So far, the main research methods for the distribution of wind resources in complex terrain are divided into two major methods: wind tunnel experiment and numerical research. Due to the huge capital required for wind tunnel experiments and the difficulty of wind tunnel construction for wind farm research, computer technology has developed rapidly in recent years, numerical simulation has become the most common and effective means of wind resource assessment. Numerous studies have shown that the mesoscopic simulation method is the most effective, economical and reasonable method in dealing with engineering problems. Among them, the longest use time and the most accumulated experience are the mixed length model and the \( k - \varepsilon \) model.

This paper uses the Boussinesq Approach-based buoyantBoussinesqSimpleFoam solver, which involves the temperature field and the buoyancy field in the open source software OpenFOAM. Uses the \( k - \varepsilon \) turbulence model with wall functions, performs CFD calculations on a uniform, constant
atmospheric boundary layer.

Firstly, the CFD simulation calculation of flat terrain is carried out to verify the correctness of the model and solver used in this paper. Then, through the CFD simulation calculation of Askervein Moutain and Bolund Island, and comparing the calculation results with the actual wind measurement results, the rationality of the model used in this paper is further verified.

2. Research on numerical model of flat terrain based on OpenFOAM

There are a large number of fluid-related phenomena in nature and engineering. All these fluid-related motion processes follow basic physical laws such as mass conservation, momentum conservation, and energy conservation [1]. For the problem of fluid flow, three methods are currently used for research: theoretical analysis, experimental test, and computational fluid dynamics (CFD method). With the development of computers and the superiority of the CFD method itself, the CFD method has become a powerful tool for solving various fluid flow problems and heat transfer problems. At present, the commonly used numerical simulation methods include direct numerical simulation, large eddy simulation and Reynolds time-average simulation [1].

Under different atmospheric stability conditions, that is, when the atmospheric boundary layer is in a neutral state, the steady state and the unstable state, the atmospheric boundary layer flow is fully developed. In flat terrain, the velocity gradient in the flow field should be zero or close to zero along the flow direction at the same height [2]. In wind field simulation, CFD simulation of flow fields in complex terrain must be based on accurate simulation of horizontal atmospheric boundary layer flow along the direction of fluid flow [3].

2.1. Numerical model

The Reynolds time-averaged N-S equation is solved using the buoyant Boussinesq SimpleFoam solver in OpenFOAM. The turbulence model is a standard $k-\varepsilon$ turbulence model with wall functions. The Neutral model, the Stable model and the Unstable model are respectively established for the neutral state, the steady state and the unsteady state of the atmospheric boundary layer. The computational domains of the three sets of models are all set to simple cuboids. The airflow flows in from the inlet at the front end and exits at the outlet at the end.

2.1.1. Boundary conditions.

- First, set the boundary conditions of the inlet velocity, the turbulent kinetic energy, the turbulent dissipation rate, and the temperature of the Neutral model, the Stable model, and the Unstable model fluid flow according to the following formula:

\[ U = \frac{U_*}{\kappa} \ln \frac{z - z_{\text{Ground}} + z_0}{z_0} \]  
\[ k = \frac{U_*^3}{\sqrt{C_p}} \sqrt{C_1 \ln \frac{z - z_{\text{Ground}} + z_0}{z_0} + C_2} \]  
\[ \varepsilon = \frac{U_*^3}{\kappa(x + z_0)} \sqrt{C_1 \ln \frac{z - z_{\text{Ground}} + z_0}{z_0} + C_2} \]  
\[ T = T_{\text{Ground}} - \Gamma(z - z_{\text{Ground}} + z_0) \]

Where $z_0$ is the surface roughness length, $z_{\text{Ground}}$ is the altitude of the entrance ground, $T_{\text{Ground}}$ is the surface air temperature, $\Gamma$ is the air temperature dry adiabatic decline rate, $\Gamma$=9.8 K/km. Where $C_1$ and $C_2$ are determined by:

When $z - z_{\text{Ground}} = 0$, the turbulent energy is the largest, thus determining the value of $C_2$; When $z - z_{\text{Ground}} = H$, the turbulent energy tends to 0, where the value is 0.0001, thus
determining the value of $C_1$. Where $H$ is the atmospheric boundary layer thickness, here the calculated domain height.

The Stable model:

$$U = \frac{U_*}{\kappa} \left( \ln \frac{z}{z_0} + 4.7 \frac{z - z_0}{L} \right)$$  \hspace{1cm} (5)$$

$$T = \frac{\theta}{-\frac{p_0}{P_0} \frac{z-1}{z}}$$  \hspace{1cm} (6)$$

In the middle: $\theta = \theta_* - \frac{\sigma_r \rho \kappa U_*}{C_r \rho \kappa U_*} \left( \ln \frac{\frac{z}{z_0}}{\frac{z - z_0}{H}} \right)$

The turbulent kinetic energy and turbulent dissipation rate are consistent with those selected by the Neutral model.

The Unstable model

$$U' = \frac{U_*}{\kappa} \left( \ln \frac{z}{z_0} + \ln \left( \frac{(n_0^2 + 1) (n_0 + 1)^2}{(n_1^2 + 1) (n_1 + 1)^2} + 2(\tan n_1 - \tan n_0) \right) \right)$$  \hspace{1cm} (7)$$

In the middle: $n_0 = (1 - 15 \frac{z}{L})^{0.25}$, $n_1 = (1 - 15 \frac{z}{L})^{0.25}$

The turbulent kinetic energy and turbulent dissipation rate are consistent with those selected by the Neutral model. The temperature model is identical to that chosen for the Stable model.

- For the outlet of the fluid flow in the calculation domain, the boundary condition of the velocity is set to inletOutlet, and the exit boundary condition of the turbulent energy, turbulent dissipation rate, and temperature is set to zeroGradient.
- The boundary conditions on both sides of the calculation domain are set to slip.
- The top boundary condition of the calculation domain is set to slip.
- The bottom temperature boundary condition is set to turboblendHeatFluxTemperature. The bottom speed is set to 0.

2.1.2. Model parameters. According to the review of relevant literature and actual simulation calculation, under a set of three different atmospheric stability conditions, a set of basic parameters are selected for CFD simulation of flat terrain, and are listed in table 1.

| Basic parameters | Neutral | Stable | Unstable |
|------------------|---------|--------|----------|
| $T_0$            | 293     | 293    | 293      |
| $L$              | $\infty$ | 300    | -2000    |
| $q_w$            | 0       | -20.5  | 3.7      |
| $T_r$            | 293     | 294    | 293      |
| $U_*$            | 0.4131  | 0.4131 | 0.4131   |
| $H_{ref}$        | 10      | 10     | 10       |
| $U_{ref}$        | 6       | 6.01   | 5.8      |
| $z_0$            | 0.03    | 0.03   | 0.03     |

2.1.3. Analysis of calculation results. The velocity distributions of the three models in the height direction on the x=10, x=490, and x=990 planes are respectively taken as shown in Figure 1, Figure 2,
and Figure 3. It can be seen from the figure that the calculation results of the three models Netural, Stable and Unstable agree well along the flow direction velocity profile. All three models can well simulate the flat boundary atmosphere boundary layer. Among them, the speed profile of the Netural model is better, and the simulation results are ideal.

Figure 1. The calculation results of Neutral model.

Figure 2. The calculation results of Stable model.

Figure 3. The calculation results of Unstable model.

3. Numerical simulation of Askervein Mountain

3.1. Introduction to Askervein Mountain
The Askervein Mountain is 116 m above sea level and is located on the west coast of South Island, Scotland. The vegetation on the surface of the mountain is mainly low shrubs and grasslands. The Askervein Mountain is blowing southwest wind all the year round. The Askervein Mountain wind test data was released in 1983 and 1985. Because the Askervein Mountain itself is relatively simple in terrain and the measurement data is complete, the Askervein Mountain wind test data has become the field measurement data commonly used in atmospheric boundary layer flow CFD calculation. The Askervein Mountain wind test was conducted from September 1982 to October 1983. The data used in this paper is the experimental data of TU-03B. In the text, the lineA line is 10m from the ground and passes through the point HT. The wind measurement points on the lineA line are numbered along the positive direction of the x-axis: 1, 2, 3, 4, 5, HT, 6, 7, 8 [4-7]. The lineHT is the vertical line where the HT point is located. The HT is the highest point of the Askervein Mountain.

3.2. Computational domain and grid
The height of the calculation domain in the Z direction is 1500 m. The mesh in the X and Y directions is 40 m×40 m, the mesh extension ratio in the Z direction is 1.06, the first layer mesh is 3.5 m high, and the total number of meshes is 757900. Since the map source file has been oriented, the X-axis
direction is 210°N, which is consistent with the average wind speed flow direction [1]. The ground grid is shown in figure 4.

![Figure 4. The ground grid of Askervein Mountain.](image)

3.3. Calculation method and boundary conditions
The turbulence model set as the standard k-e turbulence model with wall functions. Select the Neutral model with better simulation results above and use the buoyantBoussinesqSimpleFoam solver for simulation calculation. The boundary conditions are exactly the same as the Neutral model under the flat terrain above, Where $U_*$=0.6183, $\kappa$=0.4. Because the upper reaches of the Askervein Mountain are about 3m above sea level, and the terrain is flat, we set the value of $Z_{Ground}$ to 3 and the solid wall to rough wall with a rough length $Z_*=0.03$.

3.4. Analysis of calculation results
To facilitate the analysis, we introduce the dimensionless parameters speedup and $k^*$, where: 
\[
\text{speedup} = \frac{(U - U_{in})}{U_{in}}, k^* = \frac{k}{U^2}
\]
where $U_{in}$ is the wind speed at the corresponding ground level at the entrance to the calculation domain. Figures 5 and 6 compare the simulation results of the dimensionless parameters speedup and $k^*$ on the lineA line with the wind measurement experimental results; figures 7 and 8 compare the simulation results of the dimensionless parameters and $k^*$ on the HT line with the wind measurement results.

Analysis of figure 5 shows that the analog value curve along the lineA line speedup is consistent with the measured value trend. The simulation results are in good agreement with the measured results, and the CFD calculation results for the wind speed on the lineA line are accurate.

Analysis of figure 6 shows that the analog value curve of the dimensionless parameter $k^*$ along the lineA line is consistent with the measured value trend. It can be seen from the figure that the errors of the two points of 7 and 8 are large, and the other simulation results of 1, 2, 3, 4, 5, HT and 6 are ideal. In general, the CFD simulation results of the turbulent kinetic energy agree well with the measured results, especially for the curve matching in the region suitable for wind turbine layout.

![Figure 5. Comparison of measured and simulation speed up along the lineA.](image)

![Figure 6. Comparison of measured and simulation $k^*$=k/u^2 along the lineA.](image)
Analysis of figure 7 shows that the analog value curve along the line HT speedup is consistent with the measured value trend. In addition, through the analysis of the simulation results, it is found that: the position of 40 m and above is more in line with the installation requirements of wind turbines, because at a position below 15 m, the change of wind speed along the height direction is obvious, that is, the wind shear is large, at 40 m and above, the wind shear is small and the wind speed is large.

Analysis of figure 7 shows that the analog value curve of the dimensionless parameter $k^*$ along the line HT line is consistent with the measured value trend. There is a certain deviation between 15 m and above. Since the expression of $k^*$ contains the simulation result of wind speed, the CFD result of wind speed will have some influence on $k^*$. For example, in figure 7, the simulation values of the three measurement points of 15 m height and above are smaller than the measured values, and in figure 8, the simulation results of the introduction speed of the dimensionless parameter $k^*$, the simulation values of the three measurement points of 15 m height and above are larger than the measured values.

4. Bolund Island numerical simulation

4.1. Bolund Island wind test
The Bolund Island wind test was conducted from the end of 2007 to the beginning of 2008 and received a large amount of reliable experimental data.

The west side of Bolund Island is a steep cliff. Except for the cliff wall, the surface of the island is covered by dwarf grass, and there is no vegetation growth on the cliff wall. The 10 wind towers in figure 9 are numbered according to 0~9, where M0 and M9 are used to measure the basic parameters such as the wind speed of the east and west [8]. We set the boundary conditions of the model inlet wind speed according to the measurement data of M9. We set the boundary conditions of the model inlet wind speed according to the measurement data of M9.

Figure 9. The location of 10 wind tower on the island of Bolund.
4.2. Numerical calculation model

This chapter selects the wind condition of east wind (90°). See table 2 for basic parameters. M0 is installed on a platform on the seabed. Due to factors such as sea waves on the sea surface, the height data measured by M0 is not fixed. The sea level is unified to 0.75 m. The land surface roughness length is set to 0.015 m. The rough surface length of the sea surface is set to 0.0003 m.

The calculation domain is selected as ((-400, -250) (400, 250)), and the height in the vertical direction is 500 m. Select the Neutral model described above for calculations. The reference temperature is set to 288 K.

| Case         | wind direction [°] | z0[m] | U-[m/s] |
|--------------|--------------------|-------|---------|
| East wind    | 90                 | 0.015 | 0.509   |

Table 2. Simulated case.

4.3. Calculation results

Along the lineB, the calculated data at the heights of 2 m and 5 m in the vertical direction are selected and compared with the measured data.

It can be seen from figures 10 and 11 that the CFD calculation results are consistent with the trend of the measured values. Due to the relatively flat land surface on the eastern side of Bolund Island, the wind speed increases at a certain distance from the front of Bolund Island. When the wind flows through the M8, it is affected by the sudden increase of the terrain, and the speed at the M8 at the foot of the mountain reaches a minimum. When the wind flows through Bolund Island, the wind speed changes more gently, and the wind speed curve is consistent with the topographic trend of Bolund Island. Observing the wind speed curve before and after passing through Bolund Island, the simulation results are ideal.

![Figure 10](image1.png)  
**Figure 10.** Simulation results along the height of 2 m lineB.

![Figure 11](image2.png)  
**Figure 11.** Simulation results along the height of 5 m lineB.

5. Conclusion

In this paper, the wind field flow field under flat terrain and actual complex terrain is numerically simulated using OpenFOAM's buoyantBoussinesqSimpleFoam solver. After verifying that the numerical calculation model of the wind farm based on OpenFOAM can accurately simulate the neutral atmospheric boundary layer, the stable atmospheric boundary layer and the unstable atmospheric boundary layer, the Neutral model is selected for the actual terrain of Askervein Mountain and Bolund Island. The wind resource distribution was simulated, the Neutral model was selected to simulate the wind resource distribution of the actual terrain of Askervein Mountain and Bolund Island. Based on the above research content, this paper mainly draws the following conclusions:

- The three models used in this paper have ideal simulation results for the atmospheric boundary
layer, and can accurately calculate the atmospheric boundary layer containing temperature and buoyancy effects. The simulation results in the Neutral model are more accurate.

- By comparing the calculation results of Askervein Mountain with the experimental data, it is found that: The calculation model and solver used in this paper can better calculate the wind resource distribution under complex terrain conditions, and the calculation results are accurate, which is in good agreement with the experimental values.
- By comparing the wind measurement data of the Bolund Island wind measurement experiment with the CFD calculation results of Bolund Island, the practicality of the CFD solution tool and calculation model selected for the wind field distribution of complex terrain wind field is further verified.

6. Outlook
In this paper, the CFD calculation model of wind farm flow field based on OpenFOAM is analyzed and studied in detail, which basically determines the practicability and accuracy of the calculation model and solver used in this paper for wind farm flow field under complex terrain conditions. However, through the CFD simulation and analysis of Askervein Mountain and Bolund Island, it is found that the accuracy of the simulation results within a certain distance above the highest point of the calculation domain is insufficient. The simulation results after the mountain are slightly insufficient compared to the mountain front. In the future work, the buoyantBoussinesqSimpleFoam solver should be studied in more depth to improve the accuracy of CFD simulations at the highest point of the calculation domain and behind the mountain.

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