Study of Invelox Wind Turbine Considering Atmospheric Boundary Layer: Based on Numerical Simulation

Li Ding*
National Environmental Protection Research Institute for Electric Power, Nanjing, China

*Corresponding author e-mail: dingli_18@126.com

Abstract. The flow field characteristics of increased velocity (Invelox) system under different wind direction were studied by computational dynamic fluid (CFD) method. Since the Invelox wind turbine system needs to be placed in external space to operate, the atmospheric boundary layer (ABL) wind profile must be considered. The Invelox system was simulated with uniform velocity inlet and exponential wind profile inlet. The results show that when the wind direction is more than 90 degrees from the axis of the venturi pipe, the power generation efficiency of the system will decrease sharply. When the Angle exceeds 120 degrees, the system does not generate electricity. After considering ABL, the speed ratio (SR) of the system will decrease.

Keywords: CFD; Invelox; ABL; SR.

1. Introduction
Wind energy is rich in resources, widely distributed, clean, renewable and locally available. Reasonable development and utilization of wind energy can effectively alleviate energy shortage and environmental pollution. According to the report of the Global Wind Energy Commission, the total installed capacity and annual installed capacity of wind turbines in the world are gradually increasing [1]. According to the data from the national energy administration, by the end of 2018, China's wind power added 20.59 million kilowatts of grid connected capacity in the same year, with a total capacity of 184 million kilowatts, up 12.4% year on year. Among them, the installed capacity of wind power of national energy group is 38.29 million kilowatts, ranking first in the world, and China's wind power has moved towards large-scale development and commercial development.

However, although the development of wind turbine is very rapid, the energy conversion efficiency of wind turbine is always low due to the constant changes of environmental wind speed and wind direction, and it can not provide very stable electric energy. In order to improve the energy conversion efficiency of wind turbines, scholars have proposed a variety of wind turbines. In order to improve the energy conversion efficiency of wind turbines, scholars have proposed a variety of wind turbines [2-6].

According to its structure, the traditional wind turbine can be divided into horizontal axis wind turbine and vertical axis wind turbine. The wind energy capture efficiency of horizontal axis wind turbine is high, but when the wind direction changes, the yaw mechanism is needed to adjust the wind turbine, which has reached the best working condition. Vertical axis wind turbine can accept wind in any direction and convert it into electric energy, but the conversion efficiency is low.
Allaei et al. [7] designed a wind turbine system called Invelox, which can collect wind from any direction into the pipeline, and install horizontal axis wind turbine in the pipeline, so as to realize wind power generation. Figure 1 shows the Invelox wind turbine system presented by Allaei et al [7].

Figure 1. The Invelox wind turbine system proposed by Allaei et al. [7]

One of the advantages of Invelox is that it can capture wind from all directions without any yaw mechanism [8, 9]. Allaei et al. found that the airflow velocity in the Venturi section of the Invelox wind turbine system can reach twice of the ambient wind speed through measurement and numerical simulation research [10, 11]. Anbarsooz et al. [12] numerically studied the main effective geometrical parameters of Invelox, including the inlet area, diameter of the Venturi section and the height of the funnel. Their results showed that at a certain inlet area, the most important parameter which affects the Invelox SR is the Venturi diameter. After that, Anbarsooz et al. [13] optimized the Invelox wind turbine by adding partition. The results show that the wind speed in the Venturi section can be increased about 25% by increasing the diaphragm. Meanwhile, when the wind direction and the axis of the venturi exceed 90 degrees, the acceleration ratio of the Invelox system will decrease sharply.

In the above research on Invelox wind turbine, the velocity entrance is a uniform velocity field, but the wind turbine must be placed in the atmospheric environment to have practical significance. However, in the real atmospheric environment, the wind is not evenly distributed, but gradient distribution, which is the wind profile, and the ABL should be considered. Sotoudeh et al. [14] investigated the performance of Invelox wind turbine (IWT) in Sistan plain by a finite volume code and field tests. It was revealed that by increasing the assemble height from 10 to 40 m, the output power rises by 87.5%, while the power acoustic level increases by 39.3%. Unfortunately, they did not calculate the performance of wind turbines in all wind directions.

In this study, numerical simulation will be used to calculate the acceleration ratio of Invelox wind turbine system in different wind directions, taking into account the influence of the atmospheric boundary layer.

2. Numerical model

2.1. Geometry
The Invelox wind turbine system has been introduced by Allaei et al [7]. Figure 2 shows the geometry of the Invelox wind turbine system. The main dimensions of the model are consistent with those provided by Allaei et al. [7] and Anbarsooz et al. [13], but local (especially the curve at the entrance) may not be consistent.

2.2. Mesh
The quality of the mesh plays a significant role in the accuracy and stability of the numerical computation. The computational mesh shown in Figure 3 is composed of 1.36 million tetrahedral cells.
2.3. Boundary conditions
In the studies presented by Anbarsooz et al. and Allaei et al., the velocity inlet boundary was uniform, 6.7 m/s. The ground and lateral faces are slip walls. However, when considering ABL, the ground and the surface of cooling tower were assumed to be no-slip and adiabatic boundary conditions. The boundary conditions at the leeside of the computational area was the pressure outlet; the boundary condition of windward side was the velocity inlet, with the form defined as:

\[ U(z) = U_r \left( \frac{z}{10} \right)^\alpha, \]  

Where \( z \) is height. In this study, \( U_r = 4 \) m/s was the velocity at the referred height (10 m), and the wind profile index \( \alpha \) was assumed as a typical value of 0.2. The turbulent kinetic energy \( k \) and the turbulent dissipation rate \( \varepsilon \) were set following the guidelines provide by Tominaga et al. [15]

3. Model Validation
Figure 4 is a comparison of the calculation results with those of Anbarsooz et al. [13]. It can be seen that the velocity ratio distribution in the two figures is basically the same. In order to reduce the error as much as possible, the grid type, the number of grids, the size of the computing domain and the related software settings used in this paper are consistent with the references. There is a certain difference in the maximum value, which is mainly due to the inconsistency between the two models.
4. Results and discussion

The angle between the air flow direction and the center line of the venturi is shown in Figure 5. Figure 6 shows the change of SR to wind Angle. It can be seen that when the wind Angle exceeds 90 degrees, the SR will deteriorate sharply. When the wind Angle exceeds 120 degrees, the SR becomes directly negative, meaning that the wind is flowing backwards from the outlet of the Invelox system into the venturi tube. At this point, the Invelox system was unable to generate electricity. This means that the system is not able to generate electricity from any wind direction.

It can also be seen from the figure that SR decreases after ABL is taken into account. This is not only the case with a small wind Angle, but also when the wind Angle exceeds 120 degrees. This is because, after considering ABL, the Invelox system has a higher air inlet and a lower air outlet, the ambient wind speed at the inlet is greater than the outlet. Therefore, the influence of ambient wind on the air outlet is not as great as that under uniform incoming flow (ABL is not considered).

Figure 7 is the velocity vector diagram in the symmetric plane. It can be clearly seen that, regardless of the velocity inlet boundary condition, the airflow velocity in the venturi tube can gain a good gain when θ=0°. When θ=180°, the flow in the venturi tube moves in the opposite direction to the design value, and the Invelox system fails to generate electricity. When you consider ABL, this situation is much less severe.
5. Conclusion

Invelox wind turbine system is a new type of wind turbine device. The device can collect air flow from all directions and generate accelerating air flow through venturi tube. In this paper, the acceleration ratio of air flow in different wind directions is studied by means of numerical simulation. When the angle between the air flow direction and the center line of the venturi exceeds 90 degrees, the acceleration ratio will deteriorate rapidly. When the angle between the air flow direction and the center line of the venturi exceeds 120 degrees, the air flow direction in the venturi will change. At this time, Invelox system cannot provide effective airflow for wind turbine. After considering the atmospheric boundary layer, the acceleration ratio will be smaller. Similarly, when the angle between the air flow direction and the center line of the venturi exceeds 90 degrees, the acceleration ratio will deteriorate sharply. However, the degree of deterioration is less than that without considering the atmospheric boundary layer.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (grant number 11872212), Natural Science Foundation of Jiangsu Province (grant number BK20190386) and Science and technology project of Guodian Science and Technology Research Institute (grant number HB2020Y07).

References

[1] Global Wind Report: Annual Market Update 2014[R]. Global Wind Energy Council, 2014.
[2] Sørensen JD. Aerodynamic aspects of wind energy conversion. Annu Rev Fluid Mech 2011;43(1):427-48.
[3] Aslam Bhutta MM, Hayat N, Farooq AU, Ali Z, Jamil SR, Hussain Z. Vertical axis wind turbine: a review of various configurations and design techniques. Renew Sustain Energy Rev 2012;16(4):1926-39.
[4] Akwa JV, Vielmo HA, Petry AP. A review on the performance of Savonius wind turbines. Renew Sustain Energy Rev 2012;16(5):3054-64.
[5] Shukla V, Kaviti AK. Different analysis on wind turbine blade: a review. Int J Sci Res Dev 2015;3(09).
[6] Walker SL. Building mounted wind turbines and their suitability for the urban scaleda review of methods of estimating urban wind resource. Energy Build 2011;43(8):1852-62.
[7] Allaei D, Andreopoulos Y. INVELOX: description of a new concept in wind power and its performance evaluation. Energy 2014;69:336-44.
[8] Allaei D, Turbine-intake tower for wind energy conversion systems, Google Patents, 2010.
[9] Allaei D, Power generating skin structure and power generation system therefor, Google Patents, 2010.
[10] Allaei D. Using CFD to predict the performance of innovative wind power generators. In:
Proceedings of the 2012 COMCOL conference, Boston, USA; 2012.

[11] Allaei D, Tarnowski D, Andreopoulos Y. INVELOX with multiple wind turbine generator systems. Energy 2015;93(Part 1):1030-40.

[12] Anbarsooz M, Hesam MS, Moetakef-Imani B. Numerical study on the geometrical parameters affecting the aerodynamic performance of Invelox. IET Renew Power Gener 2017;11(6):791-8.

[13] Anbarsooz M, Amiri M, Rashidi I. A novel curtain design to enhance the aerodynamic performance of Invelox: A steady-RANS numerical simulation. Energy 2019;168:207-221.

[14] Sotoudeh F, Kamali R, Mousavi SM. Field tests and numerical modeling of INVELOX wind turbine application in low wind speed region. Energy 2019; 181:745-759.

[15] Tominaga, Y.; Mochida, A.; Yoshie, R.; Kataoka, H.; Nozu, T.; Yoshikawa, M.; Shirasawa, T. AJJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. J. Wind Eng. Ind. Aerodyn. 2008, 96, 1749–1761.