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Effects of rain on vertical axis wind turbine performance

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ABSTRACT

The ambient atmospheric environment significantly affects the performance of wind turbines operating in different meteorological conditions. As rain is a common meteorological condition, the understanding of rain effects on the performance of wind turbines can be helpful in selecting a proper site for a new wind farm. This paper comprehensively investigates the effects of rain on a NACA 0015 airfoil, which is commonly used in VAWTs (vertical axis wind turbines). A two-way coupled Eulerian-Lagrangian multiphase approach is proposed to study the rotating and oscillating performances of the NACA 0015 airfoil in rainy conditions. It is found that the VAWT performance can seriously be deteriorated in different rain conditions. Following is an exploration of the potential physics behind the interaction between the raindrop and the airfoil. Finally, the dimensional influence on evaluating rain effects on the wind turbine performance is investigated.

1. Introduction

With a great deal of consumption of non-renewable energy nowadays, there is an increasing need to make use of the renewable energy resources, such as wind, tide and solar energies. The renewable energy generators produce few harmful emissions compared to many other generation sources of fossil fuel. As renewable energy is environment friendly, energy from these resources is also called clean or green energy. Therefore, researchers from all over the world have been engaged in development and improvement of the renewable energy. Among the various kinds of renewable resources, wind energy is a popular one that has been widely developed especially in the plateau and coastal regions all over the world. Wind energy is extracted by wind turbines to generate energy. Wind turbines are classified into HAWT (horizontal axis wind turbine) and VAWT (vertical axis wind turbine) based on the direction of rotation axis, as shown in Fig. 1. HAWT is better suited for large-scale energy generation while VAWT is suitable for small-scale and micro-scale energy generation (Mclaren, 2011; Mohamed, 2013). Due to its characteristics of convenience of installment and off-the-grid energy generation, VAWT plays a critical role in wind power.

Rain is a very common meteorological condition in the nature but has been extensively proved to have various adverse effects in many industrial application fields. For example, rain-induced loads can pose undesirable displacements and vibrations on transmission tower-line systems (Fu and Li, 2016) and inclined cables of cable-stayed bridges (Taylor and Robertson, 2011). Rain impact on aircraft lifting surfaces can decrease the aerodynamic lift reduction and increase the drag (Cao et al., 2014). Rain water can cause erosion in the surfaces of wind turbine blades (Amirzadeh et al., 2017a, 2017b) and buildings (Erkal et al., 2012), etc. Particularly in the wind turbine field, as wind turbines usually work in an open condition, their performance can inevitably be influenced by the ambient atmospheric environment like rain. Despite this, a very limited research work is available in the literature on rain effects on wind turbine performance. Most of the existing studies involving rain effects have been done for aviation applications (Hansman and Craig, 1987; Douvi et al., 2013a; Wan et al., 2013; Yue et al., 2016a, 2016b; Wan et al., 2016; Ismail et al., 2014a, 2014b, 2014c; Wu et al., 2013; Wu and Cao, 2015, 2016; Douvi et al., 2013b). The major findings can be summarized as follows: (1) Rain can induce a decrease of lift and an increase of drag for an airfoil in rain. (2) A laminar airfoil suffers more severe performance penalty in rain than a turbulent airfoil. (3) As raindrops impinge an airfoil, some are splashed back and accelerated by the air, which is hypothesized to decelerate the boundary layer. (4) The rest of the incident raindrops form a thin water film upon the airfoil surface. The film is impacted by the subsequent raindrops, which causes many craters and

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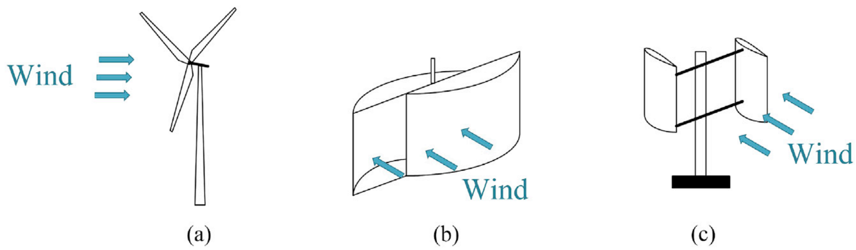

Fig. 1. Wind turbine: (a) HAWT; (b) drag type VAWT; (c) lift type VAWT.

results in an uneven film that effectively roughens the airfoil surface and increases the drag.

Although rain has also been found to induce remarkable power losses to wind turbines since the 1980s (Corrigan and DeMiglio, 1985), not enough attention has been paid until recently some scholars published their research achievements regarding rain, which redrew people's attention to the effects of rain on wind turbine performance. Al et al (Al et al., 2011). found that the wind speed, the voltage, the optimal tip speed, the maximum power conversion coefficient and the torque coefficient are all reduced while the drag is increased in rain. They concluded that the increase in the drag force would be expected due to a roughening of the surface by the droplet adhesion on the surface. This is similar to the conclusions from that found in the aviation research. Arastoopour's (Cai et al., 2012) group analyzed the performance of a HAWT airfoil in rainy conditions using a multiphase CFD (computational fluid dynamics) approach and found that the lift is reduced and the drag is increased when rain is introduced at most of the AOAs (angles of attack), thus causing a decrease in the lift-to-drag ratio. The results show a significant degradation of the airfoil performance due to film formation. Their follow-on study (Cohan and Arastoopour, 2016) found that at low rainfall rates, the airfoil performance is highly sensitive to the rainfall rate. In brief, all of the existing studies suggest that rain can significantly degrade wind turbine performance. Therefore, there is an urgent need for further studies of wind turbine performance in rainy conditions.

The current issue is essentially within the regime of multiphase flow. Each phase in a multiphase flow can be categorized as either a continuous phase or a discrete phase. Currently there are two approaches for numerical simulation of multiphase flows, i. e., the Eulerian-Eulerian approach and the Eulerian-Lagrangian approach (Wu and Cao, 2015). The Eulerian-Eulerian approach treats all the phases as interpenetrating continua and solves the continuum conservation equations for each phase. Interphase exchanges of mass, momentum and energy are included as source terms in the appropriate conservation equations. This approach is more easily implemented for particles of a uniform size. While the Eulerian-Lagrangian approach solves the continuum conservation equations for the continuous phases and integrates the Lagrangian equations of motion for the discrete phases, which is also called Discrete Phase Model (DPM) approach. There are two models including a one-way coupled model and a two-way coupled model in the Eulerian-Lagrangian approach. The one-way coupled model assumes that particle motion is affected by the continuous phase but the continuous phase is not affected by the dispersed particle phase. The two-way coupled model considers the two-way exchanges of mass, momentum and energy between the two phases.

In this study, an Eulerian-Lagrangian CFD approach is proposed to simulate the performance of a NACA 0015 vertical axis wind turbine airfoil in rainy conditions. Lift and drag coefficients have always been adopted to evaluate rain effects in most of the previous studies. As tangential force is responsible for the power produced by VAWTs, it is also focused on in this study. Initially, a single-phase CFD simulation is performed on a static airfoil and a rotating rotor to validate the single-phase model against the experimental data. Afterwards, the model is used as a baseline to simulate the NACA 0015 airfoil in the cases of quasi-steady revolution and dynamic oscillation in the presence of rain.

2. Methodology description

2.1. Force analysis

As shown in Fig. 2, the tangential velocity (V_t) and normal velocity (V_n) for a VAWT blade can be written as (Islam et al., 2008)

$$V_t = U(\lambda + \cos\theta) \tag{1}$$

$$V_n = U\ \sin\theta \tag{2}$$

where U is the induced velocity and can be assumed to be equal to the air freestream velocity (U_∞) provided there is no flow restriction, $\lambda = \omega R/U_\infty$ is the tip speed ratio, θ is the azimuthal angle, and ω is the angular rate.

Thus the effective wind velocity (V) and angle of attack (α) can be written as

$$V = \sqrt{V_t^2 + V_n^2} \tag{3}$$

$$\alpha = \arctan\frac{V_n}{V_t} \tag{4}$$

In most researches on rain, lift coefficient (C_L) and drag coefficient (C_D) are the two common parameters selected to evaluate the aerodynamic performance in rain, which are defined respectively as:

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 c} \tag{5}$$

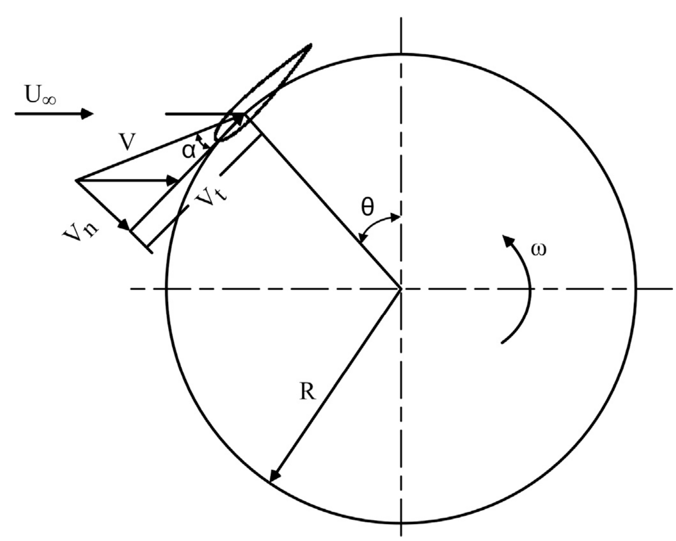

Fig. 2. Force relationship for a vertical axis wind turbine.