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Numerical and experimental investigation of threshold de-icing heat flux of wind turbine

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ABSTRACT

Cold region wind turbines are highly likely to lose their aerodynamic efficiency and power production due to icing problems. Electro-thermal anti/de-icing systems have been consequently developed to eliminate ice accretion on wind turbine blades. As an important index of cost-efficiency, the threshold de-icing heat flux of these systems always attracts a lot of attention. Unlike most of previous calculation methods, this article proposed a numerical approach to determining the threshold de-icing power density by computing the loose-coupled fluid field and temperature field. Meanwhile, in order to provide essential ice shape and corresponding validation for the model, icing and threshold de-icing experiments on a customized small-scale wind turbine have been conducted. The influences of ambient temperature and wind speed have also been investigated. On-site meteorological data, which were observed by Xuefeng Mount natural icing station, are adopted in the experiments and simulations. Results of this article indicate that the numerical predictions are in good consistence with experimental values. Among all cases, the maximum fractional error is calculated to be 9.3%. The ambient temperature is found to have a great impact on required power density. But the influence of wind speed is believed to have a foreseeable upper limit.

1. Introduction

Cold regions always spark a great interest for wind farms because their higher air density will bring in an approximate 10% increment of wind power production (Fortin et al., 2005; Han et al., 2012). Although cold-climate wind turbines have their advantages in power production, their blades are prone to suffer from problems that caused by extreme environments. One of the major problems is ice accretion. Even small amounts of ice accretion on the leading edge will have a great impact on the aerodynamic performance of wind turbine blades (Fakorede et al., 2016; Lamraoui et al., 2014; Kraj and Bibeau, 2010; Hu et al., 2017; Alessandro et al., 2017). In cases of extreme icing, wind turbine may loss up to 50% of its annual production due to the degradation of aerodynamic efficiency (Maissan, 2001; Wang, 2017).

Since the mid-1990s, electro-thermal anti/de-icing systems have been introduced from the aviation industry to eliminate the influence of ice accretion on wind turbine blade (Dalili et al., 2009). Anti-icing mode needs continuous heating to prevent ice from accreting on the blade while de-icing mode only requires intermittent heating to remove the ice layer from the surface (Parent and Ilinca, 2011). Considering the fact that the wind industry emphasizes more on power consumption of the systems rather than immediate effect of ice melting, wind turbine electro-thermal systems are usually operated in de-icing mode. In order to provide fundamental data support for the energy-saving design and operation of wind turbine de-icing systems, it is of great significance to figure out the minimum heat flux that allows de-icing systems to come into effect, which is called threshold de-icing heat flux.

Researches that directly focused on wind turbine de-icing or threshold de-icing problems are rarely reported in the open literature. In another word, most of related investigations have been conducted on anti-icing rather than de-icing problems because the calculation of required heat flux for anti-icing is based on clean airfoils while de-icing problems demands extra participation of unobtainable ice shapes. Mayer et al. (Mayer et al., 2007). conducted wind turbine icing/anti-icing experiments and provided useful ice shapes for further investigations. However, only forced convection heat was considered and the airfoil was taken as a flat plate when calculating the required heat flux. Fortin et al (Fortin and Perron, 2009). provided a more comprehensive anti-icing

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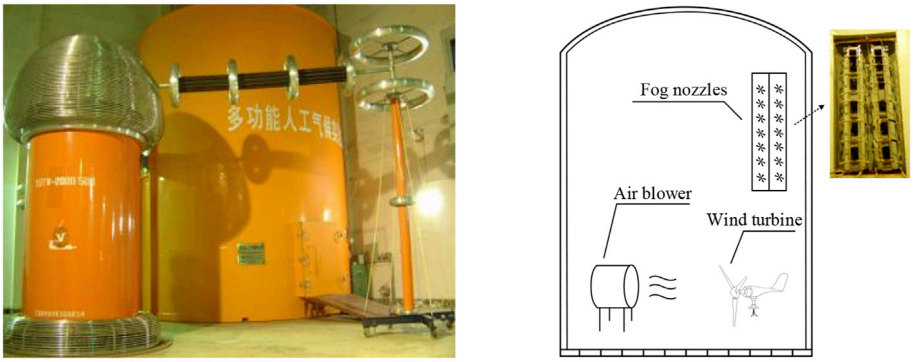

(a) Whole view (b) Fog nozzles and air blower

Fig. 1. Artificial climate chamber.

heat balance but still used a smooth flat plate equation to calculate the forced convection heat. In order to improve the calculation, Suke (Suke, 2014) and Mohseni et al (Mohseni and Amirfazli, 2013). adopted a combination of a cylinder and a flat plate to substitute the airfoil. It is obvious that taking the airfoil as basic configurations like flat plate or cylinder may simplify the problem to some extent but brings in inaccuracy at the same time. Based on the experimental data obtained by Mayer et al. (Mayer et al., 2007), Fernando et al (Villalpando et al., 2016). developed a numerical approach to predict wind turbine anti-icing heat flux. The energy was determined by calculating the latent heat of solidification of the super-cooled water droplets that captured by the airfoil. In terms of electro-thermal de-icing, Hu et al. (Hu et al., 2015). analyzed the de-icing threshold power density by following the methods in (Fortin and Perron, 2009) and (Suke, 2014), which means the influence of ice accretion was not taken into consideration. During wind turbine de-icing process, the participation of irregular ice accretions will dramatically change the flow field around the airfoil and reform the temperature distribution on the leading edge. In other words, the inaccurate method that used in anti-icing heat flux estimate will be no longer suitable for de-icing calculation.

It can be summarized from the above recent progress that the difficulties in predicting threshold de-icing heat flux mainly arises from two aspects. One is the lack of proper wind turbine icing and de-icing experiments which provides realistic ice shapes and corresponding experimental heat flux values. The other is the lack of valid numerical models which are capable of simulating the loose-coupled flow field and temperature field around the iced airfoil. Therefore, this article is going to conduct artificial icing and threshold de-icing experiments on a small-scale wind turbine and then develop a numerical approach to predicting the threshold de-icing heat flux. This model will be validated by the experimental results and the influence of variations in ambient temperature and wind speed will be investigated as well.

2. Icing and threshold de-icing experiments

2.1. Test facility and specimen

The experimental investigations were carried out in a multi-functional artificial climate chamber (Fig. 1) which has a diameter of 7.8 m and a height of 11.6 m. The temperature inside the chamber is controlled by a proportional integral differential system and can be adjusted to a minimum of - 45 ± 1 °C (Hu et al., 2016). Besides, two rows of fog nozzles customized according to IEC standard are installed in the chamber so as to produce a spray with specific median volume diameter (Hu et al., 2007). By adjusting the ratio of input water pressure and air pressure, the median volume diameter of water droplets could be controlled between 20 μm and 120 μm. An adjustable air-blower is adopted in the chamber so as to drive the wind turbine with a maximum wind speed of 10 m/s. Via the cooperation of cooling system, spraying system, and air blowing system, this chamber is capable of simulating on-site meteorological environments for wind turbine icing and de-icing.

As depicted in Fig. 2, a small-scale horizontal axis wind turbine, which has a rated output power of 100 W, is chosen as the specimen. The blades that used in these experiments are made of NACA 2408 airfoils and have a radius of 750 mm. As the most important part of this experimental setup, two of the three blades are reserved for recording experimental ice shapes. The rest one is equipped with electric heating system and temperature monitoring system. Specifically, 5*115 mm flexible polyimide-based heaters are mounted on the leading edges of both pressure and suction side of the blade, occupying 15% length of the blade. By adjusting applied voltage, the wattage density of the heaters could be increased linearly to their maximum capacity of 10 kW/m^2. In particular, the specific iced airfoil which was taken out from the centerline of the heated region is used for the following two-dimensional simulations. Corresponding geometric characteristics and operating parameters that measured during the experiments of this iced airfoil are

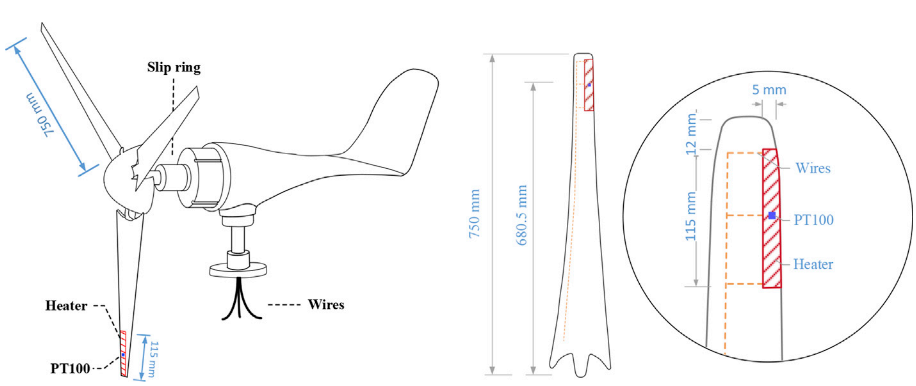

Fig. 2. Configurations of tested 100 W wind turbine and its heated blade.