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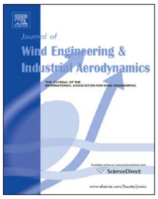

Utilizing cavity flow within double skin façade for wind energy harvesting in buildings

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ABSTRACT

Efficient wind energy harvesting by utilizing small-scale wind turbines in the urban environment requires techniques to enhance the desirable flow characteristics, including velocity magnitude and uniformity, and diminish the unfavorable characteristics, including high turbulence and intermittence. This study proposed a Double-Skin Façade (DSF) system with strategic openings to harvest wind energy in the built environment. A series of wind tunnel tests and CFD simulations have been conducted to investigate the characteristics and related mechanisms of flow within the cavity of DSF integrated with a tall building model at different incident wind angles. The discrepancy between numerical and experimental results generally remains within an acceptable range of 15% which validates the capability and accuracy of the developed CFD simulations in predicting the flow characteristics. It was found that the flow becomes more uniform while the turbulence progressively decays as flow progresses through the cavity for all wind directions. Hence the regions in the middle of both the leading and trailing sides of the cavity are favorable locations for installing small-scale, building-mounted wind turbines. Overall, the DSF system with a strategic opening can effectively enhance the flow within the cavity for a wide range of incident wind angles and can be adapted for wind energy harvesting purposes.

1. Introduction

Decentralized energy generation in the urban environment by exploiting diverse types of energy resources has the potential to supply a part of increasing energy demand and help to overcome energy crises and climate change (Ayhan and Sağlam, 2012). Energy generation at the point of use can also benefit from minimizing the energy loss due to transmission and expansion of the high voltage electricity network (Mithraratne, 2009). Due to these sustainable motivations, small-scale renewable energy technologies have gained increasing attention in the building and construction sector, and many governments have set targets for electricity generation from these renewable resources (Shafiullah et al., 2012; Yusaf et al., 2011).

Despite the low speed and high turbulence wind characteristics generally found in urban environment, an increasing trend has been observed in research and development of adaptive wind energy harvesting systems for application in the built environment. Many studies have been conducted to assess the wind resource in the urban environment and address the challenges associated with the application of wind energy harvesting systems, including low velocity and high turbulence of urban wind, building-mounting difficulties, vibration and noise problems (Drew et al., 2013; Karthikeya et al., 2016; Millward-Hopkins et al., 2013; Sunderland et al., 2013; Walker, 2011; Yang et al., 2016). The applications and techniques of wind energy harvesting and their economic and environmental benefits have been investigated and reported by Ishugah et al. (2014). Toja-Silva et al. (2013) compared suitable building-mounted wind turbines, including Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs), and potential sites around buildings have also been identified. Peacock et al. (2008) investigated the techno-economic aspects of micro wind energy generation and energy yield in the UK domestic sector. They reported a large discrepancy in the measured wind speed and power output obtained based on two data-sets within 1 km of each other. Walker (2011) reviewed existing methods for predicting urban wind speed and wind power production, and listed issues causing concern regarding the current methods for estimating

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power output of micro-scale wind turbines in the urban environment. Simões and Estanqueiro (2016) recently proposed a methodology for the assessment of urban wind resource based on the construction of a complex terrain which also includes existing adjacent buildings.

Identification of suitable locations in the built environment in and around a building which helps to efficiently exploit wind energy is an essential step to integrating wind turbine(s) to a building. Mertens (2002) described how Building Augmented Wind Turbines (BAWTs) can take advantage of concentration effect close to buildings. In addition to wind turbines installation in existing buildings, one approach being used in a number of benchmark buildings is to integrate micro wind turbines into buildings by taking advantage of architectural aerodynamic design of buildings. Bayoumi et al. (2013) developed Wind Energy Optimization Tool (WEOT) which provides recommendations to architects in the early stage of planning and enables them to estimate energy yield through the exploitation of wind energy at designated locations along the building envelope.

In general, possible locations for incorporating a wind turbine system to a building, particularly high-rise buildings, can be classified into four groups as shown in Fig. 1: (a) on rooftops, (b) in between two buildings, (c) inside through-building openings, (d) integration into building's skin.

(a) **On rooftops:** The main focus of the existing literature has been the application of wind turbines on the rooftop of buildings (Abohela et al., 2013; Lu and Ip, 2009; Toja-Silva et al., 2013, 2015; Wang et al., 2015). The main reason for rooftop installation of the wind turbines is harvesting the wind energy where the wind velocity has achieved its highest magnitude not only due the maximum elevation from the ground but also due to the amplification resulted by concentration of the bypass flow over the building. However, this idea can be undermined if a wind turbine is located below the separated shear layer created by the edge of the roof where the reversal and high turbulence flow in the separated region dramatically decrease the efficiency of the turbine.

(b) **In between two buildings**: While the studies of flow characteristics in the passages between two buildings were primarily attributed to pedestrian comfort (e.g. Blocken et al., 2008a; Blocken et al., 2008b; Li et al., 2015), a number of studies have been conducted to explore the potential of venturi effect between neighboring buildings for wind energy harvesting (Heath et al., 2007; Khayrullina et al., 2013; Lu and Ip, 2009). The main drawback here is that this method needs early urban planning in design of neighboring buildings. Moreover, while upper elevations may benefit from a high wind speed, at pedestrian levels, high wind speed is undesirable for pedestrians and may cause a discomfort.

(c) **Inside through-building openings:** Apart from the investigation on the effect of holes, slotted corners and vented fines in buildings to reduce the wind-induced response of structures (e.g. Kwok, 1988), the application of through-building openings for wind energy harvesting have been investigated for a generic CAARC tall building model (Hassanli et al., 2016; Jafari et al., 2016) and for Pearl river tower (Li et al., 2013, 2016).

(d) **Integration into building's skin:** The integration of a wind turbine into the skin of the buildings is a fairly new concept. Park et al. (2015) proposed to incorporate micro wind turbines into the entrance of a ventilated façade and use guide vanes to increase wind velocity to a sufficient level for harvesting.

In this study, an innovative design for Double Skin Façade (DSF)[1] with strategic openings was proposed to exploit wind energy in urban environment. A series of wind tunnel tests was conducted to investigate the flow behaviour within the DSF integrated into a tall building model. The capability of a RANS model to predict mean velocity within the cavity of the DSF for a series of incident wind angles was assessed. The flow mechanism and characteristics, including mean flow velocity, flow uniformity and turbulence, within the cavity for different wind direction were investigated. Suitable regions of harvesting wind energy within the cavity were identified and the required design factors for the selection of a wind turbine governed by the characteristics of the flow within the cavity were discussed.

The proposed integrated DSF accommodates strategic openings based on the pressure field around the building to enhance the flow in the cavity for energy generation purposes. A building-high vertical opening at the centre of the external façade and two openings at the corners of the building are considered, as shown in Fig. 2b. When the approaching wind is normal to the DSF, air enters the cavity through the central opening (high pressure regions), flows along the cavity width and discharges from the side openings (low pressure regions). This design is particularly suitable for mid-rise and high-rise buildings where the wind speed is generally sufficiently high for generating electricity using small-scale building-mounted wind turbines. It should be noted that thermal effects have not been considered so the airflow is driven primarily by wind pressure rather than buoyancy. Architecturally, DSF conceals and confines the wind turbines in an aesthetic fashion. It also potentially contributes to noise reduction but this is outside of the scope of this paper. This study aims to investigate the potential application of a building-integrated DSF with strategic openings to harvest wind energy in urban area.

2. Methodology

2.1. Building and double skin façade geometry

A 1:150 scale model of the CAARC standard tall building integrated with a building-high Double Skin Façade (DSF) was employed in both wind tunnel tests and CFD simulations. The height, breadth and depth of the scaled model were H=1200 mm, B=300 mm, and D=200 mm, respectively, as shown in Fig. 3. The cavity depth between the interior and exterior facades was 13.3 mm. A vertical opening 27.3 mm wide was created in the middle of exterior façade along the entire height of the building. The thickness of the external façade was 1.5 mm and the cavity was open to the exterior on all sides and at the top.

2.2. Wind tunnel test setup

To evaluate the flow characteristics within the cavity of DSF, a series of wind tunnel tests were conducted in the 3 m ×2 m high speed test section of the boundary layer wind tunnel of the CLP Power Wind/Wave Tunnel Facility at the Hong Kong University of Science and Technology (Fig. 4). The blockage ratio of the scaled model in the wind tunnel was about 6%, which is lower than the recommended upper limit of 8% proposed by the ASCE Aerospace Division Task Committee on Wind Tunnel Studies of Buildings and Structures (Cermak and Isyumov, 1999). The Reynolds number based on the breath of the building model was approximately 2×10^5.

The flow velocities within the cavity of DSF were measured by using Kanomax anemometer, which is an omni-directional thermal probe with a working wind speed range from 0.1 to 25.0 m/s with a resolution of 0.01 m/s. The Kanomax anemometer was calibrated against a constant temperature hot-wire anemometer. The calibration

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[1] DSF is a façade consisting of two distinct planar elements separated by an air cavity which is conventionally used for thermal and sound insulation, ventilation and aesthetics (Poirazis, 2006). The natural ventilation of a typical DSF is primarily driven by the stack effect although wind pressure could affect air flow within the cavity. The stack effect is the movement of air resulting from the buoyancy associated with the difference in air density due to different temperature at different heights. The openings are generally placed at ground level and at the top of DSF to create the maximum stack effect resulting from heating the cavity flow by solar irradiation.