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Impact of roof geometry of an isolated leeward sawtooth roof building on cross-ventilation: Straight, concave, hybrid or convex?

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ABSTRACT

The roof geometry of a leeward sawtooth roof building can have a large influence on the cross-ventilation flow. In this paper, five different leeward sawtooth roof geometries are evaluated using Computational Fluid Dynamics (CFD). The 3D CFD simulations are performed using the steady Reynolds-Averaged Navier-Stokes approach with the SST k–ω turbulence model to provide closure to the governing equations. The computational grid is based on a grid-sensitivity analysis and the computational model is successfully validated using PIV measurements for a generic isolated building from literature. The five different roof geometries that are studied include one straight and four curved roofs. The curved roofs can be subdivided in one concave, one hybrid (convex–concave) and two convex roof geometries. It is shown that a straight or convex roof geometry can maximize the underpressure in the wake of the building, where the outlet opening is located, which results in enhanced wind-driven cross-ventilation flow. Analysis of the results shows that for a normal wind incidence angle (0°) the straight and convex leeward sawtooth roof geometries can result in an increase of the volume flow rate by 13.0%, 12.5% and 12.3% respectively compared to a concave roof geometry. Furthermore, the increase of the indoor air velocity can be as high as 90% in the upper part of the occupied zone (at $h=1.7$ m above ground level) for convex versus concave roofs.

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1. Introduction

The application of a sawtooth roof on buildings can contribute to a sustainable and healthy indoor environment as it can allow additional daylight and natural ventilation compared to a standard flat roof. Often, sawtooth roof buildings have openings in the lower part of the facade and upper-level openings near the roof top in the opposite facade. Using the upper-level openings located near the roof, the sawtooth roof can achieve more uniform and higher daylight intensity levels than the levels obtained by an opening located in the middle or in the lower part of a facade (Robbins 1986). The ventilation flow in a building with a sawtooth roof depends – among others – on its orientation to the oncoming wind flow (Gandemer and Barnaud, 1989). In a building with a leeward sawtooth roof, with supply openings in the bottom part of the windward facade and exhaust openings in the top part of the leeward facade, the wind-driven natural ventilation can be improved since the upward wind-driven cross-ventilation flow can be assisted by possible buoyancy forces. Although the possible advantages of a leeward sawtooth roof in naturally ventilated buildings are known, the potential of buildings with a leeward sawtooth roof has not yet been extensively explored and this type of roof is still not applied on a large scale (Bittencourt, 2006). In the past, several studies have been carried out on wind-induced loads on a sawtooth roof (Saathoff and Stathopoulos, 1992; Stathopoulos and Saathoff, 1992; Cui, 2007), gable roof (Holmes, 1994; St. Pierre et al., 2005; Quan et al., 2007) and arched roof (Holmes and Paterson, 1993), however, these studies did not focus on the ventilation flow of the building as a function of the different roof geometries. To the best knowledge of the authors, only one study by Fatnassi et al. (2006) investigated the impact of the roof shape for buildings with asymmetric opening positions and with respect to building ventilation. In addition, Kindangen et al. (1997a, 1997b) analyzed the effect of the roof shape on natural ventilation of the building, however, all the buildings in these studies had symmetric opening positions (openings located at the

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same level). Furthermore, these studies were not performed for a sawtooth roof building. In general, there is a lack of knowledge on the effect of roof geometry on the airflow pattern inside cross-ventilated buildings (Kindangen et al., 1997a), which is even more pronounced for buildings with a pitched roof (either a straight or curved geometry) and with asymmetric opening positions (inlet at lower part and outlet near roof level), such as sawtooth roof buildings. A systematic study is required to quantify the effect of a range of roof geometry parameters, e.g. roof inclination, roof shape, roof overhang, roof height, as the indoor airflow is the result of the combined effect of each of these geometrical parameters. A previous paper by the authors showed that a 27° roof inclination angle with the outlet opening near the roof top can increase the volume flow rate through the building with 12% compared to a flat roof (Peren et al., 2015). However, more studies on this topic are needed to increase the understanding of the ventilation flow through these buildings, and to optimize the performance of leeward sawtooth roofs for this purpose.

The current paper analyzes the impact of straight, concave, hybrid (concave–convex) and convex leeward sawtooth roof geometries with a 27° implicit roof inclination angle (i.e. the angle measured by drawing a straight line from the windward edge of the roof to the rooftop) and with asymmetric opening positions. Fig. 1 shows the five leeward sawtooth roof geometries that are analyzed in this paper. The main objective is to analyze which type of roof geometry can increase the volume flow rate and indoor air velocities, and eventually also the air exchange, ventilation and heat removal effectiveness. In this study, the performance of each roof geometry is evaluated based on the volume flow rate through the building and the mean air velocity ratios in the occupied zone, measured at four different heights: (h=1.7 m, 1.1 m, 0.6 m and 0.1 m), which are considered as reference for the evaluation of thermal comfort conditions of a seated or standing person, at a steady-state and moderate environment, i.e. where the environmental conditions are close to the thermal comfort standards proposed by ISO 7730/2005 (ISO, 2005). Computational Fluid Dynamics (CFD) is employed with the 3D steady Reynolds-Averaged Navier–Stokes (RANS) equations with the SST k–ω turbulence model to provide closure. The simulations are based on grid-sensitivity analysis and on validation with previously published wind-tunnel measurements.

The results presented in this paper are part of a large research project on the enhancement of wind-driven cross-ventilation of residential buildings by adjusting the roof geometry. In this research project, among others, the effect of a range of sawtooth roof geometries (this paper), roof inclination angle (Peren et al., 2015), the addition of eaves, the size of the building and the roof span on the natural ventilation flow through a single-zone building is studied. For the sake of brevity and to enable a detailed assessment of the flow behavior in and around the building resulting from modification of a certain part of the building and/or roof geometry, this paper will focus on one part of the results obtained in this larger research project, namely the effect of roof geometry.

The building geometry and roof geometries that are analyzed using CFD are presented in Section 2. The validation study is addressed in Section 3. In Section 4 the computational settings are described and the results of the grid-sensitivity analysis and the horizontal homogeneity test are presented. Section 5 shows the results of the analysis of the different roof geometries. Section 6 (Discussion) and Section 7 (Conclusions) conclude this paper.

2. Building and roof geometries

Fig. 1 shows a schematic representation of the five different roof geometries selected for this study. Each geometry is designated by a letter: A, B, C, D and E. Geometry A has a straight roof, whereas geometry B has a concave roof, C a hybrid convex–concave roof and the geometries D and E have convex roofs. Note that we adopt the definitions of "convex" and "concave" as used in the description of mathematical functions, where "a convex function is a continuous function whose value at the midpoint of every interval in its domain does not exceed the arithmetic mean of its values at the ends of the interval" (Wolfram MathWorld, 2014). These five roof geometries have been chosen as fairly representative of the domain of different leeward sawtooth roof buildings, as schematically represented in Fig. 2. This figure distinguishes between the main categories "convex–concave" on the horizontal axis and "curved–straight" on the vertical axis. In addition, the distance from the origin of the axes system is a measure of the roof inclination angle.

Fig. 3 shows a front view, a vertical cross-section and a perspective view of the building with geometry A with its main dimensions. Apart from the roof shape, all five geometries have the same: (a) maximum roof height (H=5.7 m); (b) building depth (D=6 m); (c) building width (W=3 m); (d) inlet and outlet opening size (corresponding to 5% windward wall porosity); and, (e) inlet and outlet opening location (the outlet is located at $\frac{3}{4}D$). Since all five buildings have different roof shapes, each building has a different internal volume V: V_A=54.18 m^3, V_B=60.58 m^3, V_C=53.52 m^3, V_D=50.78 m^3 and V_E=49.91 m^3. The distance from the ground to the bottom of the inlet and outlet opening is 1.42 m and 4.60 m, respectively.

The roof inclination and the outlet opening position are important factors that influence the volume flow rate and the mean indoor air velocities, as pointed out in a previous paper by the authors (Peren et al., 2015). However, it is important to highlight that in all five geometries, the roof has an implicit roof inclination angle of 27° and the outlet opening is located at exactly the same height near the roof top.

3. CFD simulations: validation study

Validation is imperative for CFD simulations in general, and more in particular for CFD simulations based on the 3D st eady RANS equations (Franke et al., 2007; Tominaga et al., 2008; Blocken, 2014). The CFD model employed in the current study has been validated extensively in a previous publication (Peren et al., 2015). In this section a general overview of the validation study will be provided. The reader is referred to Peren et al. (2015) for more information and an extensive analysis of the sensitivity of the results to a range of computational settings and parameters.

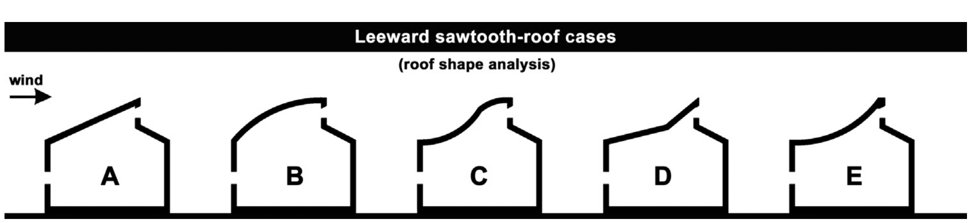

Fig. 1. Leeward roof shapes analyzed in this paper. All the geometries have the same plan dimensions, the same maximum roof height but different internal volumes.

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