Evaluation of wind-driven ventilation in building energy simulation: sensitivity to pressure coefficients

Citation for published version (APA):

Document status and date:
Published: 01/01/2011

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 28. Jul. 2019
EVALUATION OF WIND-DRIVEN VENTILATION IN BUILDING ENERGY SIMULATION: SENSITIVITY TO PRESSURE COEFFICIENTS

R. Ramponi\textsuperscript{1,2}; D. Cóstola\textsuperscript{1}; A. Angelotti\textsuperscript{2}; B. Blocken\textsuperscript{1}, J.L.M. Hensen\textsuperscript{1}

1: Building Physics and Systems, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
2: Dept. Building Environment Science & Technology, Politecnico di Milano, via Bonardi 3, 20133 Milano, Italy

ABSTRACT

Building Energy Simulation (BES) tools integrate wind-driven ventilation in buildings either by imposing the airflow rate in a Zone-Airflow module or by calculating it through Airflow Network (AFN) models. When the AFN models are used, pressure coefficients are crucial for obtaining accurate results. This is particularly important in case of complex geometries or buildings with large openings, when the uncertainties related with the use of simplified models are higher and can affect the results. This paper describes a preliminary study on the effects of the pressure coefficients on the BES simulations of a cross-ventilated building with large openings. The single-zone building has a high thermal mass and is subjected to wind-induced night ventilation. Simulations are performed with the Zone-Airflow module and the AFN model within the code EnergyPlus. The airflow rate imposed in the Zone-Airflow module is obtained by performing Computational Fluid Dynamics (CFD) simulations of the opened-building (i.e. the building with ventilation openings). The pressure coefficients used for the AFN simulations are obtained in five different ways: (i) the surface-averaged calculation in EnergyPlus, (ii) the Air Ventilation and Infiltration centre (AIVC) database, (iii) the Tokyo Polytechnic University (TPU) database, (iv) wind-tunnel measurements and (v) CFD simulations performed on a closed (sealed) building (i.e. the building with ventilation openings closed). Results are compared in terms of airflow rate and indoor air temperature during a Design Day characterized by a constant wind speed. Differences in airflow rates are up to the 15\% among the values predicted with the AFN models and increase up to the 24\% when the results of the Zone-Airflow module are compared with the ones obtained from the AFN model simulations. For the case under study, the airflow rates are very high and the indoor air temperatures are not affected by the variation of the pressure coefficients. The results indicate the importance of the pressure coefficients in predicting the airflow rates through large openings. Other ranges of airflow rates might be investigated to see the effects on the indoor air temperature for more realistic building configurations.

INTRODUCTION

Natural ventilation due to wind and buoyancy is a valuable approach to obtain comfortable and healthy indoor environments. The ventilation performance of buildings can be estimated by using simplified analytical and empirical models, measurements and computer simulations [1]. A suitable integration of ventilation models in Building Energy Simulation (BES) tools is done through Airflow Network (AFN) models, which describe a network of airflow paths from the outside and through the building zones which are driven by pressure coefficients \((C_p)\). Pressure coefficients for the AFN models can be acquired from primary sources, i.e.
wind-tunnel measurements or Computational Fluid Dynamics (CFD) simulations on a sealed body, or from secondary sources, i.e. analytical and empirical models [2].

Simplified models can be used for simple building geometries with small openings, when the outdoor wind flow conditions can be used as boundary condition for calculating the indoor air flow (i.e. the sealed-body assumption [3]). However, large discrepancies can be obtained for more complex geometries and in case of large openings, when the sealed-body assumption is no longer valid [3; 4]. A correct estimation of \( C_p \) for these cases is therefore crucial for performing accurate building energy simulations, as well as investigating the uncertainties related with the use of different \( C_p \) sources for airflow rate calculations [5].

This paper describes a preliminary study on the effects of the \( C_p \) data sources on the airflow rate and the indoor air temperature of a cross-ventilated building. \( C_p \) extracted from primary and secondary data sources were applied to the BES simulation of a single-zone building with the openings on the opposite and adjacent walls. Wind-induced night ventilation is considered for the simulations performed with the Zone-Airflow module and the AFN model within the code EnergyPlus [6]. The airflow rates used in the Zone-Airflow module simulations are taken from the CFD simulations of the opened-building. The pressure coefficients used for the AFN model are taken from (i) the surface-averaged calculation in EnergyPlus [7], (ii) the Air Ventilation and Infiltration centre (AIVC) database [8], (iii) the Tokyo Polytechnic University (TPU) database [9], (iv) wind-tunnel measurements [10] and (v) Computational Fluid Dynamics (CFD) simulations performed on a closed-building [11].

**BUILDING CONFIGURATION**

A single-zone building (Fig. 1) was defined in order to reproduce, at full-scale, the geometry of the reduced-scale model tested in the wind tunnel [10; 12]. The full-scale dimensions are 20 x 20 x 16 m³. Two openings are placed in the centre of the opposite (Case A) and adjacent (Case B) walls at the height of 6.2 m. The openings, sized 9.6 x 3.6 m², provide a wall porosity of the 10% [12] and can be characterised by a discharge coefficient of 0.61 [10].

![Figure 1: Geometry of the building configurations under study and view of windward facade with opening (a) and opening configurations for Case A and B (b).](image)

The thermal transmittance of the building walls (U-value) is equal to 0.512 W/m²K for the external walls, 0.039 W/m²K for the floor and 0.318 W/m²K for the roof [13]. The internal loads were considered as a constant value of 10 W/m². Wind-induced night ventilation was imposed from 22:00 to 7:00. The heating system is considered always off, The cooling system is working from 7:00 to 22:00 with a set point temperature of 27°C. Based on the climate conditions of Denver (USA), a design day was defined for the analyses by considering the temperature conditions of the maximum dry bulb temperature day of the year (26 July) and imposing a constant reference wind velocity of 3.24 m/s at 10 m height.
INPUT DATA FOR THE AIRFLOW CALCULATION

Zone-Airflow module
Reduced-scale models (scaled 1:200) of the opened-buildings in Case A and B were simulated with the software Fluent [14]. The computational domain and grid were created with the code Gambit 2.4.6 using the surface-grid extrusion technique [15] and in accordance with the existing guidelines [16, 17]. An approaching-flow wind velocity profile was described by a power-law with an exponent of 0.12 and a reference velocity of 6.97 m/s at the building height (0.08 m – 16 m full scale); the turbulence intensity at the same height was 10% and 17% near ground level (0.01m). The building is placed in open terrain. The 3D steady Reynolds-averaged Navier-Stokes equations were solved with the RNG k-ε turbulence model and successfully validated with the wind-tunnel measurements by Karava [10] and Karava et al. [12]. Further details on the simulations can be found in [11]. The calculated airflow rate through the inflow opening was used for the Zone-Airflow module simulations.

Airflow Network (AFN) model
C_p coefficients used in the AFN model are extracted from the sources described below. Note that due to the geometric ratio between the dimensions of the building (Length:Width:Height = 1.0:1.0:0.8), low-rise building methods were used for the analyses when required.

(i) Surface-averaged calculation in EnergyPlus (C_p,AVE)
The automatic surface-averaged C_p calculation for low-rise building in EnergyPlus is based on the formula by Swami and Chandra [7] for rectangular buildings. The formula allows the estimation of a surface-averaged C_p coefficient in each wall considering the building geometry (ratio between adjacent walls) and the wind direction.

(ii) AIVC database (C_p,AIVC)
In the AIVC database, C_p values for low-rise buildings are collected from different data sources [8] and presented in tables. The C_p values are surface-averaged and the building geometry (L/W ratio), the sheltering conditions and the wind direction are considered. For the present study, an exposed building with L/W=1 is considered.

(iii) TPU wind pressure database (C_p,TPU)
The TPU web aerodynamic database is based on extensive wind-tunnel measurements [9]. The database for the low-rise buildings provides surface-averaged wind pressure coefficients and C_p distributions on the building walls and considers different roof shapes, sheltering conditions and wind directions. The C_p used for the analyses are extracted from the isolated low-rise building database, considering a flat roof and a geometric ratio of L:W:H=4:4:3.

(iv) Wind-tunnel measurements (C_p,WT)
C_p values were extracted from wind-tunnel measurements conducted by Karava [10]. The geometry of the scaled model, the approaching wind profile and the ground conditions are as described above. Pressure measurements were conducted for a closed-building and are described in detail in Karava [10]. Pressure coefficients were derived by the mean pressure measured in the centre point of each wall.

(v) CFD simulations of a closed-building (C_p,CFD)
CFD simulations on a closed-building were performed to extract the pressure coefficients on the openings’ area. The same settings described above for the opened-building were used in this case although steady RANS equations have some deficiencies in modelling the surface pressures downstream the windward facade [18]. Pressure coefficients were derived from the static pressure by extracting the averaged C_p values on the openings areas.
RESULTS AND DISCUSSION

Figures 2 summarises the $C_p$ and $\Delta C_p$ values obtained for Case A and B from the primary and the secondary sources analysed. It can be noticed, that $\Delta C_p$ from the surface-averaged calculation ($\Delta C_{p,AVE}$) differs from the value obtained with wind tunnel measurements ($\Delta C_{p,WT}$) up to 10% in Case A and up to 15% in Case B.

![Image](image.png)

Figure 2: (a1, b1) $C_p$ values for Case A and B using the surface-averaged calculation ($C_{p,AVE}$), AIVC database ($C_{p,AIVC}$), TPU database ($C_{p,TPU}$), wind-tunnel measurements ($C_{p,WT}$) and CFD simulations ($C_{p,CFD}$). (a2, b2) Distribution of $C_{p,CFD}$ on the windward and the leeward faces.

Results of the BES simulations by using the AFN model with different $C_p$ and the Zone-Airflow model are compared in terms of airflow rate (Fig. 3) and indoor air temperature (Fig. 4). Differences in the airflow rates (Fig. 4) reproduce the trend shown by the $\Delta C_p$ values.

Among the airflow rates calculated with the AFN model in EnergyPlus, results vary up to 15% for Case A and to 13% for Case B. Higher discrepancies (up to 24%) are noticed when the results from the AFN model are compared with the airflow rates extracted from CFD and imposed to the Zone-Airflow model. Further efforts are necessary to understand these outcomes, focusing on the possible role of the integration between the airflow and the thermal networks in EnergyPlus and on the influence of the $C_p$ distribution on the facades.

![Image](image.png)

Figure 4: Airflow rates predicted by using the Zone-Airflow model (ZA) and the AFN model with the $C_p$ extracted from different data sources for Case A (a) and B (b).
The differences shown in the airflow rate do not influence significantly the indoor air temperature profile during the night, which almost overlaps the outdoor air profile (Fig. 5). Among the results of the AFN model simulations, only the predicted indoor air temperature using $C_{p,\text{WT}}$ and $C_{p,\text{AVE}}$ are shown in Figure 5, because of the negligible differences among the results. A small variation is noticed with the Zone-Airflow model is applied to Case B. These small differences might be due to the fact that in the chosen case study the airflow rate is steadily high. Other range of airflow rate values should be investigated.

Figure 5: Outdoor ($T_{\text{out}}$) temperature in the Design Day and indoor temperature for Case A and B obtained with the Zone-Airflow module ($T_{\text{in,ZA}}$) and the AFN model with $C_p$ values from wind tunnel measurements ($T_{\text{in,WT}}$) and surface-averaged calculation ($T_{\text{in,AVE}}$)

CONCLUSIONS

Based on the results presented in this paper it can be noticed that the values of $C_p$ are strongly influenced by the data source and the estimated $\Delta C_p$ from the CFD simulations are up to the 30% higher than the others. These differences affect the predicted airflow rates with the AFN model up to 15%. It is observed that the airflow rate extracted from the CFD simulations tends to be higher than the airflow rate predicted by using the $C_{p,\text{CFD}}$ in the AFN model (up to the 24%). The indoor air temperature is not influenced by the variation in the airflow rates, which are very high in every case tested. Further studies may focus on a more realistic building configuration.

REFERENCES


