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Erratum

Air change rates driven by the flow around and through a building storey with fully open or tilted windows: An experimental and numerical study

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ABSTRACT

Air change rates (ACH) through open and tilted windows in rooms of residential buildings driven by atmospheric motions are investigated to evaluate natural ventilation concepts. Model experiments in wind tunnels, numerical flow simulations (CFD) and thermal building simulations are used. Pressure profiles are measured on the facade of a building model for selected wind directions and velocities. A separated sample storey and a sample single room in larger scales were used to measure air transport through window openings under the influence of the external pressure distribution. The ACH was obtained by velocity measurements in the window cross sections and by tracer gas measurements using the decay method.

ACH from CFD computations of the wind tunnel environment agreed well with the experimental values. Therefore the numerical simulations were extended to real dimensions. The dependency of the ACH on the position in the external flow field and a scaling law for the ACH are presented. The wind-driven ACH obtained are much larger than the temperature-driven values prescribed in the Austrian standard Ö-NORM B 8110-3 on the prevention of high room temperatures during summer. A comparison of the impact of temperature-driven with wind-driven ACH, i.e. natural ventilation concepts, in thermal building simulations is presented.

1. Introduction

In the planning process of a building, the heating and cooling concepts are developed, and both have the ventilation concept as an integrated part. Mechanical, natural and even hybrid ways of ventilation are nowadays in use. Natural ventilation of buildings, relying on wind-induced pressure or on differences in temperature, is the most common form of ventilation. The air is exchanged through doors, open or tilted windows. For layout purposes it is important to estimate the magnitude of the air change rates (ACH) correctly. Ventilation through tilted windows is sparsely represented in the literature to date.

The amount of air exchange strongly depends on the wind direction as well as on the position and size of the openings of the building envelope and, in presence of different temperatures inside and outside the building, on thermal buoyancy. The methods for studying natural ventilation are either full-scale experiments in real conditions [1–4], wind tunnel experiments in full or model scale [5–8], or computational fluid dynamics (CFD) simulations. CFD results are compared with analytical results or data from wind tunnel measurements [2,5–7,9–13]. Furthermore, network models [14,15] which can be used to predict wind-driven ACH quite accurately, are compared with CFD models in the absence of experimental data [16].

The existing literature reports on various experimental and numerical studies aimed to estimate air flow rates through openings and the resulting indoor air quality. Allocca et al. [2] and Larsen and Heiselberg [3] investigated both wind-driven and thermally induced air exchange. In their studies, a consistent trend to predict the interaction of the two mechanisms was not found. Schulze

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and Eicker [14] investigated three cases under mixed conditions applying local weather data. For a single-sided situation they found combined wind and thermally driven natural ventilation to produce ACH between 1 and 5 h^{-1}. Nikas et al. [10] and Nikolopoulos et al. [11] studied numerically the impact of the inner topology of buildings on the ACH and compared the results with measurements of Larsen [17]. Both simulation and experiment show that the internal geometry does not alter the overall aerating volume flow rate, but is an important factor for the refreshing rate of inner regions since air exchange does not affect all zones of a room. The results from numerical simulations of Nikolopoulos et al. [11] revealed a highly unsteady character of the velocity component perpendicular to the openings for wind directions greater than 60° against the opening normal, which is due to the formation of small but intensive recirculation zones at the openings.

All of the aforementioned studies incorporated experiments or numerical simulations in full scale for single-sided window configurations or for windows on opposite walls. The corresponding literature lacks information on configurations with openings in adjacent walls, and especially on the ventilation through tilted windows. The latter is essential to the majority of natural ventilation scenarios in residential buildings during summer periods.

For ventilation with single-sided tilted windows, shafts and other special constructions in 1:1 scale under real meteorological conditions, Daler et al. [18] investigated the thermally driven air exchange and considered only wind velocities below 1.5 m/s. Furthermore, the structure, availability, costs and maintenance of such systems were addressed. Maas [19] accounted for the influence of the window reveal, various rotary and tilting positions, as well as differences in temperature and in wind conditions. Pivoted sash windows were found to be more efficient than tilted windows. Since the above approaches for similar boundary conditions yielded significantly different ACH, Hall [20] formulated a modified model to describe thermally induced ventilation through bottom hung windows for single-sided ventilation, accounting for embrasures and heating. A combination of interior embrasures and heaters reduce the air change potential by approximately 40%. The aforementioned investigations share the fact that only one ventilation opening was considered. A general overview on natural ventilation and appropriate guidelines can be found in the study [21].

The present work investigates natural ventilation concepts for residential buildings, where the usual ventilation openings are windows, either fully open or tilted. The driving force is the external wind-induced pressure. Thermal effects are neglected in this work. The aim is to quantify flow fields responsible for the air exchange and to identify the magnitude of ACH in different rooms of the same storey. The variation of the ACH caused by the relative position of a room and its window openings to the external flow field around the storey is investigated. This work includes both, single-sided ventilation and cross-ventilation for open and tilted windows. Furthermore, in contrast to the aforementioned studies, the ventilation through tilted windows in adjacent walls is also studied.

A model of a 10-storey building, in a scale of 1:75, was studied in a boundary layer wind tunnel to acquire the pressure distribution on its closed facade. Subsequently, the obtained pressure distribution was reproduced in an aerodynamic wind tunnel on a single-storey model in a scale of 1:25. Afterwards the provided windows of the single-storey model were fully opened and the resulting flow velocities in the window cross sections were measured. In addition, a single-room model on a scale of 1:10 was applied to determine flow velocities in the gaps of tilted windows. Furthermore the ACH for tilted windows were determined by measuring the concentration decay of a tracer gas in the room model. Numerical simulations of the airflow through the single storey in 1:25 model scale were performed and validated with the corresponding experimental results. This comparison supports the CFD as a tool for predicting realistic ACH values. CFD simulations in real scale (the single-storey model in the wind tunnel environment upscaled) validate an ACH scaling law. Furthermore, the dependency of the ACH on the position in the external flow field is addressed. Finally, thermal building simulations for a summer period using the determined wind-driven ACH as input parameters quantify the numbers of hours with exceeded temperature limits compared to using temperature-driven ACH for the different rooms.

In the following section we define the geometry of the investigated building. Section 3 presents the details of the wind tunnel experiments and the applied models. In Sections 4 and 5, numerical simulations of the air flow fields around and in the building and the comparison of the computed velocities with experimental data are presented. The scaling law and ACH in real dimensions based on the measurement and simulation results in model scales are discussed in Section 6. Section 7 describes thermal building simulations for the sample storey over a summer period. The conclusions follow in Section 8.

2. Building geometry

The building investigated has the dimensions of 14 m × 21 m and a height of 30 m. Within the building, the storeys under consideration differ in the height above ground only. The representative storey has a floor plan comprising typical natural ventilation scenarios for rooms with open and tilted windows. Fig. 1 shows the floor plan of the storey, including the window and room numbers. The investigated wind directions are marked by arrows. Rooms R_1 and R_5 have the same geometry. Because of the asymmetric array of windows wind directions perpendicular to three facades seem reasonable. Yawing conditions are captured by a wind direction along the building diagonal (33.3°) as a characteristic and representative case. For special investigations of the situation with tilted windows, a sample single room model with the geometry of room R_1 was developed.

3. Experimental setups and techniques

The experiments of the present study were carried out with the aim to quantify the ACH of rooms of a residential building model and provide the data for comparison with numerical simulations. For this purpose, three different models were developed and investigated in two different wind tunnels to measure (1) the pressure distribution from the atmospheric boundary layer flow on the full building facade, (2) the ACH as derived from air velocities in open window cross sections and in door cross sections in case of tilted windows, and (3) the air exchange rate with special account for tilted windows in the single room model. Two different methods for measuring the ACH were applied. The present section discusses the various setups and techniques.

3.1. The models

For the purpose of pressure measurements in a boundary layer wind tunnel, a model of the complete building was established in 1:75 scale (not shown here). One storey was equipped with pressure holes at appropriate locations on the closed surface and mounted at heights from the 2nd to the 10th floor. However, this small model scale does not allow for velocity measurements in tiny openings like windows. These measurements were therefore carried out in a separate sample storey of larger scale (1:25) implemented in an aerodynamic wind tunnel where the pressure distribution in different heights above ground in the boundary layer