Building and Environment 81 (2014) 123–138

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Natural ventilation design: An analysis of predicted and measured performance

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A R T I C L E I N F O

Article history:
Received 2 April 2014
Received in revised form
31 May 2014
Accepted 2 June 2014
Available online 24 June 2014

Keywords:
Natural ventilation
Early-design-stage
Uncertainty analysis
Air change rates
Occupant behavior
Airflow network

A B S T R A C T

We present a study of natural ventilation design during the early (conceptual) stage of a building's design, based on a field study in a naturally ventilated office in California where we collected data on occupants' window use, local weather conditions, indoor environmental conditions, and air change rates based on tracer-gas decay. We performed uncertainty and sensitivity analyses to determine which design parameters have most impact on the uncertainty associated with ventilation performance predictions. Using the results of the field study along with wind-tunnel measurements and other detailed analysis, we incrementally improved our early-design-stage model. The improved model's natural ventilation performance predictions were significantly more accurate than those of the first draft early-stage-design model that employed model assumptions typical during initial design. This process highlighted significant limitations in the EnergyPlus software's models of occupant-driven window control. We conclude with recommendations on key design parameters including window control, wind pressure coefficients and weather data resolution to help improve early-design-stage predictions of natural ventilation performance using EnergyPlus.

1. Introduction

Natural ventilation could significantly reduce building energy use and improve occupant satisfaction with the indoor environment [1]. Natural ventilation systems are common in European commercial buildings, and interest in using natural ventilation is growing in the U.S. [2]. However, significant barriers to broad adoption of natural ventilation persist. Brager [3] identified several barriers in the U.S., including a general lack of familiarity with natural ventilation design, concerns about long-term maintenance, a lack of reliable and easy-to-use design tools, and, significantly, concerns about meeting current codes and standards for minimum ventilation rates and thermal comfort conditions. Prior European studies identified similar barriers [4]. Before taking on the additional perceived risks of natural ventilation, building stakeholders need assurance that natural ventilation can meaningfully contribute to comfortable indoor air temperatures and acceptable indoor air quality. Ideally, analysis during the early stages of building design can provide this assurance and inform key design decisions that affect natural ventilation performance. Key performance parameters for natural ventilation include how well the models predict window use, air change rates and the percentage of occupied hours where minimum mechanical ventilation rates are met.

Available building simulation tools such as EnergyPlus, ESP-r, IES, TAS, and TRNSYS can integrate a building's thermal model with a multi-zone airflow network model. We selected EnergyPlus because it offers users the greatest flexibility to implement user defined control strategies.

Because building simulation tools can, in theory, provide designers with building energy and ventilation performance predictions, these tools can be used to support early design decisions. However, the performance of natural ventilation systems are very sensitive to a number of design parameters that are typically undefined during a building's early design stage [5]. Performing a detailed parametric analysis of all of these undefined parameters during the early design stage would require significant effort. And, even with such an analysis, the ventilation performance prediction

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Abbreviations: ACR, air change rate; ACH, air change per hour; CV-RMSE, coefficient of variation of the root mean square error; ELA, equivalent air leakage area; RMSE, root mean square error; SHGC, solar heat gain coefficient; VR, ventilation rate.

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http://dx.doi.org/10.1016/j.buildenv.2014.06.009
0360-1323/

distributions that would result are potentially too variable to be informative. Designers need clearer guidance regarding sources of uncertainty in natural ventilation performance predictions and ways to improve the reliability of these predictions.

Previous studies have compared EnergyPlus's simulated natural ventilation performance with measured data from naturally ventilated buildings [6,7]. Zhai [6] compared simulated and measured data for three naturally ventilated office buildings but did not collect coincident weather data or directly measure ventilation rates. Coakley et al. [7] used simulation models that were calibrated to align electrical energy consumption and zone temperatures, with natural ventilation modeled using scheduled ventilation flows in EnergyPlus. We have not identified any prior studies that explore the sources of uncertainty in natural ventilation performance predictions made during the early stage of building design. In addition, no prior studies compare early-design-stage natural ventilation performance predictions with measured data including on-site weather and measured air change rates.

In this study, we compared early-design-stage predictions of natural ventilation performance from an EnergyPlus model to field measurements of ventilation performance. Uncertainty analysis assessed the impact of uncertainties in design parameter values on ventilation performance predictions. Sensitivity analysis identified key model input parameters that affect the reliability of these predictions. Based on field study observations, we developed improved EnergyPlus models that reduce the uncertainty in predicted ventilation performance.

This analysis can help to inform decision makers by quantifying the uncertainty of performance predictions. Our results can also help designers improve the accuracy of natural ventilation performance predictions using EnergyPlus, prioritize early-design-stage analysis efforts, and select relevant input data.

2. Methods

We used data from a field study of natural ventilation performance at a small office building in Alameda, California. These data include indoor temperature and humidity, measured air change rates, outdoor temperature and humidity, wind speed and direction, window use, and the results of a coincident study of occupant thermal comfort.

Next, for the Alameda office building, we predicted a range of natural ventilation performance using a range of values for design parameters. The building's location, and climate were based on those of the existing field study building. A distribution of likely model outcomes was developed given typical variations in model input parameters. To quantify how well our model predictions of ventilation performance compared with measured results, we used four different metrics. The first metric considered how well the model predicted window use, compared with measured window use. Our metric for window use was the *window opening factor*, which we defined as the open fraction of the physically operable window area. The second metric compared predicted and measured 4 hourly air change rate per hour (ACRs). For these two metrics, comparisons between modeled and measured results were based on the coefficient of variation of the root mean square error (CV-RMSE). The CV-RMSE indicates how well each incremental model describes the variability in the performance metrics and is determined by comparing simulation-predicted data to the measured data [8]. A CV-RMSE value of 200% for example, indicates that the mean variation in measurement variable not explained by a prediction model is twice as large as mean value of the actual measurement variable [9]. The third metric was based on the number of hours during which the natural ventilation system met or exceeded the equivalent American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) standard for minimum required outdoor air ventilation rates in mechanically-ventilated buildings [10]. The fourth metric was to compare the absolute value of the average ACR for the entire simulated period, this metric was considered most relevant of the overall exposure of occupants to indoor contaminants.

We performed a sensitivity analysis to quantify the effect of uncertainty in the design parameters on the third metric of ventilation performance. This analysis identified a subset of key design parameters that drive uncertainty in early-design-stage ventilation performance predictions.

Next, we used the measured field study data to reduce uncertainty in the key model parameters that the sensitivity analysis identified. These parameters were wind-pressure coefficients, weather data frequency, indoor temperatures, and the maximum window opening factors of the windows and doors. We incrementally replaced the design parameters with values derived from our on-site measurements and related additional analysis. These field-study-based design values were used to incrementally improve EnergyPlus models. Finally, we compared the ranges of predicted ventilation performance from our early-design-stage study to predictions from our improved models and to the results from our field study.

2.1. Field study methods

The field study office occupies the second floor of a two-story building (Fig. 1) constructed in 2004 in Alameda, California. The office space is split into two, 130-m^2, open-plan areas connected by two large openings. The front room volume is 528 m^3. The back room has a false ceiling, so its effective net volume is only 351 m^3. The office does not have mechanical ventilation or a cooling system. Fifteen sash windows located on all four sides of the office provide natural ventilation for fresh air and cooling. The windows have internal shades and insect screens that are manually controlled by occupants.

Twelve ceiling fans with fully variable control are available for occupants to use to improve thermal comfort in summer. Additional heating is provided by single-user electrical resistance heaters. The monitoring for our study involved only the building's second story; the ground floor was not monitored.

2.1.1. Window-use measurements

To measure window position, LBNL's partners from the University of California (UC) Berkeley installed two digital cameras (Canon PowerShot A570) each with a wide-angle lens converter (Opteka HD^2 0.20X Professional Super AF fisheye lens, real angle of

Fig. 1. Northeast side of field study office.