Full-scale Validation of Natural Ventilation Models in Stanford’s Y2E2 Building

Chen Chen¹, Catherine Gorlé¹

¹Department of Civil and Environmental Engineering, Stanford university, United States

(The names and affiliations SHOULD NOT be included in the draft submitted for review)

(leave blank up to line 10 – remove line numbering from final version)

Abstract

Natural ventilation and cooling offer significant potential for energy savings, but their system performance is strongly dependent on local weather and building operating conditions. Computational models can evaluate these effects and support robust natural ventilation design, but their accuracy should be carefully evaluated and balanced with their computational efficiency. This study considers model validation for buoyancy-driven night-time ventilation in an operational educational building. A full-scale experiment was carefully designed and executed to support validation of (1) a building thermal model that predicts the volume-averaged building temperature, and (2) a computational fluid dynamics (CFD) model that resolves the spatial variability in the temperature field. This paper focuses on validation of the CFD model, which is shown to predict the measured local temperatures with an RMSE of less than 0.8 °C. In regions not directly adjacent to windows the RMSE can drop below 0.3 °C.

Key Innovations

- Design of a natural ventilation validation experiment using CFD and uncertainty quantification (UQ).
- Accurate measurements of air and thermal mass temperatures in an operational building with a night-time natural ventilation system.
- Comparison of experiments and CFD indicates good predictive performance, with RMSE less than 0.8°C.

Practical Implications

This model validation study demonstrates the potential of CFD and UQ to support robust design of natural ventilation systems.

Introduction

According to the U.S. Energy Information Administration, about 39% of the total U.S. energy consumption in 2017 was in residential and commercial buildings (U.S. Energy Information Administration, 2018). Around 20% to 50% of this building energy consumption is used to maintain a comfortable thermal environment with heating, ventilation, and air conditioning (HVAC) systems (Ürge-Vorsatz et al, 2015). In moderate to cold climates, there is significant potential to reduce the energy consumption for space cooling by using night-time ventilation: during the night, cold outdoor air is brought in to cool the building, such that the cooled thermal mass can subsequently counteract the heat gains during the next day. Earlier studies have shown that the use of passive cooling by natural ventilation can reduce building energy consumption by 20% to 35% compared with fully mechanically air-conditioned buildings (Ramponi et al, 2014). However, the complexity of the governing flow and heat transfer phenomena and the variability in the boundary and operating conditions make a robust design of natural ventilation a challenging task. An efficient and accurate modeling strategy that can account for this complexity and uncertainty can provide essential information during the design process. It could also be employed to inform operational control, reducing energy consumption while maintaining thermal comfort.

Before using computational models for robust design or control, it is essential to establish confidence in their predictive capabilities by performing model validation in full-scale, operational buildings. In a previous study, we considered full-scale validation of a multi-fidelity computational framework with UQ to predict the volume-averaged indoor air temperature during night-time ventilation in one of the atria of Stanford’s Yang and Yamazaki Environment and Energy Building (Y2E2). The framework combined a computationally efficient building thermal model with quantified uncertainty in the boundary and operating conditions with a more expensive CFD model to more accurately represent the complexity of the flow (Lamberti and Gorlé, 2018). Comparison of the results with building sensor measurements indicated that the sensor locations might provide measurements that are not representative of the volume-averaged temperature.

The objective of this paper is to present carefully designed full-scale experiments to (1) better characterize the thermal behavior of the building during the night-time ventilation and (2) support successful validation of the natural ventilation models. CFD and UQ were used to identify the optimal locations for temperature sensors under uncertain boundary and initial conditions. Subsequently, experiments were performed during
several nights under a variety of outdoor temperature and wind conditions. In this paper, we present the results of a single night with negligible effects of wind and compare the measurements to CFD predictions performed for the specific conditions of the experiment under consideration.

Building description

The Y2E2 building has 14,000 m$^2$ of floor space on one basement level and three above ground levels, connected through four atria (Figure 1). The building uses a combination of natural ventilation and active HVAC systems for temperature and ventilation control. In the present operation of the building, night-time ventilation is used to cool the common spaces (hallways, open areas, and lounges connected to the central atria) with no supplemental cooling. Our modeling focuses on this night-time ventilation, which is active between 8:00 p.m. and 6:00 a.m. Motorized windows in the common spaces on each floor are controlled individually by the building management system (BMS). The windows open on the condition that the outdoor temperature is lower than the indoor air temperature, which is the temperature recorded by the thermal sensors in each atrium on that floor. In addition, the indoor temperature should be greater than 22.5 °C. If the temperature on a floor cools to 20.3 °C, the windows on that floor will close. Meanwhile, based on the measured wind direction, the two leeward sides of the louver banks at the top of the atria are opened, allowing a buoyancy-driven flow that brings in cool air through the windows and flushes out warmer air through the louvers. The dimensions of the operable windows and louvers are provided in Table 1. Exposed concrete floors serve as a thermal mass that is cooled by the night-time ventilation, such that it can offset the heating during the following day.

The building is equipped with an extensive measurement system to monitor indoor and outdoor conditions and energy usage. The outdoor temperature measurement and wind sensors are located on the top of the roof. The indoor temperatures in each atrium are monitored by a building sensor on each floor. However, previous research indicates that these measurements might not be representative of the volume-average building temperature (Lamberti and Gorlé, 2018).

Experimental set-up

Instrumentation

A carefully designed experiment was performed to obtain a more accurate characterization of the volume-averaged temperature, as well as of the spatial temperature variability. Temperatures were measured at 20 locations in Atrium D using a wireless temperature sensor network. Each location had one data logger connected to up to 4 thermistors with a sampling rate of 1 second; one thermistor was used to measure the indoor air temperature, while the others were used to measure nearby floor, sidewall, and ceiling temperatures, as shown in Figure 2. In total, 20 thermistors were used for measuring indoor air temperature, while 34 thermistors were used for measuring surface temperatures (Table 2). Six out of 20 dataloggers were CR300-series, the remainder were Arduino-based sensor motes developed by our lab (Figure 2 left). The temperature sensors were calibrated using a temperature calibrator with an accuracy

![Figure 1: Y2E2 building: section through the social entry atrium (left); atrium louvers (top right); indoor view of the Atrium D (bottom right)](image)

<table>
<thead>
<tr>
<th>Axim</th>
<th>Windows</th>
<th>Louvers</th>
<th>Height(m)</th>
<th>Area(m$^2$)</th>
<th>Height(m)</th>
<th>Area(m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left facade</td>
<td>Front facade</td>
<td>Right facade</td>
<td>Left/Right facade</td>
<td>Front/back facade</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height(m)</td>
<td>Area(m$^2$)</td>
<td>Height(m)</td>
<td>Area(m$^2$)</td>
<td>Height(m)</td>
<td>Area(m$^2$)</td>
<td></td>
</tr>
<tr>
<td>12.85</td>
<td>1.20</td>
<td>12.85</td>
<td>0.32</td>
<td>15.13</td>
<td>11.07</td>
<td></td>
</tr>
<tr>
<td>7.95</td>
<td>1.20</td>
<td>10.93</td>
<td>0.35</td>
<td>15.13</td>
<td>7.30</td>
<td></td>
</tr>
<tr>
<td>6.17</td>
<td>0.35</td>
<td>7.95</td>
<td>0.32</td>
<td>3.33</td>
<td>1.11</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Heights and areas of windows and louvers in Atrium D
of ±0.3 °C, which included measurement errors caused by a time delay.

The sensor locations, shown in Figure 3, were selected based on a CFD-based design of experiments that has been described in detail in Chen and Gorlé (2019). We used CFD and UQ to identify optimal locations for temperature sensors under uncertain boundary and initial conditions where (1) the temperature difference between the volume-averaged temperature and the local point-wise temperature is small, and (2) the temperature is higher or lower than average over the duration of the night-time ventilation. This ensures that the measurements can support validation of the building thermal model that predicts the volume-averaged temperature of the entire building, while also supporting the validation of the spatial variability in the temperature field predicted by the CFD results. To achieve this goal, we divided each floor into five different zones based on the distance from the windows and on the overall geometry:

- Zone 1 and 4: Two zones for the hallways with offices on both sides
- Zone 2: The zone that includes the atrium connecting the different floors
- Zone 3 and 5: Two zones with the windows

As shown in Figure 3, we defined the optimal sensor locations to represent the volume-averaged temperature in each zone (marked as black crosses), as well as sensor locations on each floor to record lower (marked as blue crosses) and higher (marked as red crosses) temperatures during the night-time ventilation.

Experimental procedure

The experiments were conducted from 8:00 p.m. to 6:00 a.m. (+1 day) for a period of three weeks on nights that satisfied the following weather conditions:

- The outdoor air temperature was lower than the indoor temperature at 8:00 p.m.
• Low wind speed (typically less than 1 m/s at 9 m height based on local weather data)

In combination, these conditions ensure that buoyancy is the dominant driving force for the natural ventilation flow.

The BMS was overridden to make all motorized windows in the common space and the louvers on the northern and eastern sides open or close simultaneously. The temperature sensors started recording half an hour before the start of night-time ventilation at 8:00 p.m. to identify the initial thermal conditions of the building. Building occupancy was negligible during the measurements, internal heat loads were mainly due to lighting and some electrical devices.

**CFD model**

**Computational geometry and grid**

The computational domain is comprised of the common areas and hallways of Y2E2 (shown in Figure 4(a)) and the surrounding outdoor area. The far-field boundary is at least 25 m (around one building height) away from the building as shown in Figure 4(b). This is sufficiently large for an accurate prediction of the buoyancy-driven flow and temperature field in the building. A symmetry boundary condition is imposed on the lateral boundary cutting through the building hallways, mimicking the effect of the adjacent atrium.

Figure 4(b) illustrates the computational grid, which was generated using the ANSYS Meshing package and consists of 2.6 million cells. Gradual grid refinement is used to achieve a resolution of 0.09 m around the windows and louvers, corresponding to at least 28 cells at each of the windows. A resolution of 0.25 m is maintained within 2 m of the building, which results in $y^+$ values ranging from 30 to 200. Standard wall functions are applied on the building walls. A grid sensitivity analysis was performed, comparing predictions for the volume-averaged temperature for one night to the solution obtained with a finer mesh composed of 8.5 million cells. The difference between both results was less than 2% throughout the night-time ventilation; hence, the coarser mesh was used for further simulations to balance accuracy and computational cost.

**Turbulence model, boundary conditions, and solver settings**

Unsteady Reynolds-Averaged Navier-Stokes (RANS) simulations are carried to predict the time-varying air temperature in Atrium D during the first three hours of the night-time ventilation. The simulations are performed using ANSYS Fluent, solving the unsteady Reynolds-averaged equations for conservation of mass, momentum, and energy equations. The effects of buoyancy are modeled using the Boussinesq approximation. The Reynolds stresses are modeled using the Reynolds stress model (RSM) since this model has been shown to provide accurate predictions of the mean temperature for buoyancy-driven flows (Zhang, 2011). The turbulent heat fluxes are represented using the standard gradient diffusion hypothesis.

On the floors, walls, and ceilings, we prescribe the temperature profiles recorded as a function of time during the experiment. On the window openings, we prescribe

**Table 2: Temperature sensors in the Atrium D**

<table>
<thead>
<tr>
<th>Floor 1</th>
<th>Floor 2</th>
<th>Floor 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>Number of sensors</td>
<td>Height (m)</td>
</tr>
<tr>
<td>Z1-1</td>
<td>2</td>
<td>3 Air/Floor/Wall</td>
</tr>
<tr>
<td>Z2-1</td>
<td>1.5</td>
<td>2 Air/Floor</td>
</tr>
<tr>
<td>Z3-1</td>
<td>2</td>
<td>2 Air/Floor</td>
</tr>
<tr>
<td>Z4-1</td>
<td>2</td>
<td>3 Air/Floor/Wall</td>
</tr>
<tr>
<td>Z5-1</td>
<td>0.5</td>
<td>2 Air/Floor</td>
</tr>
<tr>
<td>H-1</td>
<td>3</td>
<td>4 Air/Floor/Wall/Ceiling</td>
</tr>
<tr>
<td>L-2</td>
<td>5.9</td>
<td>2 Air/Floor</td>
</tr>
</tbody>
</table>

Figure 4: (a) Perspective view of the Atrium D in its computational domain. (b) Computational grid
porous jump condition to represent the pressure drop caused by the opening angle of the window. A constant uniform pressure condition is imposed on the far-field boundary, together with the outdoor temperature as a function of time recorded by the outdoor temperature sensor of the Y2E2 building. We assume a spatially uniform indoor air temperature on each floor at the start of night-time ventilation. The initial condition for the indoor air temperature on each floor is specified following the volume-averaged temperature recorded by the temperature sensors.

The PISO algorithm is used for pressure-velocity coupling, and the equations are discretized using second-order schemes in space and a second-order implicit scheme in time. The time step is gradually increased from 0.5 seconds during the first 2 minutes, to 2 seconds during the following 13 minutes, and to 10 seconds for the remainder of the simulation, when the temporal changes in the flow and temperature field become small. At each time step, the residuals of the continuity and momentum equations dropped below $10^{-4}$ and $10^{-6}$ respectively before advancing the simulation.

**Results and discussion**

In the following, we present results for one of the experimental nights, considering an experiment with a very light SW wind (0.51 m/s recorded at the Stanford Weather Station) and a 3.4 °C indoor/outdoor temperature difference at the start of the night-time ventilation.

**Experimental results**

The presentation of the results focuses on a period of three hours, from 8:00 p.m. to 11:00 p.m. because windows and louvers are usually closed after a three-hour operation of night-time ventilation that the indoor air temperature drops below 20.3 °C. The results shown in Figures 5 – 7 have been obtained as follows:

- The indoor air temperature measurements were post-processed using a moving average filter with a 30-second window.
- The average indoor air temperature time series for each floor were computed from the volume-averaged of the measurements from the sensors located to measure the average temperature in each zone.
- The floor and sidewall temperature time series for each floor were calculated by taking the average of the surface measurements from the sensors on that floor.

Figure 5 shows the indoor air temperature time series measured in each zone on each floor. The data from Zone 5 on the third floor is missing due to a sensor malfunctioning. At the start of night-time ventilation, the temperatures at different locations are roughly the same. The initial temperature difference between indoor and outdoor air is 3.8 °C, and when opening the windows and...
louvers the cool outdoor air enters the building through the windows, while the warmer indoor air flushes out through the top louvers. The zones near the windows, where the cool air enters (Zone 5 on floor 1, and Zones 3 and 5 on the 2nd and 3rd floors), exhibit the highest cooling rates, while the zones most remote from the windows (Zone 3 on floor 1 and Zone 1 and 4 on all floors) have relatively low cooling rates, due to the lack of a direct flow path from the windows to the louvers through these zones. The zone that contains the atrium (Zone 2), where the warm air rises to exit through the louvers, exhibits a cooling rate between these high and low values.

Figure 6 depicts the average temperature for each floor during the night-time ventilation. The figure shows that the volume-averaged air temperature in Atrium D drops fast for the first 15 minutes after the start of night-time ventilation. This fast temperature drop is more pronounced on the 1st and the 2nd floors because the larger height difference between the windows and louvers results in a higher flow rate through these windows. The spatial variation in the temperature on a single floor at any given time is in the range of 2 °C.

Figure 7 shows the time series of the measured thermal mass temperatures, where the concrete floor temperature decreases by a little less than 1 °C. The time series indicate how the exposed concrete floors are cooled by the cold air entering through the windows, such that they can provide cooling when the indoor air temperature starts to increase during the following day. The floor temperatures increase slightly with the height of the floor, which can be explained by the generally positive temperature gradient in the building. The surface temperatures of the walls between the common space and offices have a slightly higher cooling rate than the floor, which can be explained by their lower thermal capacity.

Comparison of experimental and CFD results
The initial and boundary conditions for the CFD simulation are specified based on the measurements obtained during the specific night of interest. These measurements include the initial indoor air temperature...
for each floor, the time series of the outdoor temperature, and the temperature profiles for each floor and wall. The temperature field of the 3rd floor at 20 minutes after the start of night-time ventilation is presented in Figure 8, which shows that cool air entered from the windows on the left and front façades (located at Zone 3 and 5), Zone 1 and 4 are warmer than other zones, and the atrium allows warm air to escape from the louvers through the atrium. Figure 9 compares the CFD results to the full-scale measurements, indicating that the point-wise temperature predictions obtained by the CFD simulation at the sensor locations agree well with the experimental data. Figure 10 quantifies the agreements using the root mean squared error (RMSE) for each sensor. In the zones that are not directly exposed to the windows, such as Zones 1, 2 and 4, the RMSE is lower than 0.3 °C. In the zones adjacent to the windows, the difference between the CFD results and the experimental data is slightly higher, with an RMSE of up to 0.8 °C. The difference in the predictions could be due to uncertainty in the outdoor temperature measurements and the internal load, due to the uncertainty in the RANS turbulence model, or due to the reduced-order representation of the window geometry with a porous jump boundary condition.

Conclusions
This paper presents a full-scale experiment in Stanford’s Y2E2 building to (1) better characterize the thermal behavior of the building during night-time ventilation and (2) support validation of natural ventilation models. The measured indoor air, floor, and wall temperatures demonstrate that the buoyancy-driven night-time ventilation brings in cool air through the windows on each floor, cooling down the building thermal mass. An initial comparison between CFD results and the full-scale experiment shows that CFD provides an accurate prediction of the natural ventilation flow, with an RMSE in the predicted air temperature of less than 0.8 °C at all sensor locations. Ongoing work is focusing on validating a building thermal model with the full-scale experiment. This model calculates the natural ventilation flow rate using an envelope flow model and predicts the time-varying volume-averaged air temperature during the night-time ventilation (Lamberti and Gorlé, 2018).

Acknowledgement
We want to thank Lup Wai Chew and Jack William Hochschild for their invaluable support in executing the field measurement, as well as the Stanford University Science & Engineering Quad Building Management Team, Land, Stanford’s Land, Buildings & Real Estate Facilities Maintenance Technician and Stanford’s Fire Marshal’s Office for their assistance during the full-scale experiment. This research was supported by a Seed Research Grant from the Center for Integrated Facility Engineering at Stanford University.

References
Ramponi, R., Angelotti, A., and Blocken, B. (2014). Energy saving potential of night ventilation:

