Full-scale experimental investigations on a naturally ventilated building and validation of simulation models

Chen Chen [a,*], Catherine Gorlé [b]

[a,*] *Stanford University, Stanford, California, U.S., chenc2@stanford.edu*
[b] *Stanford University, Stanford, California, U.S., gorle@stanford.edu*

ABSTRACT: (10 pt)
The use of natural ventilation (NV) offers significant potential for energy and cost savings, but the performance of a NV system highly depends on climate and weather conditions and building operating conditions. Air flow and temperature predictions obtained using computational models can provide insight into this variability, provided that the accuracy of the models can be guaranteed. This study uses a full-scale experiment conducted in an operational educational building with night-time ventilation to validate two different computational models. The experiment was carefully designed and executed to validate (1) a building thermal model that predicts the volume-averaged building temperature, and (2) a computational fluid dynamics (CFD) model that predicts the time-varying temperature field in the building. The CFD model is found to predict the measured point-wise temperatures with an RMSE of less than 0.8°C. In regions not directly adjacent to windows, the RMSE can be smaller than 0.3 °C.

Keywords: natural ventilation, full-scale experiment, CFD, building thermal model, validation

1. INTRODUCTION

Natural ventilation is a key solution for significantly reducing building energy consumption, but the performance is highly affected by local climate and weather conditions and building operating conditions. A well-functioning NV system design requires profound knowledge of the complex governing flow and heat transfer; thus, NV models are essential to provide adequate information during the design process. In a previous study, a multi-fidelity computational framework with uncertainty quantification (UQ) was proposed 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 (Y2E2) building (Lamberti & Gorlé, 2018). Comparison of the results with building sensor measurements indicated that the building sensors are located in regions with higher-than-average temperatures, such that the measurements are not representative of the volume-averaged temperature. A more carefully designed full-scale experiment is needed to support validation of (1) a building thermal model that predicts the volume-averaged building temperature, and (2) a CFD model. In this abstract, we summarize: (1) the use of CFD and UQ to identify optimal locations for temperature sensors under uncertain boundary and initial conditions; (2) the experimental campaign performed during several nights under a variety of outdoor temperature and wind conditions; (3) a comparison between experimental measurements and a CFD model prediction for one single night, where the specific experimental conditions were reproduced in the CFD model to validate the model set-up.

2. BUILDING DESCRIPTION AND EXPERIMENT SETUP

2.1. Building description

* Lead presenter

The Y2E2 building has 14,000 m^2 of floor space on three above ground levels and one basement level, connected through hallways and four atria (Fig. 1(a)). The building uses a night-time NV system, which operates from 8:00 p.m. to 6:00 a.m., to cool the common spaces (hallways, open areas, and lounges connected to the central atria). Motorized windows in the common spaces on each floor are controlled separately and open on the condition that the outdoor temperature is lower than the indoor air temperature and the indoor temperature is greater than 22.35℃. If the temperature drops to 20.35℃, the motorized windows on that floor close again. Meanwhile, based on the measured wind direction, the two leeward sides of the louver banks at the top of the atria are opened, generating a buoyancy-driven flow that brings in cool air through the windows and flushes out warmer air through the louvers.

(a) (b)

Figure 1: (a) Atrium D of the Y2E2 building (left), atrium louvers (top right), and indoor view of Atrium D (bottom right); (b) Computational grid

2.2. Experiment setup

The sensor locations were selected based on a CFD-based design of experiments that has been described in detail in Chen and Gorlé (2019). CFD and UQ were employed to make sure that the temperature sensors are located where (1) the temperature difference between the volume-averaged temperature and the point-wise temperature is small, and (2) the temperature is higher or lower than average over the duration of the night-time ventilation. In combination, these measurements will support validation of the building thermal model that predicts the volume-average temperature in building, as well as validation of the CFD model. The full-scale experiments were conducted from 8:00 p.m. to 6:00 a.m. 20 temperature sensors were placed in the optimal locations distributed throughout atrium D. 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. The temperature sensors were calibrated using a temperature calibrator with an accuracy of $\pm$0.3℃, which included measurement errors caused by the sensor response time.

3. CFD MODEL

The computational domain is comprised of the common areas and hallways of atrium D and the surrounding outdoor area (Fig. 1(b)). The far field boundary is at least 25 m (around one building height) away from the building, which is sufficiently large to ensure there are no unwanted effects of the boundary conditions on the prediction of the buoyancy-driven ventilation flow. A griddependence study resulted in the selection of a mesh of 2.6 million cells with a minimum resolution of 0.09 m around the window regions. The CFD simulation was performed using ANSYS Fluent, solving the Reynolds-averaged conservation of mass, momentum, and energy equations. The Reynolds stresses are modelled using the Reynolds Stress Model (RSM). The temperature profiles recorded during the experiments were imposed on the floors, walls and ceilings. 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. The initial condition for the indoor air temperature on each floor is specified as the volume-averaged temperature recorded by the temperature sensors at the start of the experiment.

4. RESULTS AND DISCUSSION

In the following, we present results for one measurement night with a light SW wind (0.51 m/s recorded at the Stanford Weather Station) and a 3.8 ℃ initial temperature difference at the start of the night-time ventilation. The time-varying indoor air temperatures were recorded for a three-hour period during night-time ventilation. Comparison of the CFD results to the full-scale measurements indicates that the point-wise temperature predictions from the CFD simulation agree well with the experimental data recorded by the temperature sensors. The root mean square error (RMSE) for sensors located in regions that are not directly exposed to the windows is lower than 0.3℃ (Fig. 2 (a)). In the zones adjacent to the windows, the RMSE goes up to 0.8℃ (Fig. 2 (b)). Thus, the results indicate that CFD models can provide an accurate prediction of buoyancy-driven natural ventilation, provided that accurate initial and boundary conditions are specified. Ongoing work is focusing on validating an integral model with the full-scale experiment.

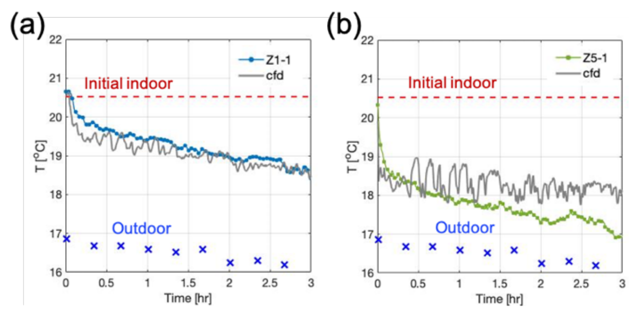

Figure 2: Comparison of CFD results and experimental data in the Atrium D during night-time ventilation

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