Assessment of Natural Ventilation using a Whole-Building Simulation Model: A Case Study of a Landmark Building

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Abstract – Whole-building simulation and field measurements were conducted at two levels: at the whole building level and at the local-space level, at a landmark building in Vancouver, Canada. The analysis shows that calibrated whole-building simulations are accurate enough and useful for the assessment of natural ventilation. For large complex spaces, the analysis needs to be coupled with computational fluid dynamics to predict thermal stratification. In the case study building, such coupling was not critical, because changes in the natural ventilation original design intent caused a large atrium to be decoupled from the rest of the building, which was detrimental to the effectiveness of the natural cooling of the building in the summer.

1. Introduction

Arguably, airflow modeling is the weakest link in whole-building simulation modeling. The effects of proper airflow modeling are less critical in designing mechanically heated/cooled buildings, and in airtight and adequately compartmentalized buildings. However, a proper engineering of natural ventilation designs is required when passive, natural ventilation is a critical strategy to achieve performance targets. The case study building was designed to rely entirely on natural ventilation for cooling. The motivations for this study were two-fold: 1) we learned that the design team placed great effort in designing a passive building with adequate natural ventilation, and 2) we learned that the initial design intent evolved during the design and construction process, resulting in potential compromises to the effectiveness of the natural ventilation for cooling. Our ultimate goal was to try to understand the effectiveness of the natural ventilation strategies and the impacts of the changes to the original intent. As such, we monitored the indoor conditions and the operation of doors and windows during two summer weeks in August (the only time available for us), and used whole-building simulation (WBS) to help as an exploration tool.

2. Airflow Network Modeling

Modern whole-building simulation models include an airflow network (AFN) modelling engine to simulate airflow across spaces. AFN models idealize a building as a collection of zones, such as rooms, hallways, & duct junctions, joined by flow paths representing doors, windows, fans, ducts, etc. Three key AFN modeling assumptions are: 1) it assumes that the resistance to airflow of a flow-limiting path between building zones is much greater than the resistance to airflow of the zones themselves. 2) The airflow within a zone is zero, which means that the pressure varies only hydrostatically within a building zone. 3) The temperatures within a given zone are uniform.

Buoyancy and thermal stratification in large spaces are modelled by stacking zones vertically, and connecting the stacked zone with horizontal virtual surfaces. Solar irradiation passes through virtual surfaces down to the bottom zone, and long wave radiation and convective heat transfer take place at each stacked zone, to simulate the warming up of air as it moves upwards. Therefore, the air stack modelling assumes one-way flow upwards only, which is a safe assumption when modeling chimneys for example. However, in large spaces such as atriums and auditoriums sub-zonal airflow patterns may involve air recirculation, due to a combination of high pressures at the top of the space and/or reverse buoyancy due to air contact with cold surfaces. In general, when detailed characterization of airflow circulation within a space is required, a higher level of granularity modeling is needed, such as zonal models or computational fluid dynamics (CFD). CFD modelling is able to consider complex turbulence behaviors that are the norm in indoor spaces.

3. The case Study Building

The case study building is the visitors centre for the botanical garden in Vancouver, Canada. The design of the building is inspired by a local orchid plant, with its roof mimicking its petals and the central atrium and oculus mimicking its stem. Tables 1 and 2 show the main spaces, as well as their function and occupancy. The whole-building simulation model was originally created in IES-VE by the mechanical design team [1], but was fine-tuned and improved to represent the actual building by the authors. The building is one-storey with a footprint of 1765 square meters.

Table 1. Space functions

Space function	Space name
Multipurpose	Flex 1 and 2, Great hall
Atrium	Atrium
Retail	Garden shop
Office	Garden shop office
Library	Library
Classroom	Classroom, Volunteer Room
Food preparation	Food Service

Table 2. Building occupancy groups

Occupancy group	Building occupancy time	Notes
1. Garden visitors	10 minutes to approximately 1 hour	Access the garden through the building, use the food service
2. Event users	Periods of 2 to 4 hours throughout the day	Rentals for events
3. Seasonal users	Whole days during summer weeks	Summer camps
4. Staff	Regular office hours throughout the year	Administrative and service staff

The natural ventilation design involved orienting the building to maximize cross-ventilation, and enhancing stack and buoyancy airflows through operable windows and a central atrium with an oculus at the top acting as glazed chimney that draws warm air from the building. The design follows passive design practices such as proper shading, high thermal mass, an extensive green roof, operable windows, and an integrated natural ventilation strategy. Furthermore, the operation of the building uses automated windows synchronizing the opening/closing of windows at the perimeter and at the atrium oculus.

4. Instrumentation

Two levels of monitoring were followed: 1) Whole-building level (2 weeks) - indoor environmental (air temperature, relative humidity, CO2) and window/door state sensors at the main spaces, 2) local level (2 days) - higher granularity temperature stratification, air speed, and oculus open/close operation measurement at the atrium. Figure 1a shows the placement of the sensors for level 1 monitoring, as well as the intended natural airflow paths. Figure 1b shows temperature/anemometer instrumentation for level 2 monitoring at the atrium. A weather station was also placed on the roof of the building. The main challenge in instrumenting the atrium/chimney was protecting the sensors from direct solar irradiation, while not interrupting airflows. To that effect, a reflective shield was placed to protect the sensors at the top. However, the intermediate sensors were not shielded in order not to obstruct the airflow. They were instead carefully placed under the shaded area of the chimney.

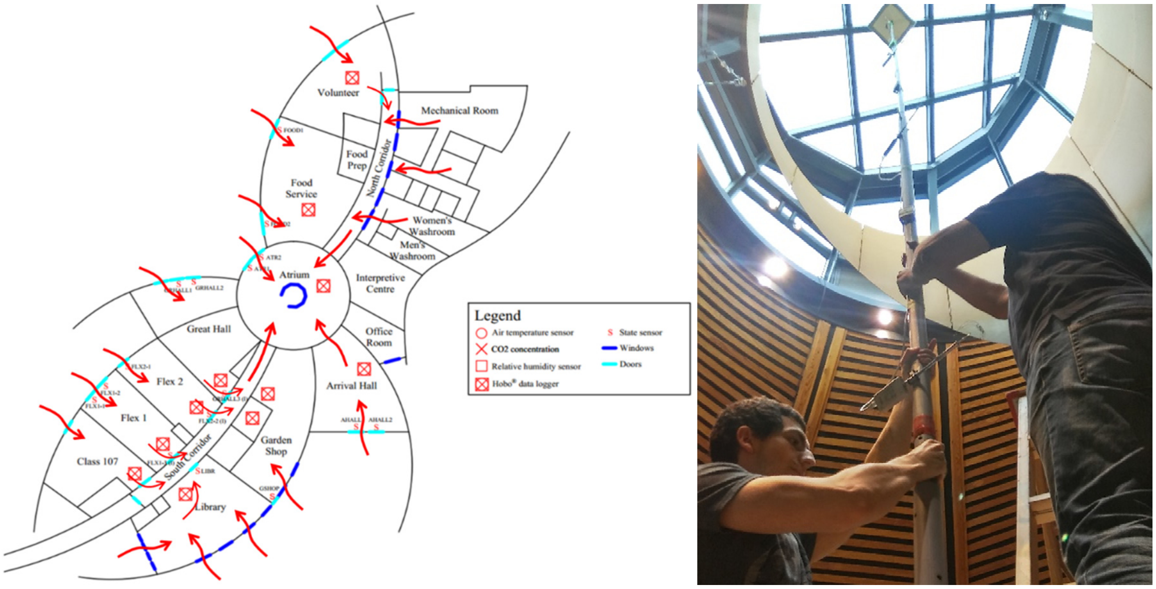

Figure 1. Instrumentation: a) whole building level, b) atrium level

5. Natural ventilation modeling

IES-VE uses AFN to model airflows. A main challenge in the modeling is the fact that all spaces in the building are tall with curvilinear heights ranging from about 3.5 meters to about 6.5 meters. The height of the atrium including its glazed oculus is 10 meters. Therefore, all the spaces were modeled as vertically stacked air nodes (Figure 2).

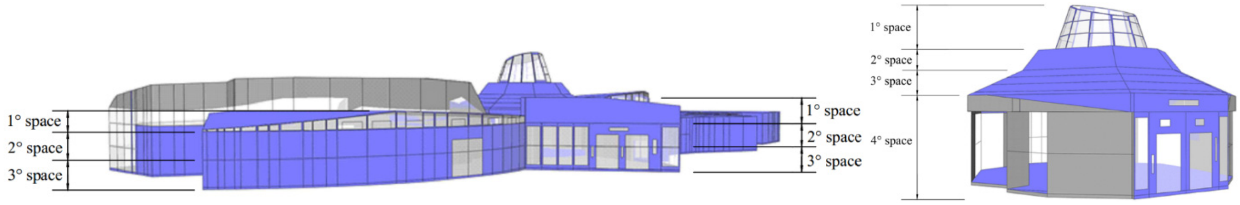

Figure 2. Stacking of air nodes to model buoyancy using AFN model [1]

5.1. Design and modelling challenges and hypotheses

Aside from buoyancy and the typical challenges in modeling natural ventilation (characterizing airflow through openings and air-node topology/connectivity), the following challenges were identified in the design and the thermal-fluid airflow modeling:

Design challenges – The original design used a large plenum connecting all the spaces at the top to collect warm air and channel it to the central chimney. However, due to privacy and acoustic concerns, the connectivity between spaces at the top was sealed. The only connection between the spaces and the chimney was through the doors at the corridors. However, most of the times, during events and summer camps these doors remained closed. As a result, the connection between spaces and the chimney became weak. Most importantly, the chimney became a short-circuiting path that draws air mainly from the main doors at the central atrium, thus bypassing the building!

Modeling challenges – The occupancy for this building is mainly transient. The building acts as a gate for the botanical garden. The doors through the gate are at the atrium. These doors are meant to be opening and closing constantly during the day. Furthermore, in summer days the exterior doors at both sides of the atrium are left wide open, as well as the exterior doors at the food service. Therefore, at periods of high occupancy, the atrium acts like a large cross-ventilation shaft, semi-isolated from the rest of the building.

Therefore, it was hypothesized that the intended natural airflows in Figure 1a are not substantiated. As a result, the natural ventilation of the main spaces is mainly single-sided, whereas the chimney draws air from the exterior doors in the atrium below, cooling it down and bypassing the rest of the building. To account for these challenges, the connectivity between spaces was carefully modelled, including logic to operate windows and doors according to both, the outdoor temperature and the occupancy schedules.

5.2. Model calibration

According to Figure 3a [2], model calibration was not to the highest level. Due to limitations imposed by the building owners, no surveys were applied to the building occupants. Uncertainty analysis was left as future work. The calibration/validation was done using the spaces temperatures and year-round energy data. Temperature wise, the aim of the model calibration was obtaining temperature patterns close to the actual ones. Energy wise, a year-round mechanical heating energy comparison was made between actual and simulated data (Figure 3b). The model was considered valid once the actual and simulated data was close enough using standard statistical metrics (e.g. ASHRAE Guideline 14-2014). Energy calibration was broken-down into systems and uses. The main discrepancy in energy consumption was found in December due to a high volume of visitors attending special events taking place in the garden.

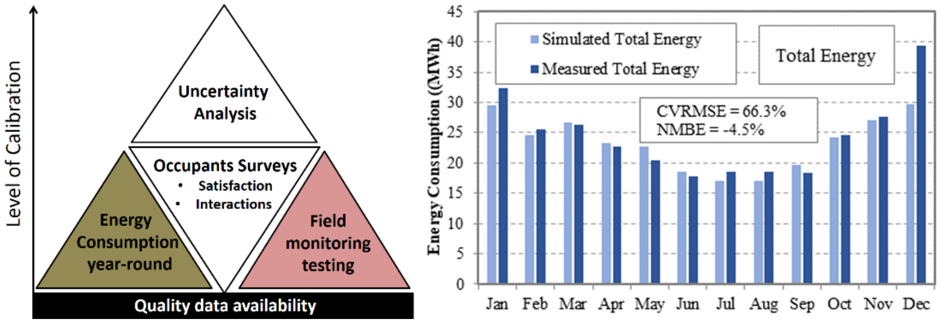

Figure 3. Model calibration: a) calibration level, b) total energy consumption [2]

6. Results

Whole-building year-round simulations used local weather data from the city of Vancouver for the same year the energy data was collected. Careful selection of system and thermostat temperature set points was necessary to match the real operation. These simulations were used for model calibration purposes and analysis at an aggregated level. For increased granularity, we studied typical sunny days when data was collected, and compared the measured room temperature data with the simulated data.

6.1. Whole-building

Space	Max. Temp. (°C)	Min. Temp. (°C)	Avg. Temp. (°C)
Atrium	28.9	22.3	24.8
Arrival hall	28.6	23.1	25.5
Classroom	28.4	23.7	25.4
Great hall	27.4	22.9	24.4
Flex 1	28.1	23.3	24.8
Flex 2	28.1	23.1	24.7
Food service	30.2	22.4	26.2
Garden shop	28.3	23.1	25.4
Gar. shop office	28.9	25.7	27.5
Library	27.2	23.4	24.9
Volunteer room	28.0	22.8	24.3

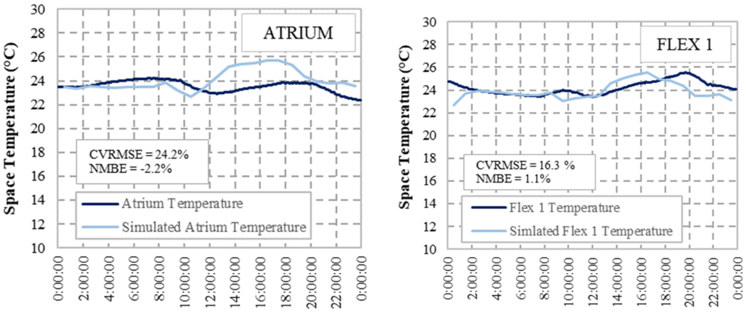

Figure 4. 2-week measured data, and comparison between measured and simulated temperatures for a sunny day

Figure 4 shows the measured data over the two monitoring weeks, as well as a comparison between the measured and simulated data for two spaces in a typical sunny day.

6.2. Atrium and chimney

A measurement station was placed at the center of the atrium with a large extensible pole holding the loggers/sensors. The sensors/logger were placed at heights of 2, 3, 5, 7, and 8.5 meters from the ground. The top logger was right at the oculus. All windows were opened during the experiment, including those at the oculus. As indicated in Figure 5, the measurement station was moved horizontally at times indicated by the vertical lines. At about 10:00 hours all atrium doors were fully opened, and left open until about 12:14 hours. At that moment, we requested the atrium doors to be closed until about 12:57, with a corresponding increase in temperatures. Between 12:57 and 14:09 half of the doors were open. At 14:09 all doors were fully opened again with a corresponding decrease in temperatures. At about 13:26 we moved the station to avoid direct solar radiation on the sensors. However, we could not avoid the sun to strike in two sensors HOBO#2 and HOBO#3. Therefore, the subsequent data from those sensors is invalid. Unfortunately, in measuring air speeds, at about 13:40 we lost connectivity of our sensors and the data was lost for about one hour.

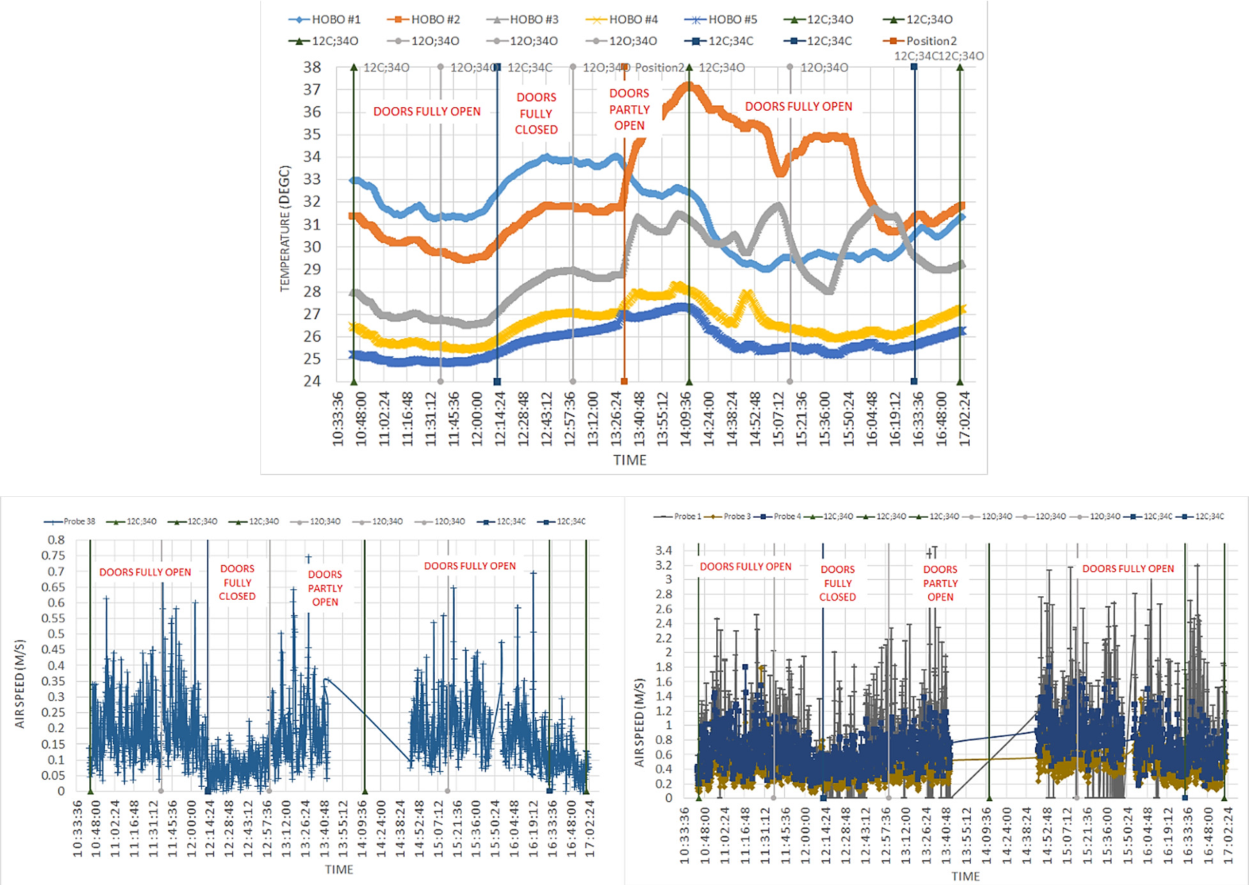

Figure 5. Measured atrium thermal stratification (top), atrium air speed (left), air speed at oculus windows (right)

From Figure 5 it is clear that the temperatures in the atrium and chimney are highly dependent on the opening of the atrium exterior doors. Thermal stratification ranges from about 25°C to 32°C in the morning when the atrium doors are open, to about 27°C to 34°C when the door are closed, and about 26°C to 30°C in the afternoon when the doors are open again. Higher air speeds were observed in the afternoon at the oculus windows level, but The afternoon cooler temperatures are likely due to increased wind speed, and cross-ventilation across the atrium and the chimney. Figure 6 shows the oculus surface temperature.

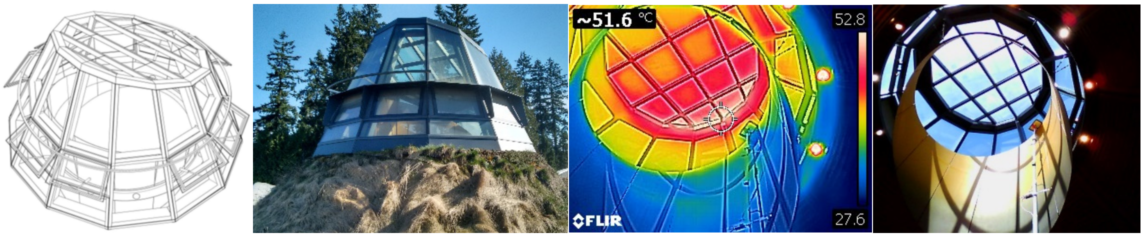

Figure 6. The chimney oculus

In Figure 7, simulated data from the same day at heights indicated in Figure 2 (right) shows the oculus air is cooler early in the morning, perhaps due to night-sky radiation, but it gets much warmer as the sun shines on it. However, as soon as the oculus windows are opened at 10:00 hours, the oculus cools down immediately! Surprisingly, in the simulations, the air flow is very effective in removing thermal stratification.

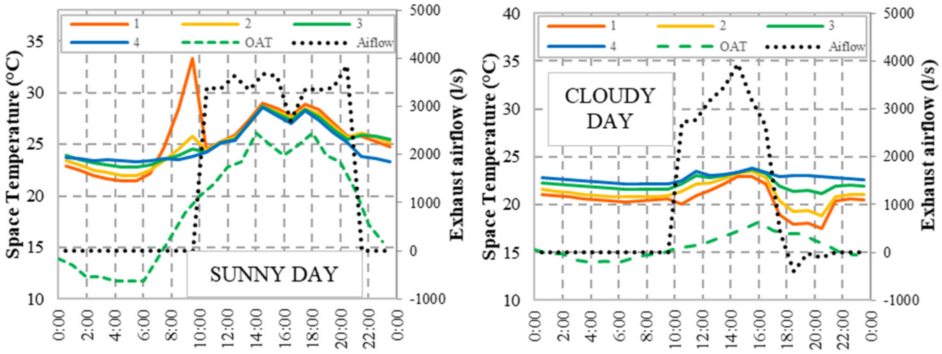

Figure 7. Simulated atrium thermal stratification in a sunny day (left) and a cloudy day (right)

7. Analysis and discussion

The results demonstrate that AFN-integrated whole-building simulation can reliably predict airflows and indoor temperatures in the whole building under natural ventilation forces. However, local-level analysis at the atrium and chimney/oculus demonstrates that the accuracy of natural ventilation in predicting thermal stratification is low. Furthermore, complexities in the shape of the atrium and the oculus led to several observations affecting the accuracy of the AFN modeling as well as the measurements:

- The shape of the chimney (atrium and oculus) is not optimized to enhance buoyancy. The atrium is wide open, and its chimney is wide and not very long. Therefore, there is little opportunity for the rising air to pick up heat from the walls, and enhance buoyancy.
- The atrium draws air simultaneously from several directions (Figures 2 and 8). The amount of air coming from each direction is highly dependent on the opening and closing of doors, as well as the wind. This complicates the measurement and simulation of airflow patterns in the atrium.
- The oculus at the top has the shape of an inverted container; therefore, its hot walls contribute little to the airflow. It is hypothesized that warm air at the very top accumulates and creates a stratified layer that overflows at the bottom.
- It was observed that at high winds, air comes into the chimney (instead of going out), thus countering buoyancy. Perhaps this was the reason why the top of the atrium was kept cooler in the afternoon. This hypothesis would need to be confirmed with more data and detailed CFD simulations.

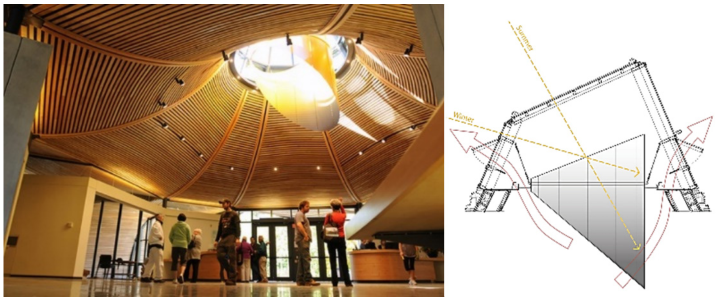

Figure 8. Atrium chimney/oculus measuring and modeling complexities

8. Conclusions and Further Work

The case study demonstrates that AFN-integrated whole-building simulation modeling is a viable tool to help assess the performance of naturally ventilated buildings. However, for large complex spaces a higher level of modeling granularity is required. In this particular project, the inaccuracies introduced by the inaccurate atrium model were minimized because the atrium was actually de-coupled from the building, contrary to the initial design intent. Detailed CFD modeling of the atrium coupled with an outdoor CFD computational domain will help better understand the airflow patterns in the atrium. Such modeling will in turn help optimize the shape the oculus and the connectivity between the atrium and the building spaces to improve the natural ventilation effectiveness.

Acknowledgements

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9. References

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2. Martins de Barros, F. C. G. 2017. Assessment of Natural Ventilation Using Whole Building Simulation – Methodological Framework. Master’s thesis, British Columbia Institute of Technology, Canada.