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ASSESSMENT OF NATURAL VENTILATION USING WHOLE BUILDING SIMULATION MODEL (WBSM) IN A CASE STUDY BUILDING

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ABSTRACT

The goal of this study is to use whole-building simulation modelling (WBSM) to assess the natural ventilation performance of a landmark building located at Vancouver. The building uses natural ventilation as the only source of cooling in the warm and mild seasons. A whole building simulation model (WBSM) of the building is developed and validated. The calibration and validation of the model are done by using data from field testing, local weather station, and energy trendlogs. The assessment includes energy consumption, thermal comfort and overheating analysis. Energywise, the building performs better than the ASHRAE 90.1 baseline. The adaptive thermal comfort model is used in order to determine the thermal comfort. The field testing and simulation indicate that the natural ventilation is effectively providing cooling for the building's occupant during the summer for most of the rooms without compromise the energy performance. It is concluded that even though a well-conceived natural ventilation design was applied to case study building, some rooms overheat during significant periods.

INTRODUCTION

The potential benefits of natural ventilation are in terms of lower energy consumption, thermal comfort, indoor air quality and operating costs. Over the years, natural ventilation designs and technologies have evolved in Europe. But there is still a lot of work needed before this design strategy can be realized in North America; the added complexity of having to consider uncertainties from natural forces and interactions with human occupancies still leads building stakeholders to prefer to rely on mechanical ventilation.

Whole building simulation modelling (WBSM) tools are emerging as viable tools to support natural ventilation design. However, there is a lack of validation through measurement of the effectiveness of natural ventilation designs in real buildings (Ellis, 2016). Whole building simulation model (WBSM), also called building energy models (BEM), are physics-based computer representations of buildings describing relevant abstractions of the geometry, properties, and behaviours of interrelated building systems and components through mathematical models of underlying physics heat, air, and moisture transport processes. WBSMs are used to simulate dynamic energy flows in buildings and estimate whole building performance under realistic dynamic boundary conditions defined by the local climate, occupancy, and processes.

The use of WBSM is becoming mainstream to support design decisions. Several commercial software applications are available and in use by the industry, notably: eQUEST (2016), IES-VE (2016), TRNSYS (2015), DesignBuilder (2016), and OpenStudio (2016). All the applications above are well established, and their models have been extensively validated. However, the reliability of the results depend on two main factors: 1) the adequacy of the models embedded in the tools to accurately represent the intended building application, and 2) the accuracy of the input parameters and coefficients used by those models. Simulating building energy flows under natural ventilation operation involves increased complexities compared to pure mechanical operation. This study has chosen IES-VE software in order to achieve its goal. Several reasons led to this decision, the first is that this particular software is well-established to model natural ventilation and other passive strategies.

CASE STUDY BUILDING

The case study is a one-storey landmark building with a design aimed to achieve net-zero energy through a variety of technologies including solar hot water, photovoltaic panels, geothermal boreholes and natural ventilation. The main motivation for using this building as a relevant case for natural ventilation assessment is that the building relies exclusively on natural ventilation to provide thermal comfort for its occupants during the warm and mild seasons.

The architectural features incorporated in the natural ventilation design are represented in the building as solar shading system, building's thermal mass and green roof, and the solar chimney.

The case study building is a multi-purpose single story building that consists of education and administration building comprising a library, visitors lounge, garden shop, flexible spaces that may be rented out for meetings, a classroom and volunteer room. Table 1 shows the function of each space according to the ASHRAE 90.1 (2010) parameters and their respective names later used in the analysis.

Table 1
Names and space functions of the case study building

	SPACE FUNCTION	SPACE NAME
CASE STUDY BUILDING	Multipurpose	Flex 1 and 2, Great hall
	Atrium	Atrium
	Retail	Garden shop
	Office	Garden shop office
	Library	Library
	Classroom	Classroom, Volunteer Room
	Active Storage	-
	Corridor	-
	Food preparation	Food Service
	WC	-
	Mechanical or Electrical Room	-

The natural ventilation strategy relies on a combination of cross-ventilation and buoyancy-driven ventilation. Cross-ventilation is achieved through automated operable windows positioned in all façade orientations. Buoyancy-driven ventilation draws air from the windows and drives it through high ceilings in all rooms, a plenum space at the top of the rooms, and a central atrium. At the top of the atrium, a solar chimney is designed to enhance the buoyancy-driven natural ventilation.

AIRFLOW SIMULATION IN WBSM

Normally, whole building simulation model (WBSM) uses the Airflow Network (AFN) approach to characterize the airflow through the building. However, modern energy software is usually fully coupled with the zonal model (i.e. similar physical background as the AFN, but instead of considering a room/space as a single node, the zonal model divides that one space in subzones) and Computational Fluid Dynamics (CFD) module. CFD could be used to describe the airflow behaviour within a particular internal space or through the whole building. But the appropriate use of CFD requires a number of special attention to details and model validation. Figure 2 illustrates a schematic example of airflow modelling in whole building simulation model (WBSM). In that example, AFN is used to model the airflow through the entire building. But for the atrium (red circle) the airflow is better detailed using CFD or a zonal model, as the assumptions adopted by the AFN do not represent the space being modelled (e.g. fully-mixed air in the space, single temperature and pressure, and etc.).

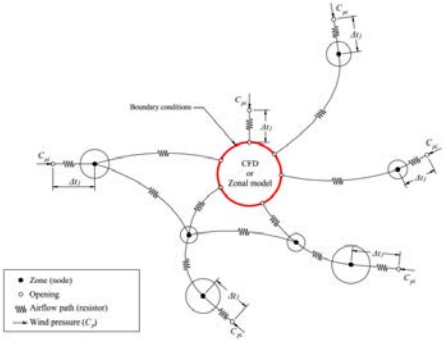


Figure 2 Schematic example of whole building simulation model (WBSM)

WBSM DEVELOPMENT FOR THE CASE STUDY

The WBSM uses a standard Test Reference Year (TRY) weather file for Vancouver. Figure 3 shows the temperature for all the hours of the year. It is observed that the mild temperatures between mid-April and September are suitable for natural ventilation. From October to March, the temperatures drop below 13 °C, which makes natural ventilation for cooling impractical for most cases. For these range of temperatures, mechanical or hybrid ventilation become a more suitable option.

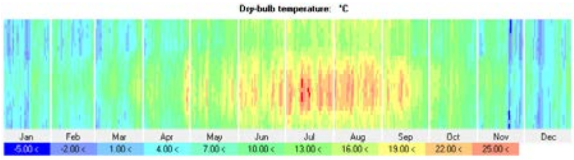


Figure 3 Vancouver whole-year hourly temperatures

To isolate the suitable temperatures for natural ventilation figure 4 is presented. In the picture, the red points represent temperatures above 14 °C and the blue points temperatures below 14°C. This specific threshold of was chosen following the case study building's automation system (BAS), which determines that the windows providing natural ventilation should be open when outdoor temperatures are higher than 14 °C and the spaces temperatures are above a certain setpoint.

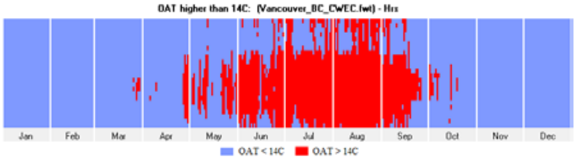


Figure 4 Vancouver whole-year hourly temperatures

During the whole year, 25.8% (2260 hours) of the total amount of hours the outdoor air temperatures are higher than 14 °C. When only the occupied hours are analyzed (between 9 AM and 9 PM), 35.9% (1572 hours) of the time the temperatures are that range. Those numbers show the potential of the use of natural ventilation for Vancouver's climate.

The case study building is surrounded by the green landscape: trees, a small lake, low-rise residential buildings, and a park. The building's neighbourhood is not composed of high-rise buildings or any major obstruction to the airflow paths. For that reason, no obstruction or surrounding structure was positioned in the simulation space of the WBSM.

The building envelope is composed of a green roof, concrete walls, a high-performance fenestration system, and concrete floor slabs. The higher building's thermal mass is guaranteed by the presence of a green roof, external concrete and rammed earth walls, and the concrete floor slabs. This feature makes part of one of the elements that enhance the natural ventilation effectiveness of the building.

The equipment loads adopted in the WBSM were carefully estimated based on the actual equipment used in the building. The lighting loads are based on the actual lighting design.

Three groups of occupants use the building: 1) transient visitors that typically occupy the building for less than about two to three hours; 2) users/renters of the multi-function spaces that occupy the building between about three hours, one day, and weeks; and 3) staff that use the building during regular work hours. Due to limitations imposed by the building owners, no surveys were applied to the building occupants. However, through informal conversation with the staff, it is possible to draw some previous observations on the how groups 2) and 3) interact with the building to achieve thermal comfort during the summer when natural ventilation is being used. Firstly, the occupants claim some thermal discomfort during the hot season. During that period it is normal to find personal fans positioned across the building. As expected, the occupants also open the doors to increase the airflow.

Regarding the buoyancy force, the WBSM divided each internal space into three zones stacked vertically. The main reasons for such configuration were: a) to handle the complexity of the roof shape, b) to account for buoyancy in each space, as all the spaces have high ceilings. Then, this approach successfully represents the buoyancy forces in the spaces and end up working similarly as a zonal model.

The external openings are composed of top hung windows and side hung doors. The majority of the windows are automatically open following certain control logic. The automatic windows are open when the outside temperature is higher than 14 °C and the spaces temperatures are above a specific setpoint. When these conditions are met, the windows are open providing cooling for the spaces. However, if the internal spaces temperature drops below the setpoint (plus the dead band) the windows are closed. When the outdoor air temperature goes below 14 °C the windows should be closed. However, in the WBSM, all the openings used the same logic behind its operation: they open when outdoor air temperatures are above 14°C and the internal space temperatures are higher than 24°C.

CALIBRATION AND VALIDATION

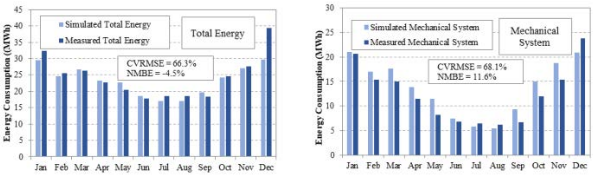
Knowing the increased level of uncertainty involved in naturally ventilated buildings, a methodology to calibrate/validate WBSMs for natural ventilation is presented by Martins de Barros (2017) and applied in the case study model. The driving forces for natural ventilation are inherently different from those in mechanically ventilated buildings; these are the outdoor weather and the human factors, both directly affecting the building usage and operation, and consequently increasing the level of uncertainty of the simulation. Therefore, the methodology proposes that the weather and human factor need to be given careful consideration in WBSM calibration and validation. Unlike mechanically conditioned buildings, the measurement of these factors is crucial to reduce the observation error/uncertainty. Thus, the methodology proposed by Martins de Barros (2017) suggests the following calibration process for a WBSM under natural ventilation:

1. Use of year-round simulation data with heating/cooling energy consumption. This is because cooling may be selectively used even in parallel with natural ventilation, especially in mixed-mode ventilated buildings. For purely natural ventilation cooling, the year-round energy consumption makes it possible validate the internal loads applied to the building.
2. Use of field testing data or data from the building automation system (BAS). Including internal spaces, operative temperatures (t_o), openings status and etc.

3. Conduct occupant recurrent surveys to analyze how they interact with the building. Identifying how the occupants operate the windows, use personal fans, and other thermal adaptive approaches.
4. Realize an uncertainty model; similar to the one suggested by Coakley et al. (2014).

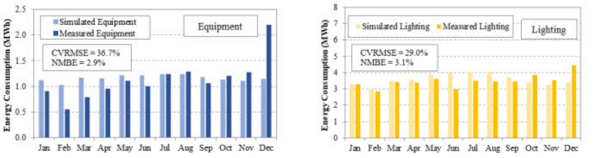
The lack of historical data from the case study building automation system (BAS) made it necessary to position sensors inside the building, to record internal temperatures, relative humidity and CO_2 concentration. The outdoor environment was recorded by a local weather station positioned on the building's roof. The main drawback to the validation process is regarding the lower quality of energy data. The energy consumption available was inconsistent and presents a number of gaps. The calibration/validation was done using the spaces temperature and year-round energy data. Due to limitations imposed by the building owners, no surveys were applied to the building's occupants. Moreover, an uncertainty analysis was not performed.

Figure 5 illustrates the comparison between the measured and simulated energy consumption throughout the year. The values of CVRMSE and NMBE are higher than expected for monthly data. ASHRAE Guideline 14 (2014) suggests that the values of CVRMSE and NMBE should be below 15% and 5%, respectively, for monthly energy consumption. However, the lower quality of energy data compromises the reliability of the energy data. Notwithstanding, the values or measured and simulated energy data fairly correlate.



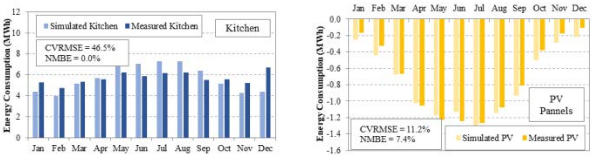
a) Total energy consumption

b) Mechanical system energy consumption



c) Equipment energy consumption

d) Lighting energy consumption

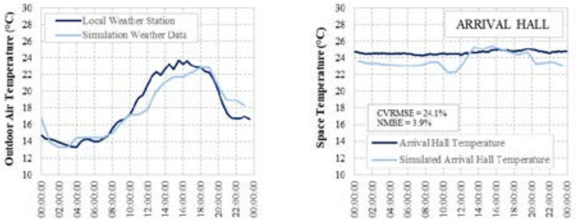


e) Kitchen energy consumption

f) PV panels energy generation

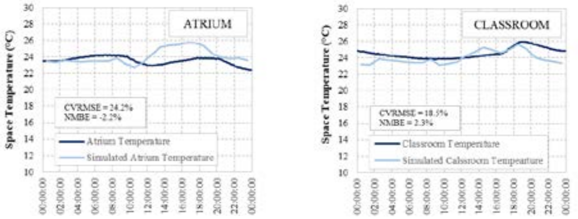
Figure 5 Comparison between measured and simulated energy consumption

Furthermore, the on-site weather data is not directly applied to the simulation. Instead, the weather data is used to compare days with similar daily weather profile. Then, the daily internal temperatures for each space are compared. This approach is used extensively throughout different days. 10 days are analyzed and compared with the simulated data. Figure 6 illustrates one typical day used to validate the WBSM.



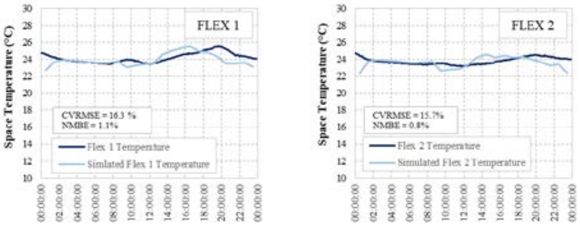
a) Comparison between simulation and real weather data

b) Arrival hall real and simulated data



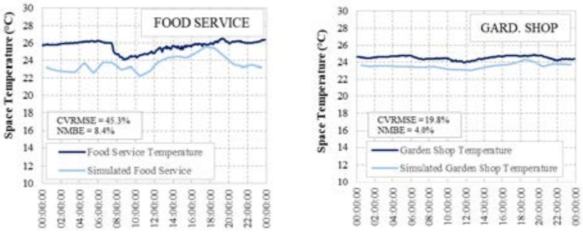
c) Atrium real and simulated data

d) Classroom real and simulated data



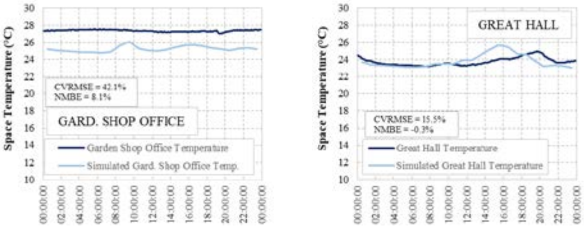
e) Flex 1 real and simulated data

f) Flex 2 real and simulated data



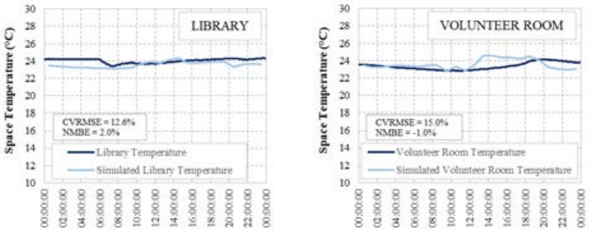
g) Foodservice real and simulated data

h) Garden shop real and simulated data



i) Garden shop office real simulated data

j) Great hall real and simulated data



k) Library real and simulated data

l) Volunteer room real and simulated data

Figure 6 Comparison between measured and simulated energy consumption

Figure 6 shows an unusual flat temperature pattern for all spaces. The main reason for this unusual pattern is the lack of night-time ventilation. Table 3 summarizes the values of CVRMSE and NMBE for all the 10 days used in WBSM validation and presents the values for all the spaces used in the validation.

Table 3
Final results on the WBSM validation for spaces temperatures

	CVRMSE (%)	NMBE (%)
ATRIUM	33.1	1.8
CLASSROOM	38.0	6.0
ARRIVAL HALL	38.9	4.8
FLEX 1	24.6	2.9
FLEX 2	26.2	3.5
FOOD SERVICE	49.3	7.6
GREAT HALL	23.9	2.1
GAR. SHOP OFFICE	60.8	11.1
GARDEN SHOP	36.3	5.7
LIBRARY	36.6	6.1
VOLUNTEER	23.5	2.3

From figure 6 and table 3, it is possible to observe that the simulation is fairly representative. The values of the CVRMSE and NMBE are equal or below 30% and 15%, respectively, for most spaces. However, two spaces are not in that range of accuracy of CVRMSE: the garden shop office and food service. These slight inaccuracies are explained by the position of the sensors at those spaces.

The data logger positioned at the food service was near the kitchen and the heat gains generated in that space. Thus, the measured temperatures in that space are normally higher than the simulated data, generating the inaccuracies observed in the validation process. The garden shop office sensor was positioned on a shelf, not well representing the room temperature, which affected the accuracy of the validation for that space. For the rest of the spaces, the values are within the expected level of accuracy, thus it is considered that the WBSM is accurately representing the building.

The results show the complexity of the natural ventilation strategy, which is composed of a number of different features. Besides the internal spaced connectively, all the other features are key architectural elements, which not necessarily is the responsibility of the building designer. This endorses the idea of having a cooperative team working together in order to have an efficient building, especially when involving a naturally ventilated building.

NATURAL VENTILATION ASSESSMENT

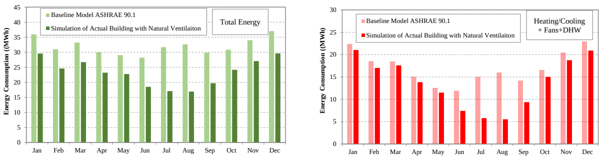
In order to determine if natural ventilation design is successfully applied in the case study building, the following criteria need to be met:

1. Reduce the annual energy use through cooling and fan savings by essentially replacing the cooling system and airflow distribution system with the natural airflow;
2. Ensure internal space temperatures are maintained at or below acceptable design conditions throughout the occupied period;

ENERGY COMPARISON BETWEEN ACTUAL BUILDING AND BASELINE MODEL

One benefit of using natural ventilation is to reduce the amount of electrical energy that would be used in mechanical ventilation and to cool the spaces. Thus, to determine if the case study natural ventilation design is successful, the building must demonstrate that its annual whole building energy use and energy cost is equal to, or less than, that of the baseline building while also maintaining design conditions and thermal comfort within the design and acceptable limits. It is considered that if the above statement is false for the building, the natural ventilation strategy has failed.

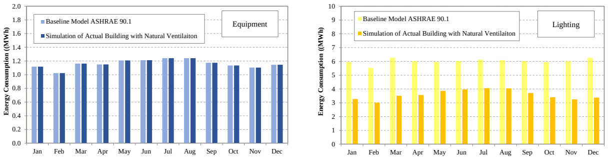
The baseline reference model is generated following the specifications determined by ASHRAE 90.1 (2010) representing a typical baseline building. In the WBSM baseline, the mechanical cooling is included, differently from the actual building that uses natural ventilation as the only source of cooling year-round. The cooling setpoint is 25°C (77°F) at occupied times and 27.2°C (81°F) at unoccupied times. Figure 7 shows the results of energy consumption for the baseline and the validated model for the case study. The energy consumption is separated in mechanical system (i.e. heating and cooling energy, fans, pumps, and domestic hot water) equipment and lighting.



a) Total energy consumption

b) Mechanical system (Heating/cooling + Fans + DHW)

Figure 7 Comparison between baseline and actual building energy consumption [1]



c) Equipment energy consumption

d) Lighting energy consumption

Figure 7 Comparison between baseline and actual building energy consumption [2]

As illustrated in figure 7, the baseline energy consumption is higher than the model of the actual building with the natural ventilation. The difference between the models is observed in the mechanical system and lighting. The energy savings of the actual building model in comparison with baseline model is 27% for the year-round. From that savings, 58% results from the mechanical system and 42% of the lighting system. The bigger savings occur in the summer resulted from the energy used to mechanical cooling in the baseline model. The actual building uses natural ventilation in order to deliver thermal comfort to the occupants during the summer. Therefore, regarding the energy performance, it is possible to conclude that the natural ventilation design is not compromising the building energy usage when compared with the baseline model.

THERMAL COMFORT AND OVERHEATING UNDER NATURAL VENTILATION

The assessment of thermal comfort and overheating is focused on the period that natural ventilation is being used. The method used to evaluate the thermal comfort during natural ventilation is the adaptive thermal comfort developed by ASHRAE Standard 55 (2013). In association, a metric used to determine the building overheating during the summer is the exceedance hours method (*EH*), also presented by same the standard. This metric allows the quantification of the number of hours in which indoor environmental conditions are outside the comfort zone requirements during the occupied hours of the period of interest. To this end, the calculation of the *EH* follows equation 1.

$$EH = \sum (H_{>upper} + H_{<lower}) \qquad (1)$$

where,

$H_{>upper} = 1$ if $t_{op} > t_{upper}$ and 0 otherwise;
$H_{<lower} = 1$ if $t_{op} < t_{lower}$ and 0 otherwise;
t_{upper}: upper comfort range;
t_{lower}: lower comfort range.

When using the adaptive model, the prevailing mean outside temperature ($\overline{t_{pma(out)}}$) was calculated using a linear average of the last 15 days temperatures, following the guidence proposed by ASHRAE Standard 55 (2013). The data used in the analysis is only related to the building occupied hours, which is from 10 AM to 9 PM at summer time. The same concept is applied to the *EH* calculation. Differently from what is recommended by ASHRAE Standard 55 (2013), which uses the operative temperatures (t_{op}) in the adaptive thermal comfort approach, the spaces air temperatures were used in the analysis instead.

The thermal comfort analysis is made using both simulated and measured data. The simulated data is relative to the months of July and August – the period of the year that natural ventilation is mostly used, and the measured data is relative to 15 days of measurements during August of 2017.

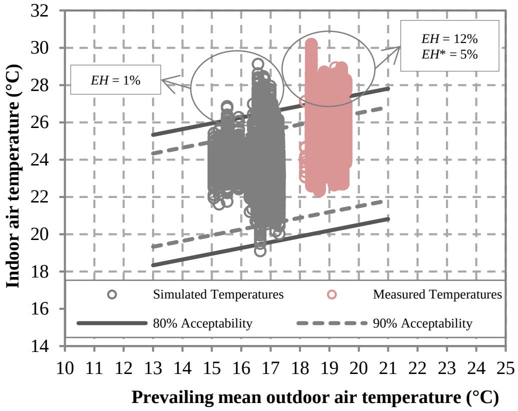


Figure 8 Adaptive thermal comfort for the simulated and measured internal temperatures

The discrepancy between the simulated and measured data is a result of the difference between the prevailing mean outdoor temperature ($\overline{t_{pma(out)}}$). The weather recorded during the filed testing were consistently higher than the simulated data. Thus, the measured data presents higher $\overline{t_{pma(out)}}$ values than the one of the simulated in the WBSM, which explains the gap ilstrated in figure 8.

The difference between the temperatures recorded on-site and the ones presented in the simulation generated higher overheating for the real building in comparison with the simulation. The simulated data showed an *EH* of 1% for the building during the occupied time. However, for the measured data, it was shown *EH* of 12% and *EH** of 5%. The *EH** does not take into consideration the garden shop office and food service, two rooms that presented considerable higher temperatures and problems in the position of the sensors (previously explained at the validation section). CIBSE TM52 (2013) defines that the exceedance hours (*EH*) should not exceed 3% of the occupied time from the period of May to September. Thus, according to that criteria, the simulated results (*EH*=1%) from the WBSM are well within the expected range. The measured data, on the other hand, presented an *EH* of 12%. But excluding two problematic sensors, the building shows an *EH** of 5%. This value is higher than expected, but the field testing when the data were measured was during 15 days of August the historically warmest month in Vancouver. If the field testing was extended to a longer period, the value of *EH* was likely to be under acceptable range. Notwithstanding, alternative measures need to be taken in order to avoid overheating during the summer.

CONCLUSIONS

The main challenges faced in the calibration/validation of the WBSM case study were the low quality of energy data. Better quality data is needed in order to achieve a higher level of calibration following the methodology used for calibration/validation. The model of the case study building is particularly challenging because all the spaces have high ceilings, and this challenges the AFN fully-mixed room air principle. So, a software workaround was needed in order to address this limitation: representing each zone as a zonal model with spaces stacked vertically on top of each other.

As a main driving force of natural ventilation, the weather brings extra complexity to building simulation when natural ventilation is considered. As observed in the thermal comfort and overheating analysis, the outside temperatures recorded on-site were consistently higher than the ones applied to the model (figure 8). That discrepancy generated higher indoor temperatures in the actual building when compared with its simulated model. Therefore, it is highlighted the importance of the weather data used in the simulation. The use of a weather file for the overheating analysis may be considered by the building designers in order to avoid undesirable high temperatures during natural ventilation.

Notwithstanding, even with the challenges faced on the natural ventilation assessment it is possible to conclude that natural ventilation design was successfully applied to the case study.

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